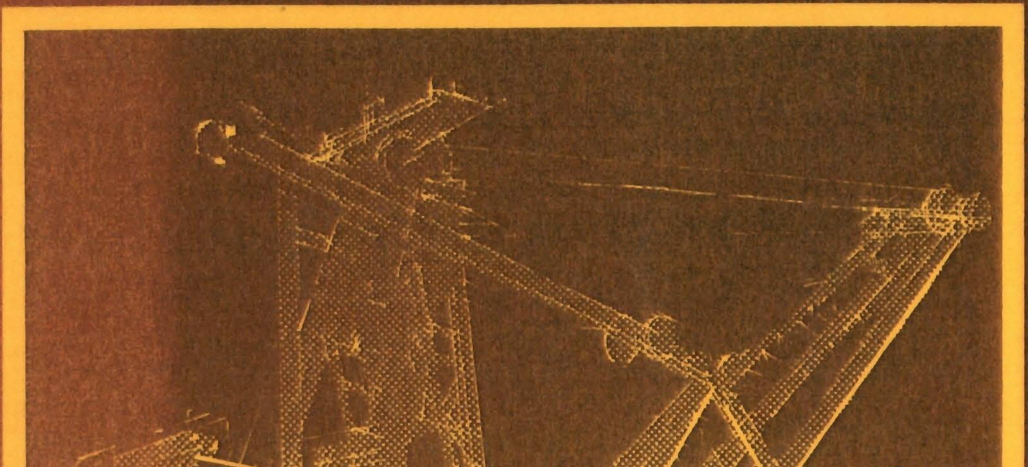
IIASA PROCEEDINGS SERIES

Future Coal Supply for the World Energy Balance

Third IIASA Conference on Energy Resources, November 28-December 2, 1977

Michel Grenon, Editor



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Volume 6

Future Coal Supply for the World Energy Balance

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FUTURE COAL SUPPLY FOR THE WORLD ENERGY BALANCE

Third IIASA Conference on Energy Resources,
November 28-December 2, 1977

MICHEL GRENON
Editor

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PREFACE

First, I should like to recall the problem of estimating mineral and energy reserves and resources. By definition, the *reserves* are geologically well known and economically recoverable. The *resources* are hypothetical, or even speculative, and/or at present subeconomic (according to the McKelvey classification).

Unfortunately, especially for the long-term energy strategy studies that are an objective of IIASA's Energy Systems Program, the resources—and their potential for being reclassified as reserves—are poorly known. This, along with the desire to supplement our own studies, is the main motivation for organizing an IIASA Conference on Energy Resources every year.

This conference was our third. The first two were *Energy Resources, Models and Methods of Assessment,** May 1975, covering the various methods of assessing coal, petroleum, and uranium resources, and *The Future Supply of Nature-Made Petroleum and Gas,*† July 1976, organized jointly with UNITAR and reviewing some twelve petroleum resources and their prospects for contributing to the world energy supply.

It was natural that our third conference should be devoted to coal and thus end the first research cycle on fossil fuel resources.

I would like to thank some of the many people who helped to organize this conference, to run it, and to prepare the papers for publication. First of all, my gratitude goes to our Soviet colleagues and hosts: to Professor J. Gvishiani, Chairman of the IIASA Council and Deputy Chairman of the State Committee for Science and Technology of the Council of Ministers of the USSR, for supporting our idea of holding the Third IIASA Energy Resources Conference in the Soviet Union and for making it possible and successful; to Academician M. Styrikovich, for chairing the Organizing Committee of the conference and for his continuous support and interest in IIASA projects; to their collaborators, for their invaluable contributions and

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*Grenon, M., ed. (1976), *Proceedings of the First IIASA Conference on Energy Resources*, CP-76-4, International Institute for Applied Systems Analysis, Laxenburg, Austria.

†Meyer, R.F., ed. (1977), *The Future Supply of Nature-Made Petroleum and Gas—Technical Report*, Pergamon Press, New York.

help in organizing the conference; and to members of the State Committee for Science and Technology and of the All-Union Institute for Systems Studies—especially Mrs. S.L. Boitsova and Mrs. S.L. Sokolova and Messrs. A.A. Arbatov, A.S. Astakhov, E.P. Cherkasov, B.A. Larionov, A.V. Nadezhdin, Y.M. Pavlov, and I.P. Shvartz.

It is also a great pleasure to thank Professor G. Fettweis, of the Montanuniversität, Leoben, for his valuable help in drafting the conference program, reviewing the papers, preparing the discussions, and enlightening me with his broad coal-mining experience. I must also thank him for his help with the difficult problem of reserves and resources, and for devoting, with indefatigable kindness, part of his valuable time to organizing our conference.

Finally, I owe a great debt of thanks to my colleagues at IIASA, especially M. Sachs and D. Tillotson for the enormous task of editing the papers, B. Lewis for her valuable contribution in checking the consistency of all names and places, and H. Frey and E. Grubbauer for redrawing a large number of figures. All of them have made this publication possible. And last but not least, my thanks go to the staff who were with me in Moscow, who shared the responsibility for the conference, and whose kindness and patience remained unwavering during all the difficulties that always accompany such a conference: I. Beckey, V. Landauer, and G. Lindelof.

M. GRENON

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INTRODUCTION

This conference, the third in a series dealing with energy resources, was more or less evenly divided between the technical and economic aspects, and national, international, and global coal policy problems.

From estimates of coal resources and reserves--more than 10,000 × 10^9 t and 640 × 10^9 t respectively, according to the last survey of the World Energy Conference--it is clear that large, still untouched coal deposits exist. In fact, these figures are continually being revised upward as a result of increased world energy prices and new exploration programs. While these programs will probably not dramatically change the dominance of the three giants--the USSR, the USA, and China--in world distribution of coal, large deposits are being found in various developing countries, thus enabling them to improve their energy situation appreciably.

It is interesting here to look at the possible production curve proposed by the World Energy Conference experts, with a maximum production level of 8.7 × 10^9 tce per year in 2020. Although the study does not state that there will be no further increase, we have assumed that production will, in fact, level at 8.7 × 10^9 tce per year for many decades: until about 2065 if the reserves are only 640 × 10^9 tce, or until 2130 if they were to climb to 1200 × 10^9 tce, a possibility mentioned by the World Energy Conference experts.

For our own studies, we have aggregated this curve with similar curves established for oil and gas by other World Energy Conference experts, and have made the same (unrealistic) assumption of constant production until final exhaustion. The result is shown in Figure 1. Fossil (conventional) energy production could, around the year 2000, reach a peak of about 17 × 10^9 tce, and more or less stabilize for a few decades at 16 × 10^9 tce, half of which would be supplied by coal. This is a fairly high level of energy consumption compared to present energy demand scenarios. Finally, if for oil and gas we would like to maintain not the declined but the maximum levels of 2020, this could be achieved by progressively phasing in unconventional oil and gas--the resources studied in our second conference--at a level of about 4.4 × 10^9 tce, with maximum fossil production continuing for a few decades at the maximum level. Thus fossil fuel, and especially coal, is able to provide the time necessary for introducing new energy technologies, be they nuclear, solar, or unconventional coal mining.

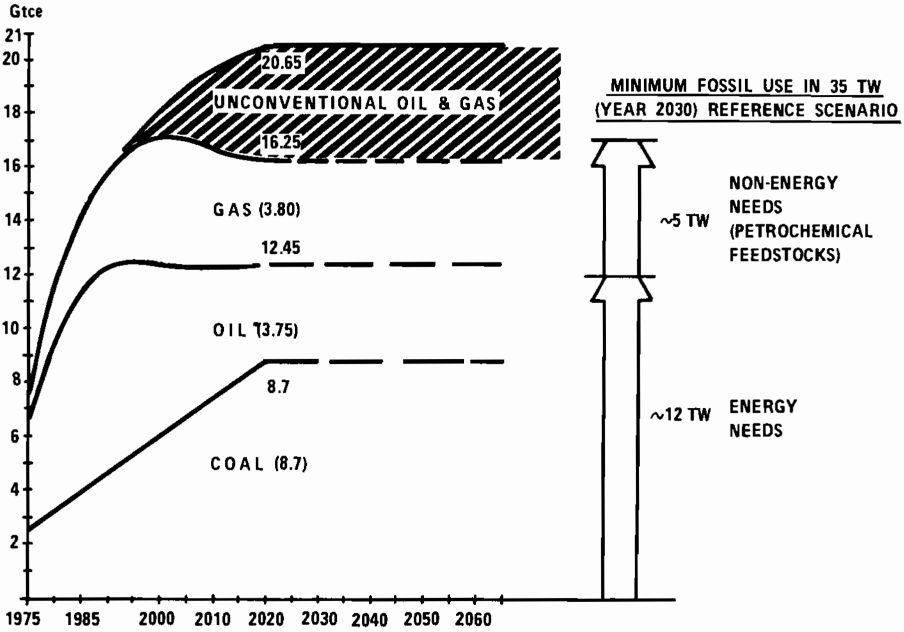

Figure 1. Total fossil fuels: possible production and lifetimes.

For comparison, at the right of the figure are the values of fossil fuel demand in a IIASA reference scenario, showing a rather high total energy demand of 35 TW in the year 2030.

To mine these huge reserves, two main types of coal extraction may be used: underground and surface. Underground mining has now reached maturity, and has greatly benefited from increased mechanization and automation. Hydraulic mining, pioneered in the Soviet Union, is now being experimented with in the USA, Canada, the FRG, and other countries. Over the long term, more radical changes--reviewed in a provocative paper from the UK National Coal Board--are foreseen, from robots to hydraulic bore hole mining, from microbiological attack to in situ liquefaction. By far the most advanced of these futuristic but promising technologies is in situ coal gasification, also pioneered in the Soviet Union during the last three or four decades. There is growing interest in many countries--Poland, the USA, the FRG, France, and others--in underground gasification (mining without miners!), including the method of high-pressure underground gasification proposed by Belgium. Should this method succeed, which is not certain, it could ease the problem of the interaction of the in situ coal process with underground water reservoirs (a WELMM aspect of coal mining). Moreover, many coal deposits now considered uneconomic or technically unexploitable owing to their depth would become exploitable and could dramatically increase world coal reserves.

Pending these long-term prospects, most of the big increase in world coal production in coming decades is expected to come from surface mining. Here, the trend is toward gigantism. This applies to equipment--such as the impressive German bucket wheel excavators able to "eat" 200,000 m^3 of rock or coal per day--and also to the opencast mines themselves: in the western USA, 10 to 20 × 10^6 tons per year; in the FRG 30 to 50 × 10^6 tons per year at Garsdorf, plus a potential production of 100 × 10^6 tons per year at the planned Hambach mine in the Rhine area; and in Siberia, at Ekibastuz (coal seam of 130 m thickness) and Kansk-Achinsk.

These developments raise the interesting question whether there is a maximum reasonable size for large-scale coal mining equipment and coal mines. (The trend toward gigantism--which of course is not peculiar to coal mining, but is met also in offshore oil exploration and production and in oil transport, as shown in Table 1--parallels some of the provocative IIASA reflections on big scales, aiming at the "terawatt domain".) According to some opinions, for instance, the bucket wheel excavators at present being built in the FRG for the Garsdorf and the future Hambach mine, with a capacity of 200,000 m^3 per day, are really approaching their limits and will begin to face "diseconomies" of scale. This is probably one of the open questions of future large-scale coal mining.

The giant mines in the western USA and in Siberia will have very low production costs--a few dollars per ton compared to the price of $100 per ton--but there is the problem of long-distance

Table 1. Comparison of some of the largest mobile energy facilities.

Equipment	Capacity [m^3] Unit	Capacity [m^3] Daily	Main Dimensions [m]		Working Weight (Unloaded) [t]	Installed Power [kW]
Stripping shovel	137-152	150,000	67	Boom	12,620	15,670
Walking dragline	167	165,000	100	Boom	11,940	14,926
Bucket wheel excavator	5 × 18	200,000	200	Total Length	13,000	14,000
Semisubmersible oil platform	--		88 × 66 × 42		41,000	15,272
Supertanker	~600,000	--	414 × 63		77,000 (Steel)	47,700

transport by rail, by pipeline, or by wire after on site conversion to electricity. It became clear during this conference that this is one of the major factors in the development of a future world coal market: unlike oil, coal does not seem to be supply- or resource-constrained, but faces great difficulties in transport, both technically and economically. The promising use of pipelines was discussed, including the (expensive) proposal to use as a transporting fluid methanol derived on site from the coal in regions lacking water resources (like the western USA).

A final comment on these technical problems results from the comparative experiences of our three Energy Resources Conferences. In considering present advanced coal technologies--and still more, future coal technologies, as described in the fascinating paper by Messrs. Evans and Tregelles--we are more and more impressed by the growing interchange of ideas, techniques, and processes among the coal, oil, and gas industries. There is a growing interrelationship also from the financial and organizational point of view, especially in the USA and increasingly in the Western countries, where oil companies are becoming ever more involved in the coal business. Some of the interrelationships between coal and oil extraction technologies, illustrated in Figure 2, are the following.

- *Seismic exploration,* one of the basic tools of oil research, is now being used to look for coal (as is shown by the paper of Farr and Peace);
- *Oil shale and tar sand mining* benefit from the big earth moving equipment that is so successfully used in surface coal mining;
- *Bore hole hydraulic mining,* which is being explored by the U.S. Bureau of Mines for coal, will draw on the experience of oil drilling;
- *Enhanced oil recovery* can contribute to possible in situ coal solvent liquefaction or chemical comminution;
- *Underground coal gasification* studies and in situ oil shale retorting will probably be developed in parallel, along with massive hydraulic fracturing for tight gas formations;
- The same probably applies to in situ *microbiological degradation.*

Similar examples could be given for the various downstream operations, from coal slurry pipelines to the production of synthetic natural gas from coal.

We feel that this is an important evolution, and that the great potential for the expansion of new coal technologies will probably be enhanced by this new husbandry, which succeeds decades of vigorous competition.

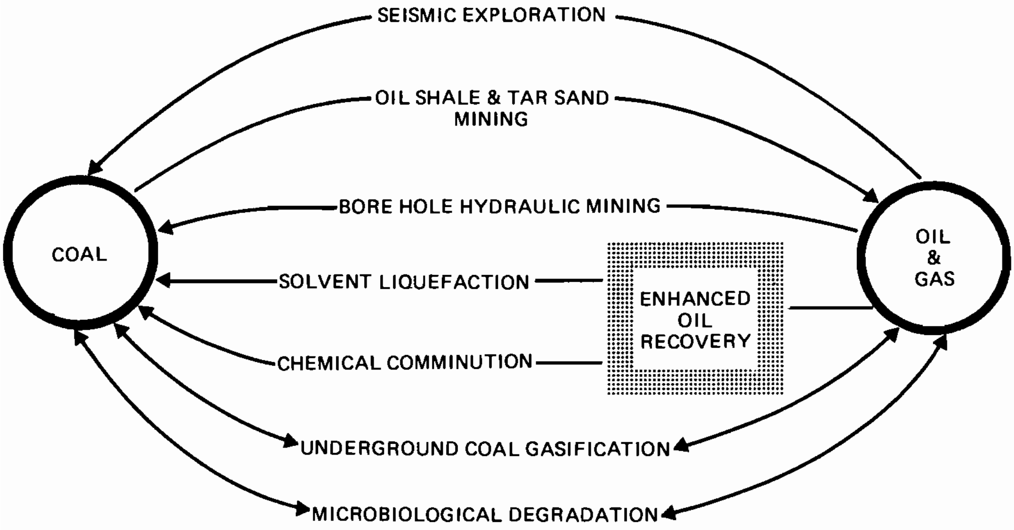

Figure 2. Some interrelations between coal and petroleum extraction technologies.

The second part of the conference was devoted to reviewing and analyzing the present role of coal and its prospects for meeting a further increasing energy demand, in line with IIASA's Coal Task Force studies. Sixteen papers examined the situation in the following ten countries: Austria, Czechoslovakia, the FRG, Hungary, India, Japan, Poland, the UK, the USA, and the USSR. The time horizon was short- to medium-term, and the main questions addressed were those of increasing national reserves; improving present mining techniques; planning coal production in view of the general energy supply situation of the various national economies; extending consumer markets for coal in order to substitute for larger fractions of the oil and natural gas markets; and protecting the environment from impacts of extended coal production and consumption.

A few general conclusions, in addition to the technical aspects reviewed above, evolved from the presentations and discussions. One is the fact that apart from metallurgical applications, coal consumption will expand mainly through its increased use for electricity production; another, that long lead times and very long-term technical choices are inherent in the extension of the coal system. Of course, evaluations of the prospects of coal clearly differed according to the general economic and resource situation in the various countries.

A rather consistent outlook on the more long-term and global prospects developed, somewhat in contrast to that for the medium-term and national prospects. Broad interest was shown in synthetic liquid and gaseous fuels, which could be produced for long periods due to the very large coal resource base. Also, it was clear that requirements to step up world coal trade exceed present national plans and projections. Such an extension is necessary, however, if coal is to maintain its present share of roughly 30% of the primary energy supply. Within this framework, liquefaction and gasification technologies depend on an ample cheap supply of coal, which itself depends heavily on a reasonably cheap transport potential, as already mentioned.

Finally, emissions of CO_2--the combustion product of coal--were discussed as an important global constraint on an expansion of the long-term coal supply. Worldwide efforts in modeling the climatic consequences of a significant further increase of atmospheric CO_2 point to climatic changes that might possibly occur in the next century. Much more work is needed before the CO_2 risk can reliably be quantified.

COAL OCCURRENCES AND COAL RESOURCES OF THE WORLD

WORLD COAL BASINS: REGIONAL TECTONIC POSITION AND COMMERCIAL VALUE

N.I. Pogrebnov, D.S. Safronov, and I.A. Berthels-Uspenskaya

INTRODUCTION

Present-day methods of development of coal deposits place high demands on the fullness and reliability of geological prospecting data and on the results of investigations of the deposit structure, which is largely determined by the tectonic processes at work during the formation of coal-bearing deposits. Regional tectonics is probably the decisive factor for the structural features of coal basins and deposits, the position of basins and deposits within the regional structure, and, finally, their commercial value.

Lately much attention has been given to these questions in the USSR. Scientific studies on the tectonics of coal basins and deposits cover a vast range of problems, from regional to purely practical ones connected with exploitation of deposits.

In this report we shall try to approach the determination of the tectonic position of the most important world coal basins and to analyze their commercial value from this point of view.

As numerous published papers on the geology of coal basins and the tectonic structure of regions show, coal basins and deposits are associated with territories of old and young platforms, with epiplatform orogens, and with areas of Paleozoic and Meso-Cenozoic geosynclinal folded structures. The position of coal basins in such areas is in turn predetermined by the existence of many smaller structures and structural zones, of which we shall examine only those associated with the most important coal basins.

Beyond doubt, the regional structure of some basins remains disputable due to the lack of geological data on certain regions and to the differences in their interpretation.

COAL BASINS OF OLD PLATFORMS

Coal basins of old platforms are located solely in the sedimentary complexes of the platform cover. Four groups of basins and deposits can be clearly distinguished by structural features, character of coal-bearing formations, and quality of coals:

- Basins confined to intraplatform synclines;
- Basins associated with grabens, rifts, and aulacogens;
- Marginal platform basins;
- Deposits of salt-dome tectonics.

The first group includes the Near-Moscow, Kama, and Dnieper basins on the Russian platform, the Tunguska basin and the Vilyui part of the Lena basin on the Siberian platform in the USSR; numerous basins on the North American platform (the Michigan, Illinois, and Texas Fort-Union basins); on the South American platform, the Rio Grande do Sul, Santa Catarina, and Alta-Amazona basins; and Witbank, Kalahari, and other basins on the African-Arabian platform. Basins of the North Chinese and South Chinese old mobile platforms--for instance, the Ordos and Shansi coal basins--are also related to this group.

Simple tectonic structure is typical of these basins. Horizontal or near-horizontal layers are weakly dislocated by gently dipping secondary structures. The thickness of coal-bearing rocks is not great (250 to 300 m, rarely up to 800 m). The enclosing rock consists mostly of sandstones, argillites, and clays, sometimes intercalated with limestone. The number of seams ranges from a few to 30, their thickness being 0.7 to 3.5 m (up to 6 to 12 m).

As a rule, the Paleozoic coals of this group are hard, characterized by an average or low degree of metamorphism. The Cenozoic coal-bearing formations contain brown coals or lignites. The basins are rather large in size--tens or even hundreds of thousands of square kilometers. The resources of such basins are estimated to be 10^{12} t.

Coal basins of the second group are widely spread on the African-Arabian and Indian platforms and include the Damodar, Godavari, Tete, Ruhuhu, Laungwa, and other basins. The Fitzroy basin in Australia is conventionally included in this group. The thickness of coal-bearing measures, represented generally by the continental terrigenic-sedimentary rocks forming these basins, runs up to 2000 to 3000 m. The blocky structure of the basins, predetermined by the presence of a great number of faults, is sometimes complicated by folding and dikes of intrusive rocks (mainly dolerites).

The number of coal seams does not exceed 20 to 30. As a rule, these are hard coals with average or high ash content. The intensity of metamorphism can reach that of coking coals but in most cases is somewhat lower. The coal resources of such basins range from 30 to 50 × 10^9 t.

Deposits of the third group are represented by the basins in the areas of marginal platform depressions adjacent to orogens, for example the Lvov-Volynsk basin on the Russian platform; the Irkutsk and South-Yakutsk basins, the Vilyui part of the Lena basin, and other basins on the Siberian platform; and the Powder-River, Denver, and Raton-Mesa basins on the North American platform. Such basins are characterized by a zonation of the tectonic structure: adjacent to the orogen, lineal-block structures are developed, generally with rather distinct lineal folding and a great number of faults; in the zone facing the platform, simple monoclines with a few faults are developed. The zone adjacent to the orogen is characterized by the greatest amount of coal and the highest seam thickness. The coal resources of basins of this type are estimated to be several billion tons.

Coal-bearing deposits of the fourth type are found in the areas of salt-dome tectonics. Their uncomplicated tectonic structure is represented by slightly dipping isometric troughs. The coals are of a low degree of metamorphism. The commercial value of such basins is insignificant.

COAL BASINS OF YOUNG PLATFORMS

In contrast with old platforms, the coal-bearing formations on young platforms developed both in the basement and in the platform cover, which is mainly of the Meso-Cenozoic age. Deposits associated with the basement are, in fact, formations of folded areas, which will be considered later in this paper.

Deposits of the platform cover may be of two types:

- Basins associated with synclines, intraplatform and marginal depressions and troughs: the Ob-Irtish basin and the Chulim-Yenisei part of the Kansk-Achinsk basin on the West Siberian platform in the USSR, the Parisian and Germanic basins on the West European platform, and the Mississippian basin on the Epi-Paleozoic platform in southern North America;

- Basins associated with grabens and graben-like structures: basins of the Lower Rhine type and a group of basins of North Afghanistan located in the southern part of the Turanian plate, as well as the Chelyabinsk, Turgai, and other basins on the West-Siberian platform.

Coal basins of the first type are characterized by vast areas of coal-bearing formations. The thickness of coal-bearing rocks is not great, rarely exceeding 1000 m. Coal seams along the strike are sometimes of great, though variable, thickness. The degree of metamorphism is insignificant: as a rule, these are brown coals. The tectonics of such basins is simple; gently dipping inherited structures weakly affected by faulting predominate. The resources of these basins are estimated to be some hundreds of billions of tons.

In the graben-type structures, the coal basins are considerably smaller in extent, but the thickness of coal-bearing formations and of the seams also increases, the latter reaching 100 m. The blocky structure accounts for the complexity of the deposit tectonics. The reserves of the graben-type coal basins vary from a few billions to tens of billions of tons.

COAL BASINS OF EPIPLATFORM OROGENS

Among the basins of epiplatform orogens are those originating in the period of formation of the platform cover, and those formed during orogenic transformation of platforms.

To the first group belong the coal basins of the Sierra-Pampa orogen, which appears to be a block of the South American platform; this block was involved in orogenesis in Cenozoic times. Due to the intense orogenic activity of that period, coal-bearing formations in this region were preserved in rather narrow grabens separated by horsts. As a rule, the coal-bearing deposits are highly deformed. Their age is determined as Carboniferous, Triassic, and Cretaceous; their commercial value is insignificant.

To the second group belong a number of basins of epiplatform orogen of the Rocky Mountains in North America--for instance, the Big Horn, Wind River, Green River, Uinta, and San Juan basins, and several smaller ones. Such basins have, as a rule, simple tectonics. The structures are represented by relatively simple asymmetric depressions with rather even occurrence of the seams in the central parts and complicated limbs adjacent to the uplifted blocks. The western limbs of the depressions dip more steeply than the eastern ones.

Within the depressions the basement is as low as 2000 m or more. Along the limbs of the depressions, brachy-anticlinal and domal uplifts are frequent. The uplifts are arranged in echelon, forming one or more anticlinal zones.

The formation of the coal-bearing strata, varying in thickness from 2 km (the San Juan and Big Horn basins) to 7 km (the Hanna basin), coincided with the period of subdivision of this part of the platform into several blocks in the Mesozoic folding displayed in the Cordilleras. The coal basins mentioned above are associated with the subsided blocks. Coal-bearing sediments are concentrated in the upper parts of the Cretaceous sequence. They consist mostly of aleurolites, sandstones, shales and sporadic limestones. The thickness of the coal-bearing strata is about 300 m, rarely up to 1800 m. The number of coal seams varies from 8 to 15, their thickness ranging from 0.75 m to 3.5 m and sometimes increasing to 9 to 13 m (the Uinta basin). The coals are mostly subbituminous and partly bituminous, with high and medium content of volatiles. The degree of metamorphism abruptly increases near the fault blocks of the basement, which was subjected to intensive movements accompanied by the intrusion of magmatic rocks in Cenozoic time.

Coal basins associated with the Rocky Mountain orogen possess large commercial reserves of coal, but until recently their exploitation was carried out slowly. Lately these basins were given an important place in the US energy program as a coal-supplier not only for the western states but also for the central and even the eastern ones.

COAL BASINS OF FOREDEEPS

Foredeeps are mostly associated with Paleozoic and Mesozoic geosynclinal folded areas. The largest coal basins of both the Northern and the Southern hemisphere are connected with the foredeeps of Paleozoic, mainly Hercinian, folded complexes.

The Pechora basin in the USSR is of this type, as are the Boulogne, Pas de Calais, Sydney, and Bowen basins. The coal-bearing deposits of these basins are characterized by great thicknesses (8 to 10 km) and a very large number of seams. In the platform part the deposits are weakly dislocated: the seams are inclined, with frequent dome development. In the part adjacent to folded complexes, long narrow folds often connected with faults occur. The folds are dislocated by numerous faults transiting into thrusts. Metamorphism is average, and the coals are of high quality, often coking. Owing to their large reserves (up to 10^{12} t) these basins take the first place in world coal output.

From the coal-saturation point of view, foredeeps associated with the areas of Meso-Cenozoic folding are of less interest: the coal basins connected with them are not numerous. In the USSR these are the Ziryanka and Bureya basins; elsewhere, the Colville and Alberta basins. The tectonic structure of these basins is rather complicated, especially in the zones adjacent to folded complexes.

The tectonics is simpler in the near-platform parts where the seams dip slightly. Metamorphism of the coal is not high except in the Alberta basin in North America, where it reaches the degree of anthracites. The resources of such basins amount to tens of billions of tons.

COAL BASINS OF FOLDED AREAS

In folded areas, the coal-bearing formations are widely spread and of various kinds. Those of the orogenic areas are divided into three types according to location. To the first type belong the areas of Karelian and Baikalian folding; to the second, the areas of Caledonian folding; and to the third, the areas of Hercinian, Mesozoic, and Alpine folding.

There are no coal-bearing formations of geosynclinal development in the folded areas of the first type. Here the formations of the postorogenic stage predominate. The main structural forms of the coal basins in the areas of Karelian and Baikalian folding are superimposed depressions (the Chara, Chetkanda, and Bukacha deposits of the USSR).

Caledonian Folding

The areas of Caledonian folding contain considerable coal-bearing formations, both in inherited depressions and in superimposed basins. The Karaganda basin is located on Caledonides of the Central Kazakhstan folded area in an inherited depression. The Kuznetsk coal-bearing formation is connected with inherited depressions of the Altai-Sayany Caledonides. The Carbonic-Permian coal basins in West Mongolia, Scotland, and northern England are also of this type.

Coal-bearing formations of inherited depressions are characterized by thicknesses reaching 8000 to 10,000 m, a high percentage of coal, and rather complicated tectonics (Kuznetsk, Karaganda basins). Inherited depressions as a rule adjoin large normal faults, near which small folds and numerous faults occur. In the inner parts of the depressions the tectonics is less complicated. The coals are of an average degree of metamorphism.

The superimposed basins on Caledonides comprise the Maikyuben, North Sokur, and Mikhailovsk basins in the Central Kazakhstan folded area in the USSR. A number of similar structures located on Caledonides of the Transbaikalian area contain coal-bearing formations (Chikoi, Khilok, Ingoda, Uda basins). The Jurassic coal-bearing formation of the Kuznetsk and Ulugkhem basins on the Altai-Sayany Caledonides also appears to be superimposed.

On Caledonides of Mongolia, especially in their eastern part, Cretaceous, and to a lesser degree Jurassic, superimposed depressions occur. The formation of such depressions is associated with the existence of long-lasting faults, as a result of which their inner structure is usually complicated. The coal-bearing formations mostly contain brown coals, the reserves of which are not great.

The Jurassic coal basins associated with superimposed depressions (Muli, Datun, Yotse, Shaou, Lishan) are located on Caledonides of Tsilienshan and the Cathasiatic folded area. The basins are small, and the coal seams characterized by complexity and instability of structure; nevertheless, the coals here are hard (except in several basins in Tsilienshan). In the southwestern part of the Cathasiatic folded system there is the Anchau super-imposed depression formed of Triassic-Cretaceous detrital sediments of great thickness, with which the largest coal basins of Vietnam are connected.

On Caledonides of Asia as a whole there is general northward rejuvenation of the Mesozoic coal-bearing formations from Triassic in Vietnam, and Jurassic in Cathasia and Tsilienshan, to Cretaceous in Mongolia, and the degree of metamorphism decreases in the same direction from anthracites to brown coals.

On Caledonides of Australia, Cenozoic, mainly brown coal basins are located; among them are the Latrobe Valley basin, which is the largest in the country, and a number of Neogene coal basins west of Melbourne.

In general, the coal-bearing formations in superimposed depressions on Caledonides have relatively small thickness (500 to 2000 m) and carry an average percentage of coal. There are coal seams of thickness up to 20 m, tending to split toward the marginal parts of the depressions; more continuous seams are located in the central parts. The degree of coal metamorphism is not high: brown coals and hard coals with a low degree of metamorphism. The tectonics is simple, becoming more complicated from the center toward the periphery of the troughs. The marginal parts of superimposed depressions often adjoin the scarp of older deposits; as a result, the near-marginal parts of troughs are often affected by faults.

Hercinian, Mesozoic, and Alpine Folding

In contrast with the Baikalides and Caledonides, the coal-bearing formations in the Hercynides, Mesozoides, and Alpides are developed in eugeosynclinal and miogeosynclinal complexes (mainly in the final orogenic stage of development), and in the younger superimposed depressions.

Coal-bearing formations of eugeosynclinal complexes are characterized by extreme instability of composition and structure, by a wide range of thickness, by the presence of igneous rocks, and by rather complicated tectonics. Their commercial value is not great. To this type belong deposits of the eastern slope of the Urals, the Irtish-Zaisan zone, the Verhoyansk, and other folded systems of the USSR; the Rhode Island, Fivemile, and Richmond coal basins in the Appalachians; the Matanuska, Tantalus, and Boucer basins in the North American Cordilleras, and some Permian coal deposits in Australia.

A special group not found outside the USSR consists of the Donetsk and Taimyr coal basins associated with the Hercinian parageosynclinal folded areas of the same name. These areas were formed on the subsided eroded basement of old platforms affected by folding in Hercinian time. The tectonics of these basins is characterized by lineal folding with many faults of overthrust type. There are many thin coal seams in these basins; the coals are of high quality; metamorphism is average to high. The coal resources are estimated to be some hundreds of billions of tons.

Coal basins of the Alpine area of Iran represent a peculiar group associated with the formation of Early-Alpine geosynclinal depressions with a shortened period of development. This group includes the Kerman, Naband-Tabas, and Elbrus basins. The coal-bearing continental, sometimes marine, measures forming these basins have a thickness of up to 5 km, and dozens of coal seams of variable thickness and structure. The degree of metamorphism of the coal varies greatly, from gas- and long-flame coals to anthracites. These basins represent the main coal potential of Iran.

Coal basins of young folded areas (Cenozoic and Early Cenozoic) are located on Kamchatka and Sakhalin. They are characterized by complicated tectonics, instability of coal seams, and insignificant metamorphism.

MAIN CONCLUSIONS

Within continents, coal basins are irregularly distributed in different structural and tectonic units of the Earth's crust. The coal basins are associated with both old and young platforms, as well as with the areas of Paleozoic and Meso-Cenozoic folded complexes.

The commercial value of coal basins depends to a large degree on their position in the tectonic structure of the regions, which determines the structural-genetic features of coal-bearing formations, the qualitative characteristics of coals, and their type and resources.

Basins associated with foredeeps of Paleozoic folded areas and with inherited depressions have the most commercial value. They are characterized by great size, relatively simple tectonics, and dozens of working coal seams, mostly of high quality. Their resources amount to 10^{12} t (the Appalachian, Pechora, Kuznetsk, Bowen, Sydney, Ruhr, and other basins).

Coal basins associated with syneclises and intraplatform depressions of platform cover deposits are also of great commercial value. These basins contain dozens of working seams, mostly of a low degree of metamorphism. Their resources can exceed 10^{12} t (the Tunguska, Illinois, Fort Union, Rio Grande do Sul, Santa Catarina, Ordos, Shansi, Kansk-Achinsk, and other basins).

Coal basins of epiplatform orogens (the San Juan, Uinta, Green River, and Middle Asian Basins) are of less commercial significance.

Coal basins of folded areas are generally small in size and rather complicated in tectonic structure, and their commercial value is not great.

Coal basins of parageosynclinal areas (Donetsk, Taimyr) have a special place; their resources are of order of 100 to 500 × 10^9 t of high-quality coals.

NILZaruleczhgeologia and the Academy of Sciences of the USSR intend to continue investigations of the tectonics of world coal basins to determine their comparative commercial value.

COAL RESOURCE ASSESSMENT FOR THE WORLD ENERGY CONFERENCE, 1977*

H.-D. Schilling

GENERAL REMARKS

At Istanbul, the Conservation Commission and its allied Resources Groups presented seven reports on the following subjects:

- World energy demand,
- Energy conservation,
- Oil resources--worldwide petroleum supply limits,
- Gas resources--the future for world natural gas supply,
- Coal resources--an appraisal of world coal resources and their future availability,
- Nuclear resources--the contribution of nuclear power to world energy supply, and
- Unconventional energy resources.

All these contributions spanned a period from now to the year 2020. These subjects were covered by four round table discussions, of which one was devoted to the coal resources report. The reports were all essentially drafts to be revised in the light of comments received at the conference and after. The revised Executive Summaries are scheduled to be published by the Conservation Commission in February 1978.

The special results of the reports on demand for oil and gas indicated that a significant demand for coal will arise at about the end of this century and beyond. Figure 1 shows the main result of the report on demand which indicates that the increasing demand for energy can only be fulfilled by a substantially increased contribution of nuclear energy and coal.

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*This is a short version of the Executive Summary presented at the World Energy Conference in Istanbul September 1977 by the Commission of the WEC and prepared by W. Peters, H.-D. Schilling, W. Pickhardt, D. Wiegand, and R. Hildebrandt. Some remarks following the discussions of the WEC have been added.

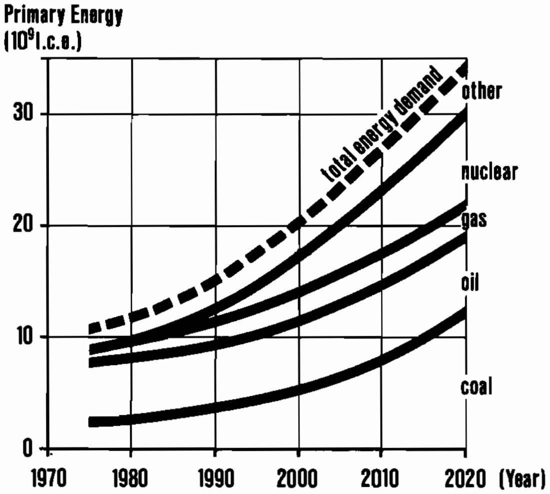


Figure 1. Development of primary energy demand (World Energy Conference 1977).

Figure 2 shows that the maximum oil supply must be expected within this century and the beginning of a consequent supply gap could occur possibly in the eighties. Figure 3 shows the possible gas supply for the world and for Europe, including proved and undiscovered reserves. According to the gas report, a maximum supply on a worldwide basis must be expected at about the end of the century; in Europe the maximum would occur in the nineties.

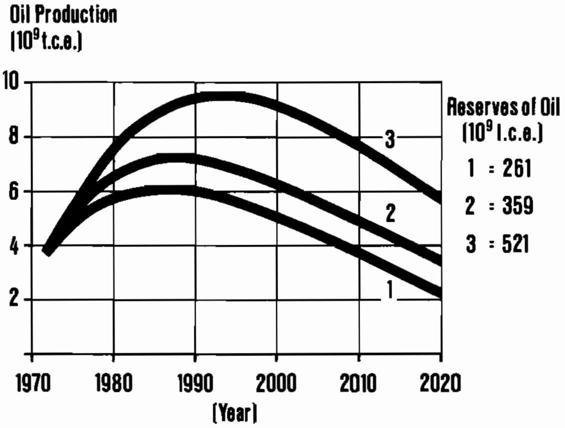


Figure 2. World oil production for different reserves (World Energy Conference 1977).

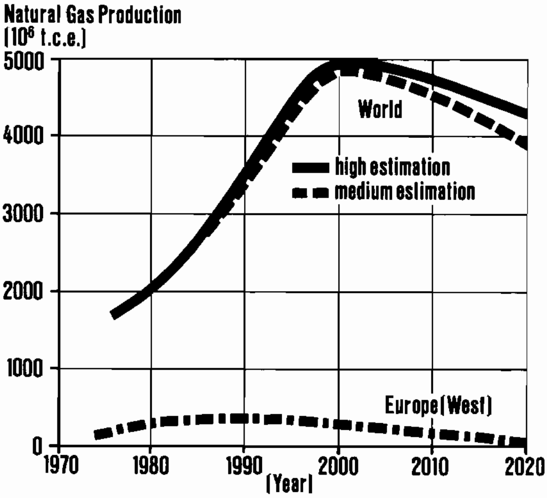


Figure 3. Development of natural gas production—World, Europe (West) (World Energy Conference 1977).

These figures may be revised in the light of comments received at and after the Istanbul Conference and so the figures here may differ a little from those in the final issue in February 1978. Because of the gas and oil shortfalls, many eyes are looking to coal and its potential: to what extent may coal be able to supply future energy demand.

With coal we have a raw material at our disposal, whose utilization and refining potential is unequalled by any other material. The product range, that can be achieved by the available conversion techniques extends from electricity, via gaseous and liquid fuels and chemical feedstocks, right through to coke for blast furnace application and to activated coal to be applied in the field of environmental protection. But there is a disadvantage: The production of coal requires a comparatively high technical and economic expenditure. Furthermore coal is a low-hydrogen, high-molecular material intergrown with mineral substances; therefore, conversion also necessitates a more or less high technical and economic expense.

Thus it must be understood, that the question of whether there are sufficient coal resources is not the only decisive one. *Large resources do not yet mean security of supply*, especially in the case of coal. The term "availability of these resources" is of equal importance.

EXECUTION OF THE STUDY

This study was carried out with two main points of emphasis: by means of an in-depth analysis of the pertinent literature, an attempt was made to obtain a broad basis for comparative statements on the world's coal resources and reserves and their availability; and with the aid of a worldwide questionnaire campaign made at the same time, supplemented by personal talks with experts from the main coal-producing countries, an additional effort was made by means of specific questions to obtain up-to-date and authentic data that would be of particular importance for estimating the coal resources and reserves and their availability. I will now discuss the main results of the study.

DEFINITION OF RESOURCES AND RESERVES

There are many valuable proposals on the classification of the resources, for instance those of McKelvey and Fettweis, but they have not been used by all countries so that it was not possible to refer to a worldwide uniform description and differentiation. We decided to make a differentiation between two categories that seemed to us of the highest importance:

- Geological Resources: resources that will attain an economic value to mankind at some time in the future.
- Technically and Economically Recoverable Reserves: reserves that can be regarded as actually recoverable under the technical and economic conditions prevailing today, i.e. that can actually be extracted. In other words, they include an exploitation factor. The data given are to be distinguished, however, from the "reserve base", in common use in many countries which does not take this exploitation factor into account. Consequently, those figures are not referred to in this report.

RESOURCES AND RESERVES

Figure 4 shows the result of the investigation, in comparison to earlier data published by the World Energy Conference (WEC). The total geological resources are 10,000 × 10^9 tce, 76% being bituminous coal and anthracite, and 24% being subbituminous coal and lignite. Only about 6% of these resources or some 640 × 10^9 tce are to be regarded as technically and economically recoverable reserves. Comparison with earlier data shows that there is an increasing trend in the resource and reserve data.

The investigation has shown that many countries have made a reassessment of their resources and reserves after the oil crisis of 1973, which led to higher resources and reserves. Some countries indicated large new resources. However, these have not

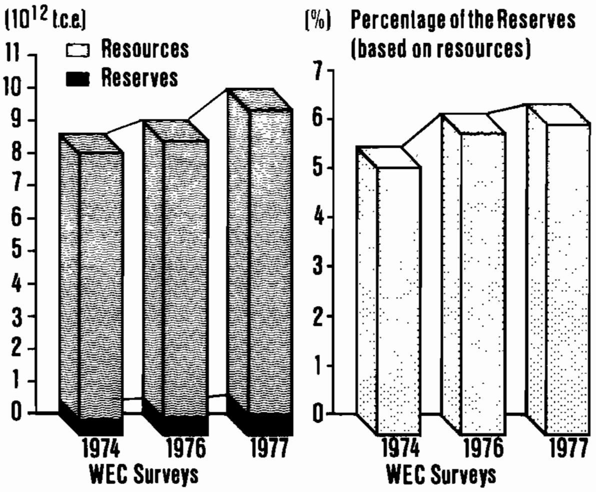


Figure 4. Comparison of coal resources estimated in different years.

been taken into account in the report since they appeard to be too uncertain for the time being. If we had done so, the total geological resources of the world would have increased to at least 12,000 × 10^9 tce.

It is assumed by a number of scientists that the figures for the resources given by some of the individual countries also contain occurrences of such thin seams, and at such great depths, that an economic exploitation can be practically excluded. However, nearly all the data given were accompanied with particulars on seam thickness and depth, which in part should be regarded as realistic under the viewpoint of extractability. In many important coal-producing countries, the figures given for the resources are moreover clearly below the figures that apply to occurrences so that the value of approx. 10,000 × 10^9 tce is to an order of magnitude that which can be regarded as realistic for resources that may be some day of economic interest for mankind. In view of insufficient exploitation in many areas of the world this figure might represent a lower limit.

With regard to the reserves that are considered today as technically and economically recoverable, their share of about 6% of the resources is very low. Countries in general have applied strict criteria in assessing and evaluating this category.

It seems then that the categories of geological resources and technically and economically recoverable reserves have a considerable enlargement potential: New prospecting and exploration activities seem to lead to the discovery of new resources;

even slight increases in the price of oil and gas in the future and new technologies of coal production leading to higher exploitation factors may lead to an appreciable increase in the category of the technically and economically recoverable reserves. In general there is considerable potential behind the resources and reserves we know today.

Figure 5 shows the distribution of the geological coal resources in the world. Figure 6 shows the distribution of the technically and economically recoverable reserves of coal in the world. It is conspicuous that the major part of the coal resources and reserves are concentrated in the northern hemisphere. The different distribution may be due to the fact that the land mass of the southern hemisphere is smaller and that exploration has not yet advanced so far there. Therefore an increase in exploration activity might well result in the discovery of further resources and reserves. The 1000 × 10^9 t quoted as a maximum by Botswana, for instance, in its completed questionnaire, but not yet included in our report owing to still existing uncertainties, and the further successful exploration projects in Indonesia and Australia would appear to confirm this possibility.

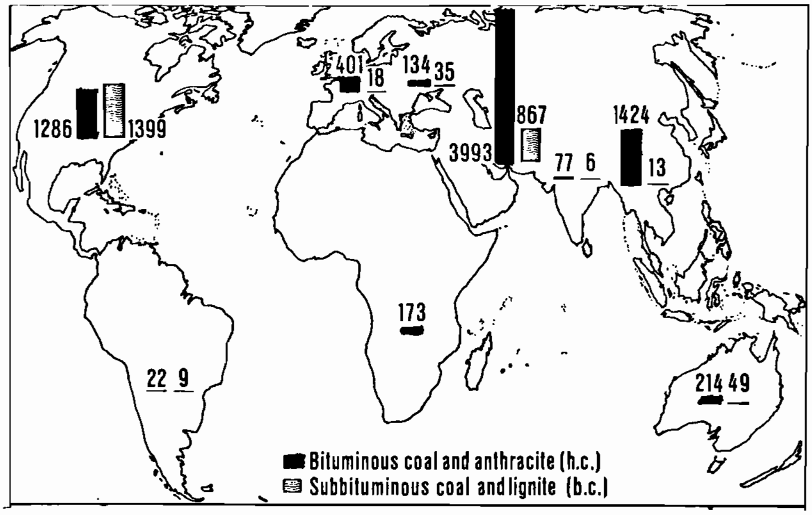


Figure 5. Distribution of coal resources in the world [10^9 tce].

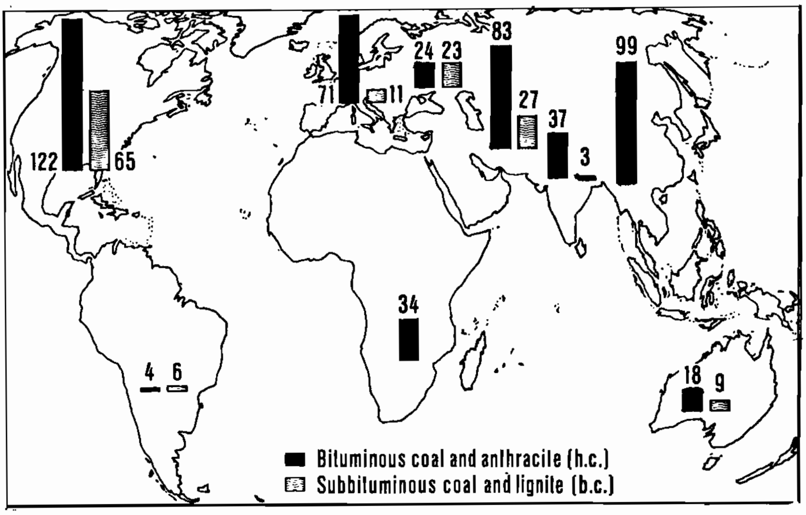


Figure 6. Distribution of technically and economically recoverable coal reserves in the world [10^9 tce].

AVAILABILITY

These large resources and reserves, however, will only constitute an assured basis of supplies if they become available on the energy market in good time, and in sufficient quantities. In this context the following criteria for the future availability of coal were subject to a closer examination:

- Conditions of the deposits,
- Infrastructure,
- Coal trade and future export plans,
- Environmental impact,
- Coal quality,
- Coal conversion processes,
- Manpower and capital,
- Domestic coal supplies,

in the following countries:

Australia

Canada

FRG

India

Japan

People's Republic of China

Poland

Republic of South Africa

UK

USA

USSR

which contain 92% of the technically and economically recoverable coal reserves. In addition, the other countries of Europe and the countries of South America were studied in lump as separate groups. The results obtained from the questionnaire campaign, literature studies, and personal talks are now summarized.

Figure 7 gives a survey of the future trend in production figures for the ten main coal-producing countries. All the countries plan a considerable increase of their production to the year 2020. The largest production can be expected from the USA, the People's Republic of China, and the USSR. The following world production figures were obtained:

1985	3.8×10^9 tce,
2000	5.7×10^9 tce,
2020	8.8×10^9 tce.

The corresponding average annual increase rates for the period from 1975 to 2020 are 2.9% for the main coal producing countries and 2.7% for the total world production. The investigation indicates that these figures can only be obtained if all bottlenecks and obstacles hindering an increasing coal production can be overcome in time; there are experts who doubt that these figures can actually be obtained.

Whilst these figures may be sufficient for regional availability it is not clear whether they are high enough for a sufficient global availability. The export availability of the coal is here of decisive importance. Figure 8 reviews the results we obtained in our study. It shows the development of the export/production ratio (in percent) of the main coal producing countries. From the present and current estimates of future coal exports the following figures were obtained:

1985	308×10^6 tce,
2000	580×10^6 tce,
2020	786×10^6 tce.

That is, the average export quota of coal lies between about 7 and 10% of the world production figures.

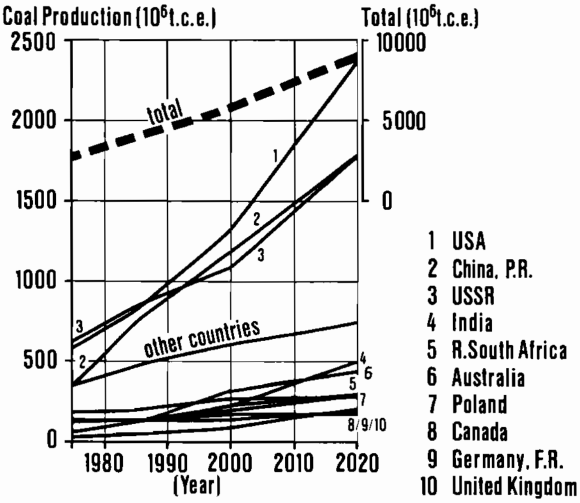


Figure 7. Development of coal production of main coal producing countries (nearly 92% of the reserves in the world).

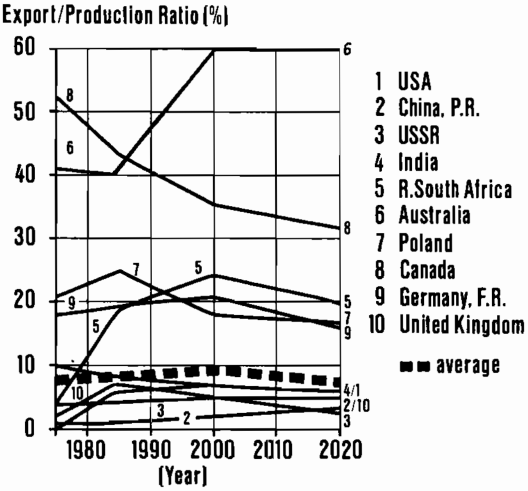


Figure 8. Development of the coal export rate of main coal producing countries (nearly 92% of the reserves in the world).

This means that most countries, so far, seem to plan their future coal production mainly to meet their own future requirements. The rates are too low to meet the demand of coal importing countries. They are also insufficient for developing an extensive international coal trade. Figure 9 shows the development of coal production and coal export of the world.

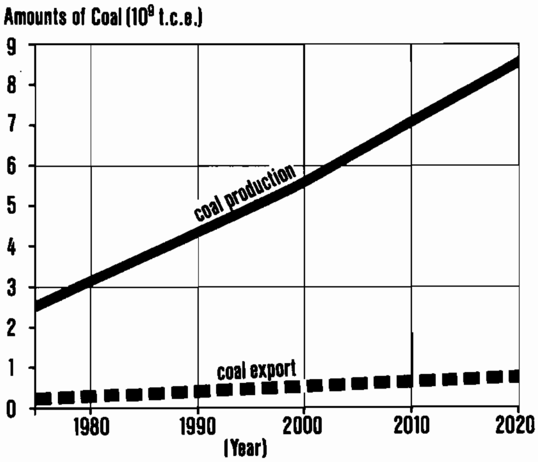


Figure 9. Development of world coal production and coal export.

It should of course be emphasized that these results are based on currently available information. Significant changes in the energy market that result in high world coal prices, will naturally constitute an increased incentive for higher coal production, and may lead to increased exports. However, there are a number of obstacles making it doubtful that the gap in demand, which could well occur in the near future, can be closed with certainty:

- The recruitment of a sufficient number of qualified miners and engineers.

- The establishment of a suitable infrastructure and of adequate transportation facilities.

- Various environmental problems, both in production and in consumption.

- Potential markets for coal are not yet being sufficiently developed in many parts of the world, since other sources of energy are still offered at lower prices. This means that there is also a lack of interest on the part of potential investors to commit themselves to the development of coal.

- The long lead times required for opening up new mines, establishing the necessary infrastructure, transportation facilities, etc.

The measures necessitate, among others, high capital investments, which, due to the long lead times, have to be carried out a long time before a shortage on the energy market occurs. This means that the prospects of the profitability of initial capital investments are uncertain, and this compels the energy industry to proceed extremely cautiously with their forward planning. Capital investment funds might be deployed at a time of shortage on the oil and natural gas market, but this might well be too late, as the productive effects of these measures would only be felt at a relatively late date due to the long lead times. This factor might therefore be the most serious obstacle for coal reserves becoming available at the right time. Action must be taken now if the maximum use of the potential offered by coal is to be made; appropriate policy decisions by governments in concordance with the coal producers and consumers are imperative. These decisions should aim at enabling potential coal consumers to commit themselves to long term contracts. This again, would enable and encourage potential investors to commit themselves in time, and without unacceptable risks, to the necessary development of coal.

During and after the Istanbul conference it was felt by numerous participants and experts that the demand and production figures do not take into account sufficiently the demand of the developing nations. In fact the demand on energy would be much higher to ensure the economic and social development of these nations.

The main obstacle for a higher increase in coal production is believed by all coal producers to be the missing economic incentive. If, for instance, by an energy policy, regionally and globally agreed, such an incentive could be provided, the upper limit of coal output would be determined only by technical barriers. During and after the Conference, leading energy and coal experts expressed the view that from technical considerations alone a substantially higher increase of coal production would be feasible. This would be true specially for the countries with large coal resources, such as the USA, the USSR, Australia, the People's Republic of China, and the Republic of South Africa. An average annual production rate for the period from 1977 to 2020 of about 3.7% was believed to be realistic under such conditions. This would lead to the much higher production of 7.4×10^9 tce for the year 2000 and 13×10^9 tce for the year 2020. The figure for the year 2020 would mean an additional output of 5×10^9 tce which would be available for export.

Also these figures show that to dispose of the tremendous potential of coal to overcome an energy shortage we cannot rely on self-regulation of the market; the support of an energy policy appears to be necessary to make this potential available in good time.

ACKNOWLEDGMENTS

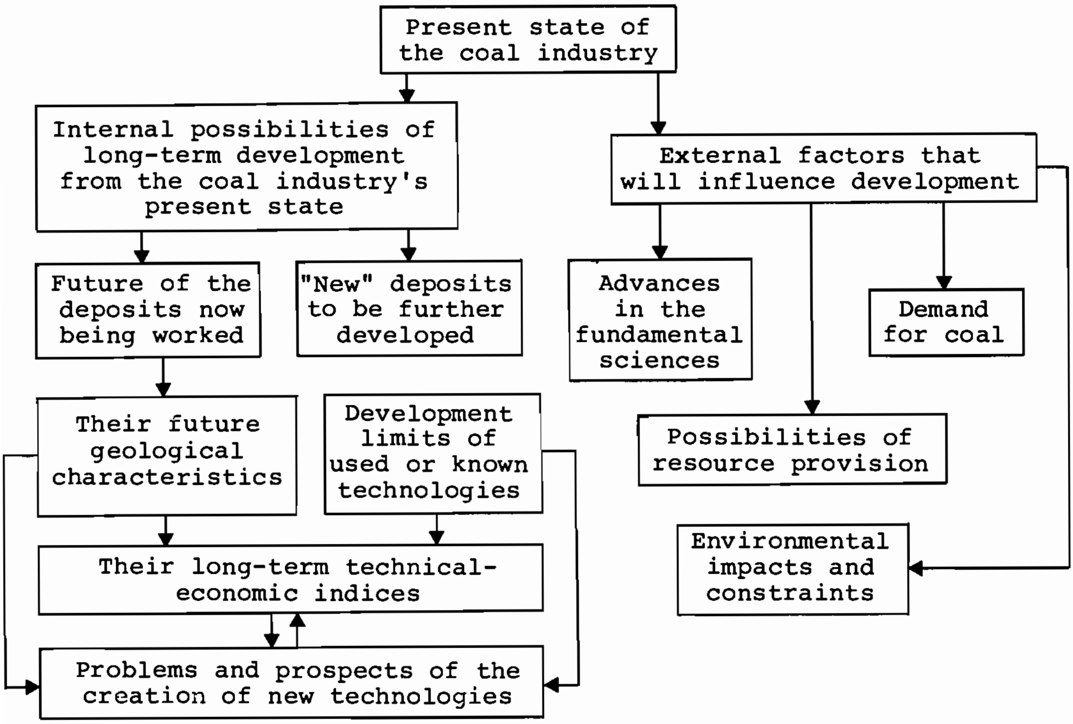
I would like to thank the organizing committee of this Conference and its chairman, Professor Grenon, who invited me to give a short report on the results of WEC on coal resources. I would also like to thank the Secretary-General of WEC, the Chairman of the Conservation Commission, and the Secretary-General of the German National Committee for giving me the opportunity to do so.

DEVELOPMENT POSSIBILITIES OF USSR COAL MINING IN THE FIRST QUARTER OF THE 21ST CENTURY

A. Astakhov

INTRODUCTION

Any outline of the possible development of the coal industry in the first quarter of the 21st century requires clarification of the points shown in the diagram below.



Many of these questions can be answered only with a certain probability, and they must still be investigated. No unique conception of so distant a future of the coal industry has yet been developed, nor does this report present one; it merely discusses certain hypotheses based on investigations of these problems. The report concentrates mainly on appraisals of the internal possibilities of coal industry development and hardly touches on the external factors mentioned in the diagram.

PRECONDITIONS OF THE COAL OPTION

Serious consideration of coal as one of the main alternatives of the energy and fuel strategy of the USSR in the first quarter of the 21st century is motivated by the following factors:

- The overwhelming part of USSR fossil fuel resources consists of coal reserves--the only "inexhaustible" reserves over the next few centuries.
- Geological coal resources are much more reliable than oil and gas resources.
- A long lifetime is more characteristic of coal mines than of e.g. oil wells.
- Coal production expenses can in principle be reduced, mainly by means of development of opencast mining and increased automation of mines. Oil and gas production has no assured prospects of changeover to a new technology, and the unused possibilities of automation are fewer. Transfer of the main oil production to the eastern regions of the USSR tends to increase the expenses, because the natural conditions in the new districts are more complicated than those in the traditional ones. The reverse is true for the coal industry, and hence its competitiveness will increase.
- Oil and gas would have priority over coal in the widespread use of fossil fuels as chemical raw materials and motor fuel, and in fuel deliveries to peak electric power stations and small local consumers.
- In view of the likelihood of exhaustion of the economic reserves of oil and natural gas, it hardly seems reasonable to seek fundamentally new technologies for their production and refining at the beginning of the 21st century. Coal technology, on the other hand, should by that time be highly developed, for the following reasons. After exhaustion of oil and gas reserves, coal will represent the main raw material for the chemical industry, very likely including the production of synthetic motor fuel. Moreover, opencast mines have a long lifetime, so that those existing at the beginning of the 21st century would be maintained as suppliers of raw materials for chemistry. Thus at that time it would be more reasonable to concentrate technological research not on oil production and conversion, but on that of coal.

COAL RESOURCES AND RESERVES

The total geological coal resources of the USSR--to a depth of 1800 m and with a minimum seam thickness of 0.3 and 0.6 m of bituminous coal and lignite, respectively--exceed 8.5 × 10^{12} t. About 57% is found in the scarcely prospected and nearly inaccessible Tungus, Lena, and Taimyr basins; these resources are virtually not worked at present, nor is it planned to exploit them in the very near future. Coal reserves on 1 January, 1975, were assumed at 420 × 10^9 t, including 83 × 10^9 t at Donbass, 109 × 10^9 t at Kuzbass, 116 × 10^9 t at Kansk-Achinsk, 16 × 10^9 t at Karaganda, and 7 × 10^9 t at Ekibastuz*.

More than 47% of the coal reserves lie at a depth of less than 600 m, about 33% between 600 to 1200 m, and about 20% below 1200 m. Bituminous coal makes up 52% of the power coal reserves measured in tons (68% measured in tce); the rest is lignite. Reserves suitable for opencast mining make up 35%, two thirds of it lignite. About 75% of the total reserves are situated in the eastern districts of the country, including almost all those suitable for opencast mining.

The total coal reserves of the USSR that are mineable by well-known technologies are very large, and in terms of possible production volumes are inexhaustible for a number of decades.

PRESENT STATE OF THE COAL INDUSTRY

In 1974 in the USSR, 685 × 10^6 t of coal was produced, including 213 × 10^6 t by opencast mining and 9 × 10^6 t by the hydraulic (underground) method. For the past ten years, the coal production volume has increased at an average annual rate of 2%, and a higher rate in the eastern districts.

The average capacity of an underground mine and an opencast pit is 860 × 10^3 and 2660 × 10^3 t respectively. More than 45% of the coal is mined out of mechanized longwall faces equipped with movable hydraulic power supports.

The most important coal basins and deposits are discussed below.

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*The reserves of USSR power coals comprise 225 × 10^9 tce, including 60 × 10^9 at Donbass, 61 × 10^9 at Kuzbass, 58 × 10^9 at Kansk-Achinsk, 7 × 10^9 at Karaganda, and 4 × 10^9 at Ekibastuz.

Donetsk Basin

In 1974, this basin accounted for 32% of the total coal output (40% calculated in tce), 43% of all coal mines, 54% of the workers, and 47% of the fixed assets. The average depth of mining is 530 m, increasing yearly by 12 m. The average seam thickness is 1.09 m. About 10% of the coal is mined out of steep seams. The average heat value of the coals is 6000 kcal/kg, and the ash content is 24%. 32% of the output is mined out of fully mechanized longwall faces. Because the seams are rather thin and at considerable depths, the cost of production and the complete cost* for an output of 1 t of coal (in both tons of natural fuel and tce) is higher than the average for the industry as a whole.

Kuznetsk Basin

19% of the coal produced falls to this basin (25% in tce). The coals are of high quality (the heat value is 5800 to 6500 kcal/kg) and high standard, valuable for energy conversion. The average depth of mining by the underground method is 246 m; high coal saturation is typical. The coal seams are of different slope and some of them are thick. About one third of the coal is extracted by opencast mining in rather small pits of an average annual capacity of 2.1 Mt. The cost of coal production is 1.7 times lower than in the Donbass.

Karaganda Basin

This basin provides 7% of the coal produced in the USSR. The coal is of high quality, the depth of mining is 365 m, and the seam thickness is up to 6 m. The basin is one of the most fully mechanized with highly concentrated production and a low level of expenses.

Ekibastuz Deposit

This rapidly developing region in the Kazach SSR has relatively small geological coal resources (10×10^9 t), which are suitable for opencast mining. The average overburden/coal ratio is 1.5 m^3/t**, and the heat value of the coals is 4250

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*Complete cost Σ implies the expenses, calculated by the following formula: $\Sigma = C + 0.12\ K$, where C is production cost and K is capital expenses (for mines to be built) or fixed assets (for operating mines).

**This ratio will certainly increase: about half of the remaining coal reserves lie at a depth of 300 to 600 m.

kcal/kg. Three opencast pits with annual capacities of 10.5×10^9 t to 27×10^9 t are being exploited at present.

Kansk-Achinsk Basin

This is the most promising basin in the USSR, with tremendous geological coal resources (0.6×10^{12} t) bedding in very favorable conditions. The coal is of low heat value (3560 kcal/kg on the average) and is not economically efficient for long-distance transport in unconverted form. In 1974, two opencast pits in the basin produced 26 Mt of coal. Production increased 1.3 times in the period from 1971 to 1974 and should increase another 1.7 times by 1980.

In the long term, considerable development of this region will be possible, its scale being limited only by the technical possibilities of coal consumption and by the financial resources needed to develop the infrastructure.

In 1974, about one third of all coal production was divided in equal parts among the remaining coal basins in the European USSR, the Urals, Eastern Siberia, and the Far East.

OUTLOOK UNTIL THE END OF THE CENTURY

To the end of this century, the following trends in the development of coal mining are probable. Annual volumes of coal output will increase, mainly due to the rapid development of coal production in the eastern regions. In underground coal mining, the possibilities of further progress in technologies now used or being planned will by then have been exhausted. Face operations will have become totally automated for the whole range of geological conditions. Mine haulage of coal will have been completely automated and conveyored (in some cases, pipeline transport and self-propelled trucks will be used). We think it likely that equipment for hydraulic coal mining and transport will have been perfected to the point where at least one fifth of all underground coal output will be mined by this method. A large number of projects for mechanization, automation, and concentration of auxiliary operations will probably have been completed. The average indices of face productivity could reach a record figure in present terms (4000 to 5000 t/day), and the average daily capacity of most mines will reach, in our opinion, the target rate of contemporary projects, 8000 to 10,000 tons or more. Automatic control of economic and production processes will be widespread.

Experts estimate that labor productivity in underground coal mining may double owing to technical progress. At the same time, the development of underground coal mining would be inhibited by a number of circumstances. In 25 years the average depth of mining in the traditional coal regions will increase by approximately 250 m, reaching 850 to 900 m in Donbass and well over 1000 m in many mines. The greater mining depth, accompanied by unfavorable changes in productive conditions--such as high pressure on the set, mine shocks, unexpected coal and gas blowouts, high temperatures--would reduce labor productivity by at least 25%. Technical progress will increase labor productivity, say 1.5 times; but it will also increase the capital and depreciation costs of underground mining. Thus on the whole no substantial decrease in total production costs is likely: the complete cost of 1 t of coal will be reduced by no more than perhaps 5%.

In some regions of traditional underground coal mining (the Podmoskovny, Kizel, and Lvov-Volyns basins), output will diminish or cease as coal reserves are exhausted. In the Donetsk basin, as minining depths increase, mere maintenance of the production capacity would take such huge capital investments that development or even preservation of the large volume of coal mined here can be considered only after all the growth possibilities of opencast output have been exhausted.

We can assume that by the end of this century the total coal output of the Donbass will have increased by 15 to 20% at most if it happens at all; and that it will not increase in the European part of the USSR as a whole. The increase in coal output by that time will be due almost entirely to the extensive development of opencast mining in the eastern regions. The large coal reserves and favorable conditions in the Kansk-Achinsk and Kuznetsk basins and the Ekibastuz deposit permit the concentration there of very great volumes of coal output. The rate and scale of their development depends on the financial resources available to develop the coal industry proper, the infrastructure, and means for long-distance transport of coal or energy. The creation of building and machine building capacities and the rate of creation and production of new, highly productive quarry equipment will also play an important role. Rotary bucket excavators and power shovels of high capacity would be extensively used in these basins.

PROSPECTS IN THE FIRST QUARTER OF THE 21st CENTURY

The following circumstances limit the possible increase in underground coal mining in the European part of the USSR.

- Unexpected discoveries of large new coal fields in these regions are practically excluded.

- The coal reserves of a number of the basins now being exploited (Kizel, Lvov-Podmoscovny) will by then be almost exhausted.

- Only a small number of fields is unoccupied by operating mines; when these are put into operation, they can only compensate for depleted areas and complete the exhaustion of coal reserves.

- While the operating capacities of the Donbass mines have growth possibilities, the preservation of existing mining technology would require very large capital investments. Over two thirds of the mines would have to be worked at a depth of 1 km, and the rest at over 1.2 km. Simple deepening of the operating shafts would not be possible; new shafts would have to be sunk from the surface. Construction of mines of such depth at present requires 1.3 times as much capital investment as that of mines 500 to 600 m deep; and exploitation costs increase by 30 to 35%. Expensive (and rather ineffective) measures must be taken for degassing and air conditioning, against rock bumps, etc.--these measures serving only to preserve the capacity of a mine. We may also anticipate great difficulties and costs in obtaining workers in these conditions. Moreover, maintaining the operating capacities (especially in unfavorable conditions) is never much cheaper than creating new ones. 30% of all the USSR capital investments in coal production are spent on maintenance and some modernization of the operating mines in the Donbass. Additional investments during each 15 to 20 years of mine operation exceed the initial construction cost.

It thus appears advisable to limit, and possibly appreciably reduce, the coal mining volumes in the European USSR after 2000, even if the national fuel and energy balance is at that time based mainly on coal. This conclusion can be reversed only with the advent of an utterly new (and cheaper) technology of coal mining and utilization. Some problems in this connection are discussed below; but note that the outlines of such a technology are not yet at all clear. A more likely development is that the main coal mining volumes will come from the eastern parts of the USSR. The main difficulties of this transfer are connected with the location of most of the fuel and energy consumers in the industrial districts of the European USSR, and the increased investments for creating a particularly well-organized infrastructure. But there is no doubt that the tendency toward industrial development of Siberia will grow steadily, partly due to growing resistance to the great burden on the ecology of the inhabited industrial part of the European USSR. Thus we can assume that the difficulties of transporting the coal and energy to the western regions will be greatly reduced after 2000, since much of the production can be consumed in eastern regions themselves. The main coal mining region of the country at that time, the Kansk-Achinsk basin*, is discussed below.

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*The Kuznetsk basin also has great possibilities for further development after the turn of the century. The coal reserves of the Ekibastuz deposit, however, are concentrated in the fields now being worked, so that no increase in output is possible beyond the year 2000.

KANSK-ACHINSK BASIN

General Characteristics

At present only two coal pits--Irsha-Borodinsk and Nazarovsk --are operated in this basin. Coal output is 27.5 Mt (1975). The average overburden/coal ratio is 1.36 m^3/t, the monthly productivity per worker 910 t, and the cost of coal mining 1.10 roubles/t. Both pits were put into operation in the late 1940s and early 1950s, each with a rather small annual capacity of 1 to 1.5 Mt of coal. By the end of 1975 their capacity had reached 12 to 14 Mt each. The capacity of the Irsha-Borodinsk pit would double after reconstruction.

These two operating pits give only a slight indication of the potential and prospects of the basin. Two factors of great importance will play a role after the end of the century: the possibilities of practically unlimited volumes of coal output, and the exceptional efficiency of mining. Factors that can restrict this development are the low quality of the coal, its lack of suitability for long-distance transport, and the remoteness of the basin from the consumers in the European USSR.

The Kansk-Achinsk coal basin occupies an area of 50,000 km^2, stretching for about 800 km. It consists of 24 coal fields, of which the largest are Itatsk, Beriozovsk, Abansk, Irsha-Borodinsk, and Urjupsk. Approximate data on geological conditions and coal quality are shown in Table 1.

According to calculations made in 1968, the total geological resources of the Kansk-Achinsk basin amount to about 600×10^9 t, distributed as follows in terms of seam thickness: under 2m, 22%; 2 to 3.5 m, 18%; 3.5 to 10 m, 24%; over 10 m, 36%. The forecast resources of the first and second classes considered here account for 35 and 20% of the total geological resources, respectively. Of the forecast resources of the first group, about one fourth lie at a depth of 300 to 600 m, and the rest at less than 300 m. About four fifths of the forecast resources of the second group lie at 300 to 600 m. The proved (balance) coal reserves amount to 116×10^9, 18% of them at 300 m depth.

On the whole, the coal seams of the basin lie in very favorable mining conditions. 80% of the reserves is suitable for open-cut mining, with a rather small overburden/coal ratio. The overburden is not thick and usually consists of porous sedimentary rocks. Thus expenses for construction and exploitation are low. At present the cost of production of 1 t of natural fuel in the Kansk-Achinsk basin is slightly higher, and the complete cost is even lower, than in the Ekibastuz deposit. Both are 3.7 times lower than in the Kuzbass opencast mines. The heat value of Kansk-Achinsk lignites adversely affects the economic indices on 1 tce; but the complete cost of 1 tce is 2 times lower than in the opencast mines of the Kuzbass.

Table 1

Coal fields	Thickness of strata [m]	Depth of bedding [m]	Angle of incidence [°]	Overburden/ coal ratio [m^3/t]	Ash content [%]	Sulfur content [%]	Energy value [kcal/kg]	Water content [%]
Itatsk	30-100	10-500*	1-35	0.8-4.0	7-11	0.3-0.7	3040-3550	36-40
Beryezovsk	8-70	12-300	3-10	1.0-4.0	7	0.3	3830	32
Irsha-Borodinsk	20-50	10-78	1-3	1.0	9	0.3	3740	33
Abansk	2-24	40-80	1-3	1.0-3.5	11	0.4	3780	33
Urjupsk	40-50	7-300	0-5	1.3-2.5	7	0.3	3670	35

*Only 6% of the reserves within the boundaries of the fields now being exploited and to be exploited by the end of this century lie at depths of 300 to 500 m.

Development Problems

The main difficulties in development of the Kansk-Achinsk basin are connected with the transport of mined coal (or of the electric energy to which it is converted) to the Central European part of the USSR--2300 km to the Urals and 4000 km to Moscow. At the same time the low thermal efficiency increases coal transport per unit of energy produced: 0.28 kg of coal must be transported for each 1000 kcal of energy to be produced--1.8 times more than the Kuznetsk power coals.

The problem of the use of Kansk-Achinsk coal by consumers in the European USSR could be solved using at least two main variants:

- Transport of coal conversion products by rail;
- Transmission of energy obtained from large steam electric plants near the mines.

Investigations show that thermal conversion of Kansk-Achinsk coal into cheap, high energy, transportable fuel suitable for energetics, metallurgy, and communal needs is possible. But we must solve a number of important problems concerned with the creation and mastering of large-scale coal conversion enterprises, the choice of the type and variants of road transport to be developed, the complex use of chemical raw materials, the protection of environment, etc.

Local electric energetics could be developed near the basin, with a great concentration of power plants of great capacity. The technical water supply conditions on the whole are favorable. The production cost of 1 kwh of electric energy is expected not to exceed 0.3 kopek, including 0.1 kopek for fuel. This corresponds to the level of the complete cost of generating the electricity (in the basis regime): approximately 0.5 kopek per 1 kwh. It would also be necessary to solve very complicated problems of the economically efficient long-distance transfer of the electric energy produced, which requires lines for electric transmission of d.c., at first of ±750 kW and later of ±1200 kW.

The transfer of fuel and energy produced from Kansk-Achinsk coal over great distances would be connected with capital investments several times as high as those for mining and conversion of coal. In these conditions, it would seem expedient to develop in the next century, large fuel and electric power production in immediate proximity to the region.

Let us assume (conventionally) that investments per ton of coal capacity in the basin will be about 9 roubles. Thus, to build new pits of a total capacity of, say, 10^9 t by 2020 will take 9×10^9 roubles. Assuming a factor of 1.5 for additional expenses for maintaining the capacities built and developing the infrastructure and construction industry, this figure would rise to 13 to 14 × 10^9 roubles--the amount the entire USSR coal industry now spends during 6 to 7 years. The average annual amount would be relatively lower: about 0.3 × 10^9 roubles. Total capital investments, including those necessary for development of combined energetic-technological enterprises and the objects of the energetics, would probably be three times higher. A large-scale construction base would be required, including plants for ferroconcrete structures and mining engineering, machine building and repair shops, construction and assembly plants, and so forth. Estimates show that the necessary volumes of some building materials would be very great. If labor productivity is 2000 t per man and month, 60,000 workers would be engaged in coal mining. If this figure is multiplied by 4 to account for workers in the applied branches of industry and their families, development of the Kansk-Achinsk fuel and energy complex in the first quarter of the 21st century would concentrate no fewer than half a million people there, most of them through migration, which would require large-scale social measures.

Development of this unprecedentedly powerful complex of opencast mining, coal conversion, fuel consumption, and coal-based chemical products would demand stringent measures for limiting the unavoidable (and sometimes almost unexpected) ecological consequences. The most significant of these impacts are the following.

- Large plots would have to be allotted for mining works. The land developed in one year to mine 10^9 t of coal would amount to 3500 thousand ha--70,000 ha in the 20 years from 2000 to 2020. The recultivation volume would exceed 10 × 10^6 m^3 of soil per year.

- Large tracts of forest would be destroyed.

- For every 100 Mt of fuel used by electric power stations, 0.6 to 0.8 Mt of nitrogen oxides would be released into the atmosphere. No satisfactory means have yet been found for ensuring that the accepted limits of atmospheric pollution by nitrogen oxides are not exceeded. Such means should be found, since otherwise great losses would result from the corrosion of metal structures and the destruction of the surrounding forests due to the concentration of electric power stations.

- The high concentration of the energy capacity would cause problems with the cleaning of smoke gases from the sulfur and ash. Though Kansk-Achinsk coals are considered to be comparatively clean, about 0.25 Mt of SO_2 will be emitted into the air for every 100 Mt of raw coal.

- Electric power stations should be equipped with water cooling basins, which requires the flooding of valuable agricultural lands.

- Thermal coal conversion would be carried out, along with the disposal of a great volume of phenol water. The problem of its purification is a complicated one; the process of evaporating, followed by burning of the concentrate, appears to be the most reliable at present.

Most of these ecological consequences are not related to the specific character of the Kansk-Achinsk basin and would have occurred under any circumstances in the rapid development of the USSR coal industry; nor can ecological considerations lead to preference being given to another development alternative, more or less equal from all other points of view. Rather, ecological consequences and the cost of protective environmental measures must be considered in arriving at technological decisions, and means of implementing these must be worked out.

Together with the Kansk-Achinsk basin, the Kuznetsk and Ekibastuz basins will play important roles in the fuel and energy complex of the USSR in the first quarter of the 21st century.

PROSPECTS OF UNDERGROUND COAL MINING BY TRADITIONAL METHODS

At the same time, it is extremely unlikely that even the three most promising coal basins--Kansk-Achinsk, Kuznetsk, and Ekibastuz--could satisfy the coal needs of so large a country, particularly since the distance from each basin to the western and eastern borders of the USSR is 4500 km. With any coal transport technology available at present, or with transmission of electric power over this distance, the operating expenses (especially the capital investments) are so great that it would probably be more efficient to mine less distant coal fields with economic indices that are 2 to 3 times worse. These are the coal basins, now operated by the underground method, that lie near the most highly developed regions of the European part of the USSR and the Far East. However, the present level of the economic indices of these basins is such that development or even maintenance by means of the technologies currently used seems economically doubtful beyond the present century.

The economic effect achieved in these and other basins during the last ten years by perfecting the existing basic technology of underground coal mining in general went mostly into compensating for the unfavorable dynamics of the geological conditions of mining, such as increasing pit depth. The quality (ash content, etc.) of the mined coal deteriorated as the equipment types now in use were introduced. The capital intensiveness of coal production showed stable growth. On the whole, the tendency was toward extensive rather than intensive technical development. The potential for further development of present mining techniques will probably have been exhausted by the end of the present century, and a radical change in the methods of coal mining and the technology used will be necessary; but unfortunately the nature of a future technology is not clear. The following discussion, based on the results of the investigations performed, shows the aims of the creation of such a technology rather than its real outlines. Two new technologies, already tested to some extent, are an exception: hydraulic coal mining and underground gasification of coal.

PROSPECTS OF HYDRAULIC COAL MINING

In the USSR, 9.2 Mt of coal were mined by the hydraulic (underground) method in 1975, and more than 100 Mt since 1952. Hydraulic mining is done in the Donetsk and Kuznetsk basins. By the beginning of 1976, 7 hydromines and 3 hydrocomplexes were in operation under widely differing mining conditions--thin, poor, and thick seams that are level, inclined, and steep. A great variety of extraction systems and equipment have been tested and are in use for face, drifting, and transport operations in the mine. New hydromines are being designed and constructed. Thus, the hydraulic method is being applied on the industrial scale; and scientific investigation and design aimed at perfecting the technology are continuing.

The main technological advantages of the hydraulic method are its continuous character, the small number of inherent operations, and the simplicity of the productive process. The number of "joints" of the various processes is much smaller than in traditional methods, which greatly reduces the necessary number of miners. Hydraulic mining processes lend themselves well to automation and remote control. As they do not demand the presence of workers and equipment at the working face, the space mined generally need not be supported. If the angle of sloping of seams is more than 3°, the coal pulp can be transported by gravity. Pulp transport is mainly by continuous flow from the mine face to the dewatering plant situated at the mine surface or at the consumption site. The presence of hydrotransport reduces the cross-section of mine transport workings (and load shafts) and thus the corresponding mining volumes.

Probably the greatest advantage of hydromining is the great flexibility of the hydraulic coal breaking process at the face and its better adaptation to tectonic changes in seam bedding, which can cause serious difficulties in using the traditional technology of longwall faces. It also has advantages from the point of view of health protection. The frequency of occupational injuries in hydraulic mining is 2 to 3 times lower than with traditional methods because of the absence of workers at the face and of rolling stock and mobile equipment at mine workings. Air pollution by coal dust is insignificant, not exceeding 0.25 to 0.5 mg/m^3.

The economic advantages of hydromining derive from the technological ones. Because of the lower number of main and ancillary operations and reduced labor consumption, monthly productivity at operating hydraulic mines in 1975 reached 63 t per worker in the Donbass and from 145 up to 195 t in the Kuzbass. This is 1.3 to 2 times higher than in traditionally worked mines. The cost of production in hydromines is 10 to 15% lower than in conventional mines with the same conditions in the same basins; the cost of the hydrotransport process within a mine is 10 times less; and the cost of fixed assets per ton of coal mined is 25% lower.

The economic indices of large new hydromines being designed can be greatly enhanced. With an annual mine capacity of 3.5 to 4 Mt, the capital investments are 18 to 25 as against 30 roubles/t; the volume of mining works is 170,000 as against 420,000 m^3, and that of production buildings and enterprises 400,000 as against 760,000 m^3; monthly labor productivity per worker in mining production is 144 as against 58 t; the cost of production is 3 to 4.5 as against 6 to 6.5 roubles/t; and the complete cost is 6 to 7 as against 10 roubles/t. Fuel and electric power expenses are 1.5 to 2 times higher than those of traditional mines, and the amount of material used is lower.

The hydraulic method has been tested and has shown its applicability over a wide range of geological conditions. The best results were reached in mining seams of average thickness or greater, but even for thin seams the economic indices are better than with traditional technology. The method can be used with any seam angle higher than 2°. Application is limited by unstable roof rocks and swelling floors. Hard coals and cleavage greatly influence the efficiency of the mechanical equipment at faces, so the presence of cleavage can increase hydrobreaking productivity by 8 times. Where there are hard coals and unstable roof rocks, hydrobreaking and controlled caving of the roof cannot be used; instead, the coal and rock must be removed by mechanical-hydraulic means, with timbering of the working space and hydro-washoff after preliminary weakening of the coal massif.

There are two variants of mechanical-hydraulic coal winning. The raw coal may be separated from the face, removed by mechanical means, and transported to the shaft with lower-pressure water. Alternatively, coal winning may be carried out mechanically, and coal loading and transport by the hydraulic method. A number of mining combines for mechanical-hydraulic coal removal have been tested. In conditions where it is difficult to transport coal hydraulically, the method of mechanical-hydraulic coal and rock removal must be used: the breaking is done by the water stream (or mechanically after rifling of the cuttings by thin jets of superhigh pressure), and loading and transport of the cut mass by hydraulic as well as mechanical methods. The sphere of rational use of hydrotransport is defined by the availability of natural water sources or by the factors determining the possibilities of the closed water system.

The possibilities of efficient application of the hydraulic method are summarized below.

- The range of conditions in which the method may be used is fairly wide.
- The variety of possible technical solutions and technological means for hydromining is no less than for traditional methods; thus extensive investigation and the design of a number of different possible solutions should precede wide application of the method.
- Hydraulic coal excavation has an advantage over the mechanical method in complicated tectonic conditions of the coal seams.
- Underground hydrotransport systems could solve two difficult problems of the contemporary Donbass: reducing the volumes of expensive drifting mine workings, and eliminating the labor-consuming multistage circuits equipped with various types of transport.

As a relatively young method, hydromining has numerous possibilities for technical perfection. For hard and viscous coals, the pressure of the jet near the nozzle should be increased to 150 to 200 kg/cm^2. Intensification of hydromining in a number of mining conditions would involve preliminary relaxation of the coal massif by forcing the water into the seam through special bore holes. Coal hydrobreaking by thin water jets with pressures up to 500 kg/cm^2, and the method of hard rock destruction by pulsing water jets of high and superhigh pressures (up to 8000 kg/cm^2 and more), also seem promising. Self-propelled (traveling and walking) hydrojets with remote control should be perfected, and automated self-propelled hydraulic breaking-out units created. Some complicated problems must be solved in the sphere of automation of hydraulic transport, dewatering of coal pulp, and water clarifying at the mine surface.

SOME ASPECTS OF UNDERGROUND GASIFICATION OF COAL

Underground coal gasification is basically different from other coal mining technologies. Experimental development of this method has been carried out in the USSR for almost fifty years. Five underground coal gasification sites mined about 1.5×10^9 m^3 of gas per year in the Podmoskovny, Donetsk, and Kuznetsk basins and in Angren (Uzbekistan). In spite of the long period of developments, no great success has yet been achieved in creating a satisfactory technology for the process in terms of reliability, quality of the gas obtained, and economic indices. In view of these results and of the large reserves of cheap natural gas in the country, underground coal gasification is not being examined as a possible competitor of the common coal mining technology.

The economic indices achieved at the experimental sites did not meet the design specifications, and even in the best cases could not compete with those achieved at coal mines. The energy value of gas generally did not exceed 800 to 850 kcal/m^3 in gasification of coals of different natural energy content (from 2700 to 6500 kcal/kg). About 40% of the expenses in gas production fall to electric power and only 11% to labor. The unsatisfactory indices are mainly connected with the unstable production process and the very low capacity of the exploited sites (from 28,000 to 160,000 tce per year). At the same time these expenses were much lower than those of obtaining "artificial gas" at the surface from the stone coal first mined out.

Most of the potential merits of underground coal gasification may be realized only with a significant increase in the energy value of the gas obtained and in the stability of the process. Presumably, better results might be achieved by blowing enriched by oxygen for gasification of the deeper strata deposited among dense rocks. Should it be possible to achieve process stability and production of gas of high energy value, underground gasification has the following potential advantages over traditional technology and the use of solid coal:

- Complete elimination of the use of underground workers;
- Considerable reduction and simplification of mine working drivage (at underground gasification sites, only one fifth of the fixed assets goes into construction, as against two thirds in mines);
- The possibility in principle of complete automation of coal mining;
- Better conditions of boiler functioning;
- The possible use of gas as the domestic fuel (if its energy value is more than 4000 kcal/m^3).

If the production process were perfectly mastered and unit capacities greatly increased, the economic indices of underground gasification would be able to compete with those of coal mining by the traditional method. The possible organization on this basis of the power and chemical units of enterprises would improve them yet more. For underground coal mining in the 21st century, it is difficult to imagine any technology other than underground gasification or some analogous "bore hole" geochemical methods.

FUTURE COAL-POWER-CHEMICAL ENTERPRISES

According to some opinions of the specialists, we can formulate the following general principles as the basis of coal mining development in the 21st century.

- Manless organization of underground processes;
- Line production and maximum automation of processes;
- Complex and maximum recovery and retreatment of useful products from coal;
- Minimum environmental impacts, through use of the "wasteless" technology.

Combined coal-power-chemicals groups of enterprises could be the main type of production organization putting these principles into operation. They would operate a closed production cycle of recovering the coal reserves as well as converting them into energy and chemical products. One can assume that chemical and biochemical methods would be the basis of the mining and conversion processes.

DEFINITIONS AND CLASSIFICATION OF RESOURCE BASE, RESOURCES, AND RESERVES

COAL RESERVE CLASSIFICATIONS USED IN DIFFERENT COUNTRIES

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INTRODUCTION

A universally used classification of coal reserves does not exist at present. The classifications adopted in different countries, as well as those advanced by some organizations or researchers, are generally difficult to correlate. Terms used to characterize mineral reserves--coal, in particular--are not standardized as are other branches of geological science. It is not unusual that various researchers interpret the same term in different ways. Evaluation of world coal reserves and coal production prospects, and modeling and computerizing of the energy resources of a country's regions and of the world as a whole, become more complicated because there is no standard classification.

However, the coal reserve classification used in different countries have common fundamental provisions and thus can be correlated.

REVIEW OF COAL RESERVE CLASSIFICATIONS

At present, the classifications most commonly used for estimation and calculation of coal reserves are those adopted in the USSR, the USA, Canada, Australia, France, and the FRG.

The USSR Classification

In the USSR, the sum of the discovered and undiscovered coal in place is called "the total geological reserves". The discovered part of the reserves is registered by the State and divided into two groups: (1) *Balance (commercial) reserves* include the reserves that can be mined economically and comply with certain requirements; (2) *out of balance (noncommercial) reserves* include those that at present cannot be mined economically because of small quantity, thin beds, low quality or particularly complicated exploitation conditions, but that may become commercial in the future [4].

Each group of reserves is divided into categories A, B, C_1 and C_2 (C_2 is not distinguished in the noncommercial group) according to reliability of reserve estimation, and coal quality, and of mining conditions.

Category A includes discovered coal reserves studied in sufficient detail to provide the mode of occurrence and the shape and structure of mineral bodies, as well as coal types, commercial grades, quality, technological properties, and factors governing exploitation conditions, location and delineation of barren and noncommercial sections. These reserves are calculated within the contour of mining openings and bore holes spaced at 300 to 400 m or 600 to 800 m, depending on the complexity of the geological structure.

Category B includes discovered coal reserves studied in sufficient detail to elucidate the main features of the mode of occurrence, shape, and structure of coal beds; coal grades and types, and noncommercial sections and their exact location; of the quality and the basic technological properties of coal, and of the main natural factors governing exploitation conditions. Test holes may be spaced twice as far apart as for A category. The B category reserves are calculated within the contour of mining openings, and in case of persistent coal bed thickness and regular coal quality, also within the areas in immediate contact with the mine openings.

Category C_1 includes discovered reserves studied in detail that provides in general terms the mode of occurrence, shape, and structure of coal beds, as well as coal types, grades, quality, technological properties, and natural factors governing exploitation conditions. The reserves of this category are calculated on the basis of few test holes within areas adjacent to those containing reserves of higher categories or better-known areas of complicated structure. The C_1 category reserves are thus outlined on the basis of mining openings and by interpolation and extrapolation from general geological and geophysical data. *Category* C_1 also includes the reserves within the areas explored with many test holes but characterized by complicated structure, nonpersistent bed thickness, drastic changes in coal quality, and the like.

Category C_2 includes preliminarily estimated coal reserves. In this case, the shape, mode of occurrence, and extent of a coal bed are ascertained from geological and geophysical data confirmed by stripping of the coal bed at individual points or by analogy with areas already studied. Coal quality is evaluated from single specimens or from the data obtained for adjacent areas. The reserves of this category are outlined within the boundaries of geologically favorable structures and rock units.

To estimate the potential of large deposits, regions, or basins, predicted--so-called prognosticated--reserves are calculated. Two groups of such reserves are distinguished.

The first group includes reserves within areas adjacent to the explored sections, and in a number of cases to the developed mine fields. The amount and quality of reserves are determined by extrapolation of parameters obtained from the explored areas. Predicted reserves of this group include reserves in areas where the presence of coal-bearing deposits has been proved at individual points (drill holes, mine openings, outcrops), provided the geological knowledge of these areas suggests the regularity of coal-bearing potential between those points. The maximum distance between the points of coal manifestation outlining the areas with forecast reserves of the first group is based on the general geology.

The second group includes predicted reserves in areas adjacent to those containing the first group reserves. The structure of these areas is assumed on the basis of the data from single bore holes, outcrops, geophysical studies, and so on. This group also includes forecast reserves in areas with known geological structure where the presence of coal-bearing beds has been proved at individual points but where the regularity of the coal-bearing potential throughout the area has not been ascertained.

Coal reserve classifications adopted in the other member countries of the Council for Mutual Economic Assistance are almost completely correlated with the USSR classification, with only minor differences in requirements for the degree of knowledge and the rules for outlining the reserves of various categories.

The USA Classification

In the last few years, the US Bureau of Mines and US Geological Survey adopted the coal reserve subdivision based on V.E. McKelvey's classification, which has progressively displaced the rather uncertain classifications used previously by business circles, coal mining companies, and private firms.

The McKelvey classification is based on two criteria: the degree of economic feasibility of reserve exploitation, and the degree of geologic assurance (reliability) of reserve evaluation. According to the first dimension, the total amount of reserves, called *total resources*, is divided into "economic" and "subeconomic"; resources of the second group cannot be mined economically at present but may become economic in the future. Depending on the degree of geologic assurance, total resources are divided into "identified" and "undiscovered". By using both dimensions the author distinguishes *reserves* and *resources*. Resources include coal accumulations that can be mined economically at present or in the future. The reserves proper include only the explored part of total resources that can be extracted economically at present [2, 3, 5].

Identified reserves are calculated where a depth of coal bed occurrence does not exceed 900 m and the bed thickness is not less than 35 cm for anthracite and bituminous coals and 75 cm for subbituminous coal, brown coal, and lignite.

According to degree of reliability reserves are divided into three categories:

Measured reserves are calculated from the data on outcrops, exploration and exploitation, and mine openings and bore holes. The density of observation points and the data on thickness and extent of coal beds should make it possible to calculate reserves with an error not more than ± 20%. The observation points should be spaced at not more than 800 m. Measured reserves include those contained within a band 400 m wide from the point of observation or coal bed outcrop.

Indicated reserves are calculated by means of coal bed sections in combination with an extrapolation based upon the geological data. Areas with indicated reserves are adjacent to those with measured reserves covering a band of 800 m in width.

Inferred reserves are estimated by extrapolation from the reserves of higher categories with several coal bed sections. Areas with inferred reserves are adjacent to those containing indicated reserves covering a band of 1200 to 1800 m in width.

Measured and indicated reserves are integrated into a subgroup of "demonstrated reserves".

The undiscovered part of total resources is subdivided into "hypothetical" resources, estimated in presumed areas of known mining regions, and "speculative" ones, in presumed areas in regions where the productivity of strata is not proved.

The resources that are subeconomic at present are subdivided into "paramarginal" ones, with a cost of mining close to but still higher than the level of profitability or that cannot be mined because the land is reserved for other uses, and "submarginal" ones that can be mined if the raw material price increases to more than 1.5 times the price on the date of evaluation or if deposit exploitation becomes cheaper.

A comparison of the USSR and the USA classification schemes is given in Figure 1.

The Canadian Classification

The coal reserve classification system proposed by the Department of Energy, Mines and Resources, like that of the US, is based upon two criteria: feasibility of economic exploitation and assurance of existence. In accordance with the first dimension, *economic* (A) and *subeconomic* (B+C) resources and reserves are distinguished. Economic resources and reserves are those that are mineable economically; subeconomic resources are those whose extraction may become economic within 25 years (B with a probability of more than 50% and C with one of 10 to 50%) [3].

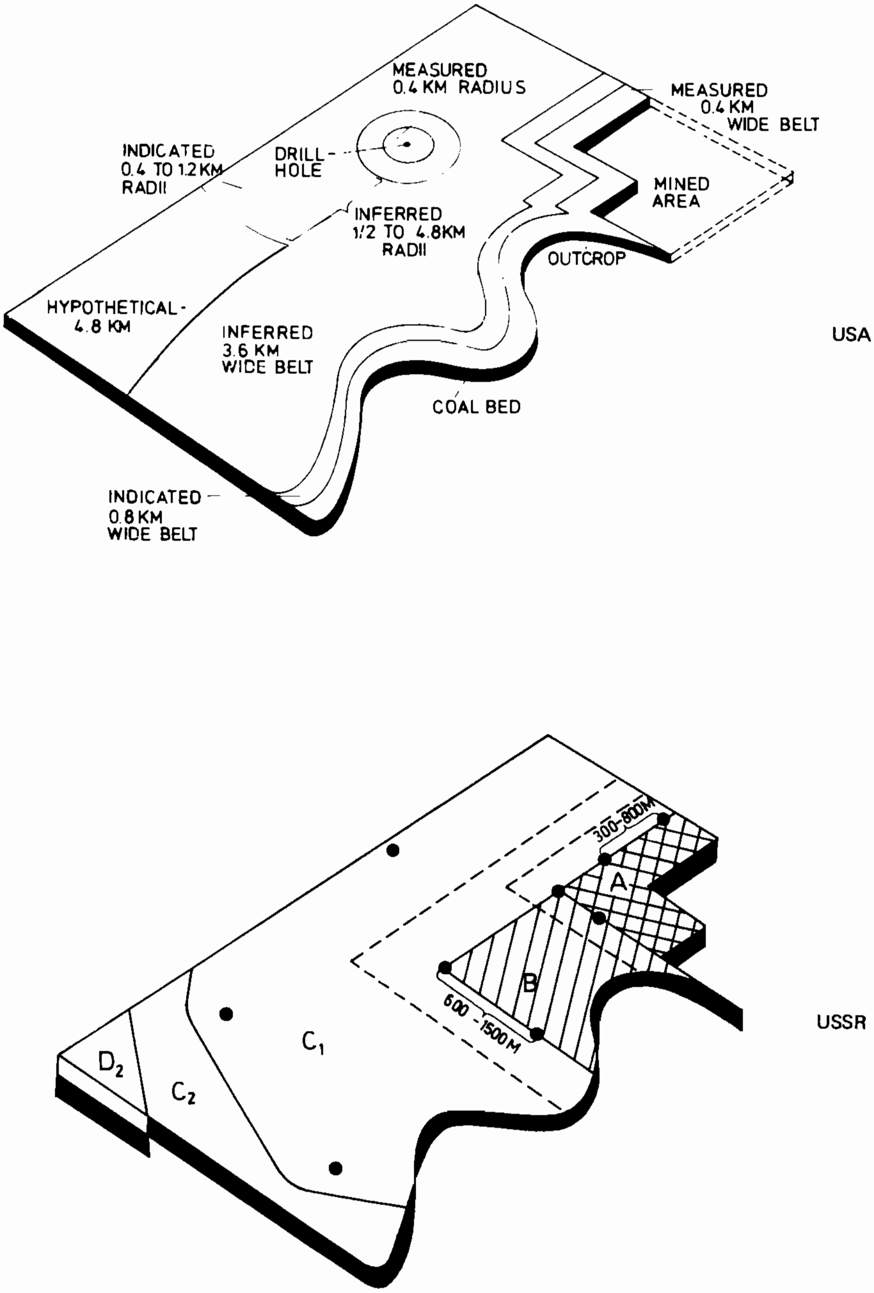

Figure 1. Coal reserve categories, USA and USSR.

According to assurance of existence, reserves and resources are divided into *demonstrated resources* (discovered and explored coal reserves), *surmised resources* (possible reserves in areas with known coal-bearing potential), and *speculative resources* (additional resources in known districts, and in unknown districts).

The categories of reserves and resources are established using both dimensions. According to feasibility of economic exploitation and assurance of existence, category 1A--the sum of "measured" and "indicated" economic reserves--is the highest. "Inferred" reserves are of category 2A. Categories 1B, 1C, 2B, 2C, 3A, 3BC, 4A, and 4BC characterize resources of considerably lower economic importance and assurance of existence.

In addition, the Canadian classification includes a *resource base* that incorporates discovered as well as undiscovered coal concentrations that may become exploitable in the distant future.

The Australian Classification

The Bureau of Mineral Resources of Australia recently approved a new classification of mineral reserves almost identical to that adopted by the US Bureau of Mines and US Geological Survey, with only minor differences in terminology. The Australian classification calls the "economic reserves" of the USA classification simply "reserves", but what is meant in both systems is reserves that can be mined economically [6].

In March 1973, the Permanent Committee on the Geology of Coal Deposits of New South Wales approved the following subdivision for calculating coal reserves.

Recoverable reserves are that amount of common coal that can be recovered from available reserves at admissible cost. The term may be used independently as well as in combination with the reserve category designations.

Marketable reserves represent the quantity of coal suitable for sale after it has been endowed with marketable properties.

According to assurance of existence reserves are divided into four categories.

Measured reserves are those calculated from an observation point pattern that is sufficient for ascertaining coal quality, coal bed thickness, depth of occurrence, and the other parameters essential for planning a deposit development. Observation points should be spaced at not more than 1 km, extrapolation for not more than 0.5 km being admitted.

Indicated reserves are those with a density of observation points that is sufficient for realistic estimate and for which there are reasons to transfer them into the category of "proved" reserves. The points of observation should be no more than 2 km apart. Extrapolation may be performed to distances of up to 1 km.

Assumed reserves are those whose existence is assumed on the basis of geological evidence and information that permits their transfer to higher categories in the future. The distances between the points of observation must not exceed 4 km.

Inferred reserves are characterized by extremely poor knowledge of their parameters. After more detailed study, they may be transferred into higher categories or their further exploration may be considered inexpedient. For preliminary appraisal, this category is divided into four subcategories: very large (more than 10^9 t), large (10 billion to 100 million ton), small (100 to 20 million ton) and very small (less than 20 million ton).

The French Classification

The French classification of coal reserves is also based upon such criteria as probability of existence (degree of assurance of appraisal) and technical and economic feasibility of development and sale [1].

According to the degree of geological assurance of appraisal, three categories of reserves are distinguished: a, b and c.

Category a includes reserves explored in detail. For slightly faulted beds of uniform composition and simple geometry these reserves are identified to limited distances from the bed outcrops with an adequate density of exploration pattern.

Reserves of *category b* are divided into those concentrated within or beneath working horizons and those associated with deeper horizons. The first must be confirmed by measurements in mining openings and drill holes; tectonic faults (even large ones) may be incompletely defined. The latter are distinguished on the basis of an adequate drill hole pattern.

Reserves of *category c* are distinguished by means of restricted extrapolation in the absence of mining openings or with an inadequate number of them.

According to technical-economic indices each category is divided into reserves whose development is technically feasible and profitable at present or in the very near future, and reserves whose development is technically feasible but not profitable in the current economic situation. To assign reserves to the first group, the following should be ascertained: coal bed structure, roof and floor characteristics, feasibility of mechanization of extraction, objectives of mining operations, equipment to be used, possibilities of increasing the product quality and their sale. The second group includes reserves for which the possibilities of improving the quality are absent, there are difficulties in their sale, or great investments are required.

The FRG Classification

In the classification system adopted in the FRG the whole tonnage of useful mineral within the limits of a deposit under consideration is divided into *mineable resources* and *potential resources*. According to the degree of geological assurance each group is subdivided into a number of categories [3].

The group of mineable resources (which essentially corresponds to "identified reserves" in the USA classification) includes the following categories: A - proved, B - probable, C_1 - indicated, and C_2 - inferred. C_1 and C_2 are integrated into "possible reserves".

The group of potential resources includes the same categories designated by small letters--a_1, b_1, c_1, c_2--plus "predicted reserves" denoted by d.

COMPARATIVE ANALYSIS OF COAL CLASSIFICATION SYSTEMS

As can be seen from the above review of classifications, in all countries coal reserves are divided into two large groups according to a single criterion: economic feasibility of mining and use (Table 1). The first group comprises reserves suitable for economic development. In the Soviet classification these are called *commercial (balanced)*, in those of the USA, Canada, Australia, and France *economic*, and in that of the FRG *mineable*. Reserves that currently cannot be mined commercially are called *noncommercial (nonbalanced)* in the USSR, *subeconomic* in the USA, Canada, and Australia, *noneconomic* in France, and *potential* in the FRG.

Despite the same approach, these groups are distinguished in different ways in different countries. This is due primarily to the absence of common rules for establishing the limit of economic mining. The thickness of a coal bed, the complexity and variation of its structure, the grade composition of coal, the mining method, the overburden thickness, the economic situation, and so on--all these are taken into account when referring reserves to one or another of the groups. In the USSR the standards for reserve estimation are established by appropriate State bodies (The State and Territorial Commissions on reserves) on the basis of technical-economic calculations proceeding from exploitation conditions, amount of reserves, the most complete utilization, and the technology of treatment. In other countries the standards are developed spontaneously, to a large measure depending on fluctuations in economic situation and price levels. Therefore, standards that meet the demands of some firms and companies often turn out to be unsuitable for

Table 1. Classifications of coal reserves and resources in different countries.

USA					Canada		France		FRG		USSR			
Total resources	Identified	Economic (reserves)	Demon- strated	Measured	Demon- strated	1A	Economic reserves	a_1	Mineable resources	A+B	Total geological resources	Discovered reserves	Balance	A+B, partly C_1
				Indicated				b_1		C_1				C_1
				Inferred	Sur- mis- ed	2A		c_1		C_2				C_2
		Subeconomic	Demon- strated	Measured	Demon- strated	1BC	Subeconomic reserves	a_2	Potential resources	a+b			Out of Balance	A+B
				Indicated				b_2		c_1				C_1
				Inferred	Sur- mis- ed	2BC		c_2		c_2				Undefined
	Undiscovered	Econom- ic		Hypothetical	Speculative	3A				d		Undiscovered reserves	Predicted	Group 1
				Speculative		4A								Group 2
		Subeco- nomic		Hypothetical		3BC								
				Speculative		4BC								Undefined
					Resource base									

others. Standardization on an international scale of even some of the estimation parameters (coal bed thickness, depth of mining) has not yet been possible.

In terms of the criterion of economic mining, the borderline between commercial and noncommercial reserves is thus uncertain. This uncertainty will probably remain for some time, but will decrease with technical and economic progress and international cooperation in production technology.

A similar situation obtains with the categories and groups of reserves. In the USSR, a number of conditions must be met before reserves are assigned to a given category: establishing the seam identity, degree of regularity in thickness, and structure and quality of coal; a certain order of working arrangement and distances between test holes, depending on the deposit type; core recovery and use of logging data. It is essential, particularly for high category reserves, to ascertain the coal quality and technological properties as well as the spatial distribution of coals with different natural properties, such as grade composition, ash and sulfur content, tar yield, degree of oxidation, and so forth. Referring the reserves to one or another category depends also on the degree of knowledge of natural factors (hydrogeological, engineering-geological, etc.) governing the conditions of mining operations.

In other countries, the criteria for reserve classification are less precise. The reserve categories are defined rather clearly in the classification adopted by the US Bureau of Mines and US Geological Survey; but even this classification takes into account only the parameters reflecting coal seam geometry, distance between points of observation, and extrapolation limits. "Measured reserves" must be ascertained with an accuracy of ±20%. However, requirements for the degree of knowledge of coal quality, and of the spatial distribution of coal of different grade composition, ash content, and so on are lacking; nor is it obligatory to study the hydrogeological peculiarities of a deposit or the engineering-geological properties of the enclosing rocks. In the French classification, rock properties of the coal bed top and bottom are taken into consideration when distinguishing the reserve category subgroups according to economic mineability, but not in defining the categories themselves.

Because of the uncertainty of the parameters taken into account in a majority of classifications, difficulties arise in correlating reserve categories. It is advisable to use the USSR classification as a basis for correlation because it is the most complete and best developed.

In the USSR classification the highest categories are A and B in accordance with the degree of knowledge. "Measured reserves" in the US and Australian classification, category 1A in Canada, categories A and B in the FRG, and category a_1 in France can be identified with the USSR A and B reserves to some degree--

probably mostly with category B. On the other hand, in the USSR classification it is totally inadmissible to assign to high categories reserves outlined by the method of limited extrapolation--that is, within mining areas whose coal-bearing potential was ascertained in a single well only (see Figure 1)--as is allowed for the US "measured reserves". In the USSR such reserves would be assigned to category C_1.

According to the distances between mining workings and points of observation, category C_1 reserves in the Soviet classification correspond mostly to "indicated reserves" in the US and Australian classification, and partly to category 1A in Canada, category b_1 in France, and category C_1 in the FRG.

Category C_2 corresponds mostly to "inferred reserves" in the USA, Canada, and Australia. In the classification systems of France and the FRG, these categories are C_1 and C_2.

All the classifications (except in France) include undiscovered reserves or resources. "Undiscovered (unidentified)" resources in the US and Australian classifications, subdivided, as in the USSR, into two groups, could be correlated with a group of predicted reserves in the Soviet classification. The same subdivision of predicted reserves is adopted in the Canadian classification. In the classification of the FRG, forecast reserves cover only an area of a given deposit or basin.

To estimate world coal reserves and resources properly, it is essential to investigate the standardization of terminology and elaboration of an international classification system. To accomplish this work a group of experts from the countries concerned should be established.

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THE CLASSIFICATION OF COAL RESOURCES FOR INTERNATIONAL REPORTING

J.J. Schanz, Jr.

During the first IIASA Energy Conference in 1975, in response to Professor Michel Grenon's suggestion, a small group interested in the problems of energy resource classification and definition assembled for an informal post-meeting discussion. Today's program of five papers on the various aspects of coal classification are evidence of how attention to these problems has grown in two and a half years.

Much about the specific nature of various national systems to measure and report upon coal reserves and how they compare one to another will be discussed at this Conference. The activity within many nations--Austria, Canada, the USSR, the UK, the US, and others--is very impressive. In addition to this work, there are multinational endeavors such as the World Energy Conference (WEC) and the International Energy Agency (IEA).

There is yet another international effort to improve our exchange of information about mineral reserves and resources. Almost simultaneously with the first IIASA Energy Conference, a United Nations resolution proposed by Canada in Tokyo was approved by the United Nations' Economic and Social Council. This resolution instructed the Centre for Natural Resources, Energy, and Transport (CNRET) to assemble a group of experts to recommend a system of terms and definitions for mineral resources.

The UN resolution specifically excludes crude oil and natural gas. Mr. Gilbert Royer at the 1976 IIASA Conference reported on the Centre's separate effort to explore some of the special problems of classification of the naturally fluid hydrocarbons. The results of this exploratory meeting were reported in the Centre's publication *Natural Resources Forum* in July of 1977.

I have been assisting CNRET in the advance preparation for the meeting of the group of experts now scheduled for the spring of 1978. It is expected that the group will number approximately ten people drawn from a cross section of nations active in mining. I expect that this will include representation from the Far East, Africa, the UK, Western Europe, the COMECON group of nations, South America, and North America. In addition, we are hopeful that either on the panel or in an official observer status we will have participants familiar with the work of the WEC, the International Atomic Energy Agency (IAEA), and the IEA.

On October 26, 1977, I delivered to CNRET a background paper on the problems of mineral classification. In this, I have relied extensively on the work of Günter Fettweis of Austria, Igor Bondarenko of the USSR while he was on temporary assignment to CNRET, and Jan Zwartendyck of Canada, to augment my own contributions. As soon as the expert group has been identified, they will receive this paper for both comment and as a means of preparing their thoughts for the meetings.

In addition to the background material, there is a twenty-item agenda designed to direct the panel through a series of conceptual decisions on what should be the framework of classification and definition for the acquisition and dissemination of mineral resources data.

The last item on the agenda will be to devise and approve the recommendations to be made to the Secretary General. For this purpose, I have suggested a skeleton format to stimulate discussion. We expect, of course, alternative schemes may be proposed by the experts to be included in this final debate.

I should emphasize that the CNRET objective is a general resource classification system to serve the UN's various needs. This means that it must first be suitable for adaptation to the special characteristics of all mineral resource commodities, not any particular one. Second, the system must be suitable for multi nation use. Ideally a scheme for universal use by all nations for both internal and international purposes should be proposed, hoping all would adopt and conform to its specifications. I feel it will prove more realistic to suggest categories and definitions which are designed to permit nations to provide data readily from their own internal reports. Also, we must recognize that the reporting capabilities of various nations are not equally developed.

Once resource data are assembled from many national sources it must permit aggregation into regional or world totals in which we have confidence in the integrity and compatibility of the information received. Finally, it is desirable that those who wish to retrieve and use the data bank for purposes of discussion or analysis can have confidence in what the resource estimates truly represent.

I feel that the task of the expert group is not unlike that facing the US Department of Interior a few years ago. The Department had to devise a system to be used by several different agencies with different missions and training and adaptable over time to the statistical peculiarities of nearly 100 mineral commodities. The Interior's plan, based on the McKelvey diagram, had a limited number of categories and the definitions are intentionally general in their language. I suspect the UN categories and definitions will have to be of a similar nature if they are to be both approved and workable in practice for many nations and commodities. Although we may admire the numerous categories and detailed definitions of the systems employed by the USSR, France, or the FRG, I am fearful they may prove too complex for multination use at this point in time.

I tend to favor at this moment an international classification system with only four major categories and a minimum of subcategories. These four would be: (1) engineering estimates of the known, currently mineable reserves; (2) engineering estimates of known, not currently producible mineral deposits; (3) geologic extrapolations of the magnitude of undiscovered resources that can be found in technically mineable deposits; and (4) mineral occurrences that are of such low quality or physical uncertainty as to existence and discoverability that they are not quantifiable--or if they are, the quantities should not be combined with estimates in the other three resource categories. Obviously, the crustal abundance of carbon bears little relationship to usable energy resources found as coal.

I also tend to favor the use of alphanumeric identifiers for resource classifications in preference to simple word combinations. They force the statistical respondent or data user to read the more detailed descriptions of the category rather than to make quick judgments based on personal experience of the meanings of single words. However, I would recommend a unique set of letters and numbers to avoid confusion with existing national systems, e.g. the USSR's A, B, C_1, C_2.

If we can surmount the many problems and personal preferences that I am sure will hinder the experts' progress toward agreement on a general UN classification system, we must eventually apply that system to the specific problems of commodities such as coal and uranium. We will be hearing in some of the following papers what progress and suggestions are being made to find a rational way of handling coal resource data problems. I will be most disappointed if the recommendations for a UN classification plan are not fully compatible with the data systems being devised for international coal.

Let me conclude this progress report on UN activities by identifying some of the problems that my experience indicates must be faced in adapting a general mineral classification system to coal in particular.

The separation of coal-in-place from the recoverable portion by using current technology at an acceptable cost to the nation in question is a problem that must be faced. An inventory of usable coal reserves is not coal in the ground but coal that can be delivered to the mine portal for final use. Some countries may simply avoid this difficulty by reporting only on coal-in-place. This does not really solve the problem.

The US in trying to avoid the problems of economic analysis and the statistical difficulties involved in dealing with the separation of economic from subeconomic coal has relied upon direct use of thickness and depth by rank of coal as proxies for more complex calculations and reporting. This has kept the reporting task manageable but it is obvious that considerable oversimplification of the actual costs of mining are involved.

The question of recoverability and economic versus subeconomic coal is basically a question of engineering economics. However, it can be compounded in difficulty if questions of environmental quality are introduced, causing sulfur, nitrogen, trace elements, or ash content to become important in the use of coal. Further, mined-land reclamation standards and other legal requirements can also affect what constitutes mineable, recoverable coal. Even official requirements on how coal data are to be reported influence the availability of coal resource data. One can also ponder what will happen to recovery factors as we introduce unconventional recovery technologies, such as underground gasification.

Because of the areal extent of coal beds and their frequent near-surface occurrence, limited attention has been directed toward the estimation of undiscovered coal. Nonetheless, new beds are still discovered, even in a well developed coal mining region such as the UK. This would suggest that perhaps more attention should be paid to the estimation of undiscovered coal, particularly at greater depths. One should be somewhat suspicious of how carefully we have defined what constitutes known coal resources from mere geologic extrapolation. In large countries with considerable coal, it is likely that extensive extrapolation and interpolation from widely spaced observation points has been used to classify coal as "discovered" when it is actually only "hypothetical" or "prognostic" coal.

A certain variation in the energy content of any fossil fuel is to be expected. But this can become extreme when one examines the actual heat content per unit weight of different types of coal. This can have a significant effect on the true magnitude of energy contained in reported coal reserves. If a ton of lignite or brown coal is combined with a ton of anthracite a major error has been committed. The energy specialist is quite comfortable if tons of coal are converted to Btu's, calories, joules, or some other more precise unit. However, the adoption of some form of "standard ton of coal" with a uniform heat content would seem attractive for more general statistical purposes.

Finally, I would like to call attention to the growing reliance upon statistical notations of reliability or probability. This is a noteworthy endeavor to provide the user of the data with some warning as to the precise nature of the data he is receiving. It, however, can lead to problems in implementation. At present, these notations appear to fall into four classes: (1) the accuracy of the measurement specifies that its actual value will fall within a plus or minus range; (2) a risk factor that corrects for the uncertainty of the estimated quantity actually proving to be smaller than anticipated; (3) a confidence factor that reflects the estimator's own judgment as to the quality of his assumptions, data, and analysis; (4) a probability of the mineral occurrence being at least of a specified minimum size but not more than a larger amount.

Although I admire the desire to substitute mathematical notations for word definitions, I am concerned that we are not clear as to which of these notations we are using. We frequently use them interchangeably or use combined measures in an unspecified fashion. This problem is compounded by variations among authors and between nations. I would suggest that in our future refinement of definitions we be more precise as to measures of confidence and probability.

I appreciate the opportunity to report to you on the status of the assignment made to CNRET and look forward to your contributions to the successful completion of the task. Certainly the long history and many national traditions of coal reserve estimations will provide a major challenge for the proper application to coal of the recommendations made by the Expert Group for adoption by the UN.

A PROPOSAL FOR DISTINGUISHING BETWEEN OCCURRENCES AND RESOURCES OF MINERAL COMMODITIES WITH SPECIAL REFERENCE TO COAL

G.B. Fettweis

INTRODUCTION

This paper is a contribution to the current interdisciplinary and international discussion on what is to be understood by resources of mineral raw materials. In mineral science we can find different meanings of the term "resources" that do not all agree with the common understanding of the word [2,10,30,31,32]. Elsewhere [12,13,14,16], the author has discussed economically oriented concepts as opposed to a geological concept. The differences in the use of the word resources in the mineral science literature are frequently not realized by users such as economists, politicians, and the layman, and serious misunderstandings can be the consequence [2,10,12,13,14,16,30,31,32]. Politicians and economists, as well as the man in the street, will naturally understand by resources quantities that can become supplies if needed. They may, however, be relying on figures that only cover geological potential, the actual availability of which has not been checked or assured in any technical and economic respect. How can we resolve this problem?

ECONOMIC VERSUS GEOLOGICAL UNDERSTANDING OF RESOURCES

In German speaking countries resources are explicitly understood and defined as the content of "Lagerstätten" (deposits). But there are two different meanings and definitions of "Lagerstätten" [14]. In the older one "Lagerstätten" have to be of economic value; all other accumulations of minerals in the Earth's crust are called "Vorkommen" (occurrences). The other meaning, the "geological concept", is based on the definition given by Cissarz and, in a derived form, by Bentz and Martini (all from the Federal Geological Survey, Hannover, FRG) for the term "Lagerstätten" [4,9]. Here "Lagerstätten" of mineral raw materials are "geological bodies of changing mineralic composition limited in extension in which certain chemical elements are enriched to a considerably higher degree by natural events than would correspond to the average of these elements in the upper Earth's crust". Therefore the amount of anything that might be included as a resource in this definition of "Lagerstätten" is exclusively according to the subjective decision from case to case as to what is to be understood by "enriched to a considerably higher degree".

In the English language an understanding of resources according to a mineral economics concept is the definition of "resources" used by the World Energy Conference (WEC) in its *Survey of Energy Resources 1974*: "In the broadest sense resources of nonrenewable raw materials are the total quantities available in the earth that may be successfully exploited and used by man within the foreseeable future" [8]. This definition has the obvious advantage of not being in contrast to the meaning of the term of resources as used in common language* as well as in the mining industry and in the economic sciences. Figures on the amounts of mineral resources corresponding to the definition of the WEC, are, therefore, not only plain for everybody, but may also serve as a basis for political and economic decisions. Certainly the actual importance of the assessment of resources of mineral raw materials lies in its application for making decisions.

As an excellent example for a mainly geological explanation of resources within English speaking countries, the fundamental statements of Brobst and Pratt [6] may be cited (Figure 1). According to them, least consideration should be taken of economic factors when assessing resources of mineral raw materials. "So many complex factors govern price at any given time that it would seem foolhardy to estimate resources in each of the economic categories and expect the results to be meaningful for very long." Correspondingly the main principle in assessing the resources should be to assess the "geological availability" of mineral concentrations in the Earth's crust: "Geological availability concerns the existence and concentration of certain elements or combinations of elements and is the most fundamental characteristic of a mineral commodity that governs its commercial use." The term "resources" introduced by Brobst and Pratt therefore also comprises undiscovered deposits of unknown economic value that may exist elsewhere (speculative resources). In addition they strictly differentiate their concept from the more economically defined concepts of the McKelvey diagram (Figure 2) [22, 28,29].

Of course Brobst and Pratt also need ways for separating the concentrations that may be called resources by their definition from the remaining Earth's crust. The difficulties of this

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*According to D.B. Brooks [7]: "'Resources' are defined in economics as those things which actually or potentially create new wealth; 'natural resources' are those existing independently of man's efforts but recognized as at least potentially useful to him."

According to Webster's dictionary resources are: "A new or a reserve source of supply or support; a fresh or additional stock or store available at need; something in reserve or ready if needed. Available means, as of country or business. That to which one has recourse in difficulty. Assets."

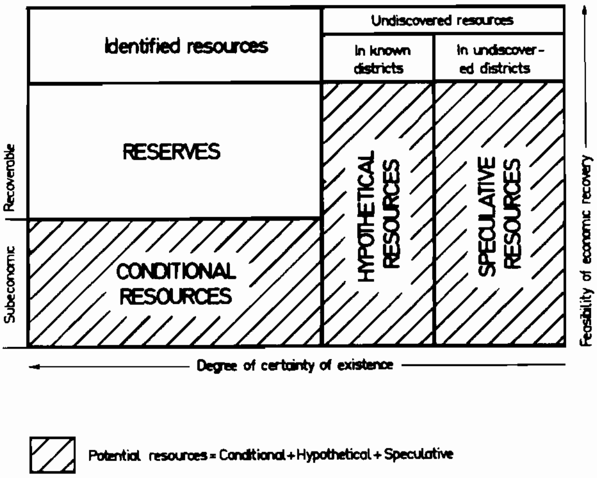

Figure 1. Classification scheme of mineral resources used by Brobst and Pratt [6].

task can be recognized in the different definitions cited by them. In the end they cannot avoid reference to technical and economic conditions even if it is a rather vague one.*

The separation of their resources from the, as they understand, "materials at present inconceivable as resources" remains

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*"Resources include not only reserves but also other mineral deposits that may eventually become available - either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not yet been discovered."

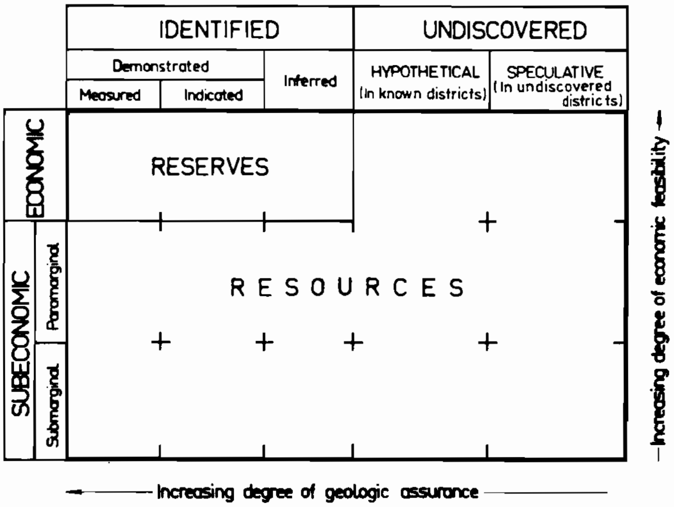
"Mineral resources, whether real or potential, are geologic entities - concentrations of one or more elements in the earth's crust...accordingly, the chapters of this volume deal with predictions based on geologic reasoning and have been written by geologists."

"Resource estimates contained herein...present an optimistic outlook...a potential, not a reality."

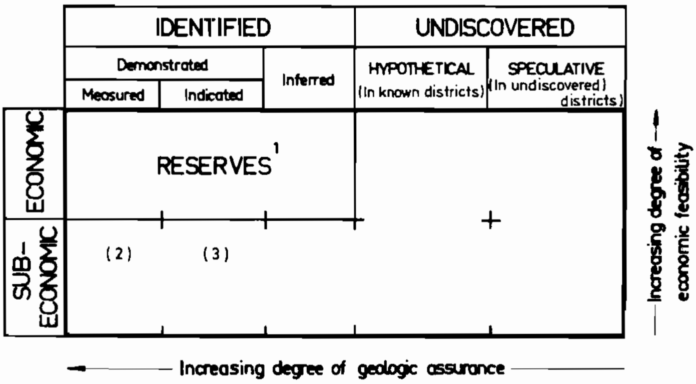
"We may define a mineral resource as a concentration of elements in a particular location in or on the earth crust (or, now, also in the oceans), in such a form that a useable mineral commodity can be extracted from it."

"Conditional resources" are "resources that may eventually become reserves when conditions of economics or technology are met."

(A) Mineral resources except coal



(B) Coal resources



[1] Recovery factor = ____

[2] Includes ____ billion tons of Reserve Base coal that are not currently minable. (see recovery factor)

[3] Includes ____ billion tons of Reserve Base that are not currently minable (see recovery factor)

Total Remaining Resources ____
Cumulative Production ____
Total Original Resources ____

Figure 2. US Geological Survey–US Bureau of Mines Classification scheme of mineral resources–McKelvey Diagram.

Source: [22,28,29]

vague and open ended too. What is, finally, "at present inconceivable"?

The geological concept of resources comprises also the questionnaires for the assessment of the world coal resources as used by the WEC since 1962* [13].

GOOD REASONS FOR USING THE DIFFERENT MEANINGS OF RESOURCES

The existence and the relatively large spread in the different concepts of resources make us recognize the necessity and justification for adequate ideas and procedures. In fact there are good reasons for using both discussed meanings.

We need data on mineral occurrences defined according to the geological concept. As Brobst and Pratt say: "There is no economic availability if there is no geologic availability. Of the two factors, geologic availability is the more fundamental because without it, economic availability is not pertinent." Therefore, the basic task with regard to future mineral supplies is to increase the geological knowledge of occurrences which also means to obtain an improved knowledge of the geological structure of the Earth's crust. The aim is to develop geological knowledge to a point where hypothetical and speculative occurrences play only a minor and unimportant part. It is necessary to find out how the various useable minerals are distributed within the Earth's crust. Reality will probably lie between the two cases that the author has discussed elsewhere as hypotheses for the distribution of metals and of coal and that are illustrated by Figures 3 and 4 [13,14,15]. In order to clear up the situation, it is necessary to have a true accounting of the different kinds of occurrences that does not only refer to their characteristics as resources from the point of view of an economic future supply and to have data on the geological amounts.

It cannot be expected for many other reasons that the study of accumulations of elements in the Earth's crust is done only from the economic point of view. Moreover it is a field that may legitimately be regarded as a branch of the "pure Earth sciences". The effort to keep geo-scientific knowledge free from the uncertainties and the time varying modifications of economic considerations, is, in the author's experience, an essential explanation for using the "geological concept" in exploring the Earth's crust, and it is supported by many geologists.

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*That is why the definitions in these questionnaires and those in the *Survey of Energy Resources 1974* contradict each other. The resources listed and published in the *Survey*, according to these questionnaires, are therefore not resources as defined in this paper.

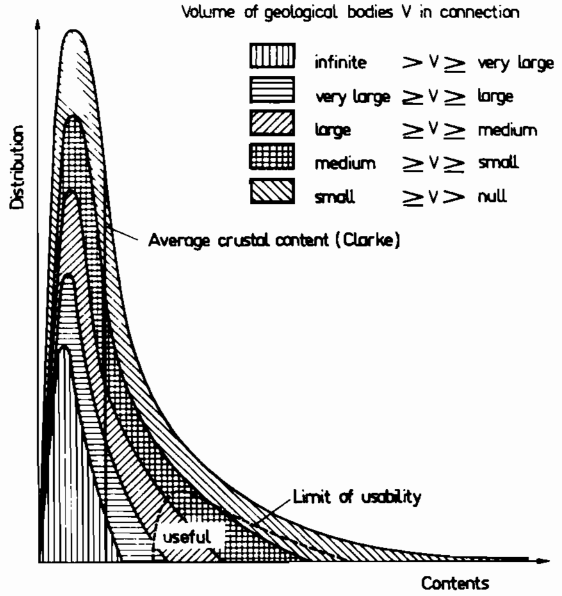

Figure 3. Scheme of log-normal distribution of metals in connected geological bodies in the Earth's crust (not to scale).

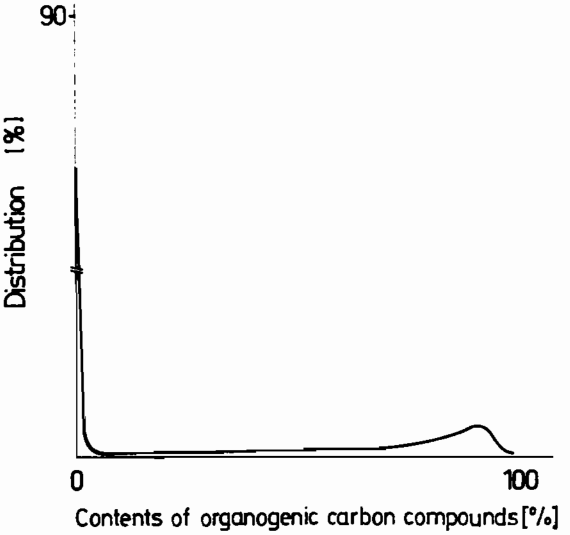

Figure 4: Scheme of the distribution of organogenic carbon combines of solid phase in the Earth's crust (not to scale).

These legitimate efforts, therefore, should be complied with in the system of mineral assessments.

From the purely practical point of view it is part of geological exploration of occurrences of mineral raw materials to establish or to be forced to establish at least in the early stages quantitative data on mineral occurrences within geological limits and without paying attention to technical or economic aspects. For want of another expression, these data are also called resources.

On the other hand in the end we need economic availability, and geologically available natural materials in the Earth's crust can only be converted into raw materials for use in economy by mining; therefore they must be economically mineable and what is economically mineable is determined mainly by technical possibilities. These are by no means infinite, for example, the mastering of rock pressure.

The author therefore also agrees with the statements made by G.T.S. Govett and M.H. Govett concerning the question of future mineral supplies. They say "The most important point at issue is technological development - of finding, mining and processing ores - and the capacity to pay". The author emphasizes like them "the role of 'economic and technologic availability' in determining both short term and long term mineral supplies" [19].

SOLVING THE PROBLEMS THROUGH ADDITIONAL TERMS

A solution of the problems of:

- misunderstandings of resource data because of different understandings of the term resources, even in the mineral science world, and
- the necessity to have data on mineral accumulations in the Earth's crust according to the different meaning of the term resources

can be found by introducing additional expressions for the assessment of amounts of mineral raw materials in the upper Earth's crust and by defining and using the word resources only in an economic sense.

This suggestion was presented in an early form as a matter for discussion at the First IIASA Conference on Energy Resources in 1975 [12] and has since been presented in more advanced versions on other occasions too [3,13,14,16,17]. This paper gives some further considerations and details of the suggestion.

Figure 5 gives the author's proposals in detail. The figure agrees with the matrix structure of the well known McKelvey diagram (Figure 2) and with the expressions used for the subdivision

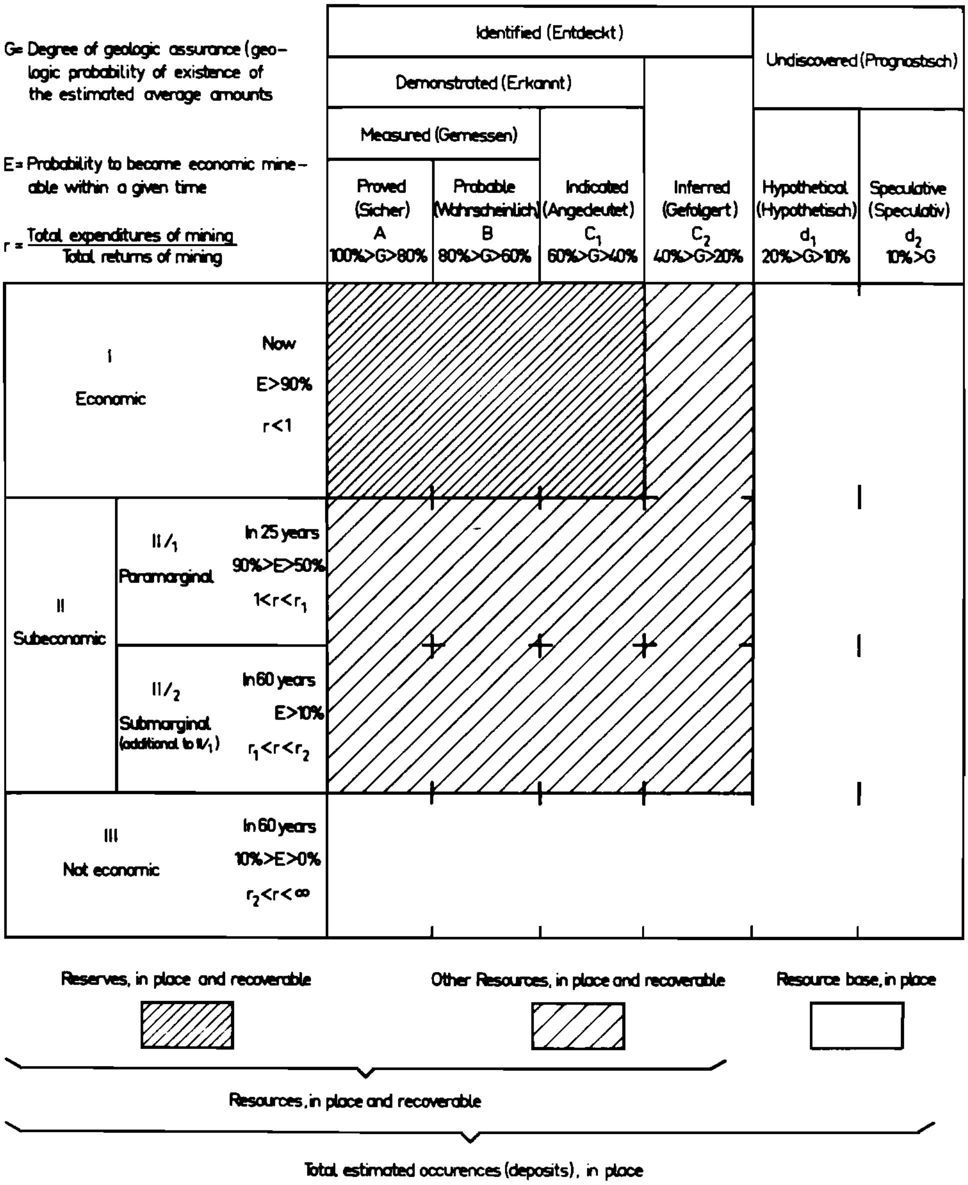

Figure 5. Proposal of a classification scheme for the international exchange of resource data. The limits of error related to the degrees of assurance should be subject to further discussion (e.g. A, ±10%; B, ±20%; C_1, ±30 to 40%; C_2, ±30 to 60%; d_1 and d_2, more than 30 to 60%).

of the axis of geological assurance and of economic feasibility. But there is one additional category of economic feasibility and some differences in the terms used for the calculated amounts.

OCCURRENCES

The term "occurrences" shall be established for the sum of all calculated occurrences regardless of their geological assurance or economic feasibility. Instead of the short term "occurrences", the longer terms "geological occurrences", "mineral occurrences", or "total estimated occurrences" can be chosen. The "mineral occurrences" are the field of the geological concept.

Of course, changing the terms does not change the necessity to mark a borderline between the total estimated amounts and the rest of the Earth's crust, which in any case is difficult to establish. The great advantage, however, lies in establishing and understanding this limit regardless of the possibilities for using the quantities in question as a supply in the foreseeable future. Accordingly boundaries can be commonly acknowledged for the restrictions of occurrences from the upper Earth's crust. They are clear, physically explained and defined from the geological point of view, and may be valid over long periods. The specific boundaries for coal, for example, can be used as they were established at the International Geological Congress in 1913, i.e. a 0.30 m thickness minimum and a depth of 1800 m maximum. For other mineral raw materials similar values will certainly be agreed upon, e.g. for crude oil with regard to the oil in place and, perhaps also, independent from the degree of viscosity or for natural gas. For metals, only depth, size, and grade of deposits can be taken into consideration and not the numerous other geological conditions of importance for mineability [18].

RESOURCES AND RESERVES

Following these proposals, the term "resources" should be clearly limited to only those assessed amounts that are resources in the common sense and in the sense of mineral economics. As already cited, a good definition of this kind was given by the WEC, in their *Survey of Energy Resources 1974* [8]. This already well known definition of resources, therefore, is the starting point of the suggestions of the author.

In the WEC definition, the expression "successfully" can only be understood in an economic sense, even if the economic consideration does not affect private economy but political economy. To use a deposit of a natural mineral material must bring an advantage for the economy of the country and thus for the corresponding transformation process, i.e. the mining of this deposit. "Successfully" might therefore be equivalent to "economically mineable".

But using the WEC definition for resources raises a key question. What is to be understood by the "foreseeable future"? "Do we have in mind resources that - assuming a demand existed for them - could be mined profitably any time in the next 10 years, 25 years or hundreds of years?" asks Zwartendyk in this connection [11]. To answer this question the purpose of the data on resources should be the starting point: they are to be the bases for economic and if necessary political decisions. In fact such decisions are usually made only for periods of up to 50 or 60 years maximum. This is--in the author's opinion--also the utmost horizon for the possibility of making reasonable forecasts. It also covers the period of two or three generations which people can experience in their lifetimes and it thus corresponds to biological reality. Thus 60 years may be considered the utmost limit for a "foreseeable future". Zwartendyk and the Canadians consider, however, a period of about 25 years to be the practical upper limit [11].

To limit the resources to within a probability of at least 10% of becoming economically mineable in the foreseeable future follows the Canadian principles [11], but according to the proposal here this can include only identified occurrences (see Figure 5). With undiscovered, i.e. hypothetical and speculative, occurrences, by definition the knowledge of the numerous geological conditions connected with the deposits that determine their mineability has not been established. Therefore, although quantities of the deposits can be roughly estimated in geological limits, generally the geological knowledge is insufficient for a proper decision on technical and economic mineability now or in the foreseeable future. An economic evaluation of these occurrences, therefore, presents too big a challenge for the people in charge, as can be seen also from the statements of Brobst and Pratt in particular.*

Objections can be made that similar forecasts should be established for the geological conditions of undiscovered occurrences, as they are necessary for the evaluation of resources under future economic conditions; geostatistical methods would be a means for that. The author cannot agree with this, at least not on the basis of the present knowledge of geology and geostatistics. Geostatistical methods are best suited for interpolations within a limited area. As Averitt states about their application to coal occurrences: "The statistical methods work

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*In USSR regulations for the classification of mineral deposits, the "prognostic" geological resources correspond to the "undiscovered" resources of the McKelvey diagram. It is of interest that, contrary to the case of identified resources, no word is said in these regulations of usability in connection with the prognostic data. The figures serve explicitly and exclusively for "estimating the potential possibilities" of whole regions on the basis of "general geological conceptions" [24].

best, when the geology of the coal and of the enclosing rocks is fully understood and much closely spaced development drilling information is available" [1]. The question whether a "one-dimensional" application, i.e. an application of geostatistical methods towards the assessment of the quantity of hypothetical deposits in known districts or even of speculative deposits in undiscovered districts, can be usefully performed in the foreseeable future may therefore be left unanswered. In any case an adequate prediction of complex geological factors such as quantity and "Bonität" (discussed in another paper by the author in this volume [18]) really cannot be expected in this field because of the extraordinary variety of geological appearances. Perhaps, however, the use of geostatistical methods in the field of inferred occurrences may produce reliable data.

Because of the circumstances discussed undiscovered occurrences cannot be considered as a resource in an economic sense.

To evaluate the occurrences "that may be successfully exploited and used by man within the foreseeable future", and therefore can be named resources is, of course, a very complex task. It can be done most effectively only by an appropriate and unprejudiced consideration of all points of view on the subject. Because of the specialization of sciences this means that it can be obtained most effectively by teamwork by different disciplines: geologists, engineers (particularly mining engineers), and economists. The evaluation requires forecasts of future economic developments and is, therefore, charged with uncertainties. But this is the nature of reality: future is a function of continuous and unforeseeable changes and is always uncertain. As M.H. Govett and G.J.S. Govett put it: "In the final analysis, both reserves and resources are changing concepts closely associated with the dynamics of economic change" [19].

It does not correspond to the reality of technical and economic changes to keep calculated resources unchanged for decades, as has partly been done for coal. Instead of sticking to ancient principles, it is necessary to repeat the technical and economic evaluation of identified occurrences for usable mineral materials in the Earth's crust from time to time. This is true for all branches of economic planning. The author gives some basic considerations on the question of resources as a function of mineability in another paper in this volume [18].

Since the suggestions made by Blondel and Lasky [5], the division of resources into two groups has been increasingly established internationally, the first group being called "reserves". It is commonly accepted that "reserves" include only such parts of the resources that are economically mineable at the time of the assessment. But there are detailed differences of the definitions too that need further discussion and clarification. Here only a few remarks are made.

The definition of the WEC in the *Survey of Energy Resources 1974* says, "Reserves are the corresponding fraction of resources that have been carefully measured and assessed as being exploitable in a particular nation or region under present local economic conditions using existing available technology; recoverable reserves are that fraction of reserves in place that can be recovered under the above economic and technical limits" [8]. According to other definitions the unqualified term "reserves" refers to the recoverable material only. As far as coal is concerned the term "reserve base" for the material in place is partly used in these cases [1,29].

Again there is no uniform limit to what is to be understood by "carefully measured". While the limits in the original McKelvey diagram and also by Brobst and Pratt (Figures 1 and 2) include the total amount of identified quantities in reserves, the most recent official American publications calculate reserve and reserve base figures for coal on the basis of geological assurances with only demonstrated quantities included [1,26,27]. Thus there are economic resources not considered to be reserve base or reserves because of their minor geological assurance.

"Other resources" is the definition used by the WEC for the resources beyond reserves. The subdivisions and definitions of Brobst and Pratt, and of McKelvey are shown in Figures 1 and 2.

To fulfill the different requirements it is advisable to estimate the figures of reserves and resources in place as well as those recoverable. This point will be stressed in more detail when discussing mineability in the author's other paper in this volume [18].

RESOURCE BASE IN A NEW SENSE

The expression "resource base" could be appropriate for all quantitatively assessed deposits according to their geological availability that do not meet the requirements to be resources. This suggestion is to some extent following the considerations of Zwartendyk and the Canadian principles of 1975 which also recommended the introduction of a "resource base" as a category in the assessment of mineral occurrences: "It is recommended that a clear distinction be made between 'resources', which (when appropriately subdivided) are roughly definable and quantifiable, and of which 'reserves' are a part and 'resource base', which extends indefinitely beyond this" [11]. But the author is aware, also, of his using the expression "resource base" not in the meaning given by Schurr and Netschert in 1960 in which it has partly been used since [20,21,23,25]. According to Schurr and Netschert resources are part of the resource base. The author thinks this to be confusing. In common usage the basis of a thing does not normally include the thing itself. On the other hand several acknowledged experts say that the term is already too well established in English to be changed without also causing misunderstandings. The author, accustomed to a different situation in German, where a corresponding term has not been used up to now, will keep to his original proposal as a subject for discussion in this paper*. Of course it is possible to use another expression instead of "resource base", e.g. "other estimated occurrences".

The main point of the author's proposal is to use another term instead of "resources" for the content of those occurrences (deposits) estimated according to "geological availability", for which it is not or not yet possible to say that they "may be successfully exploited and used by man within the foreseeable future" and that therefore are not available in an economic sense. The author's "resource base" comprises two parts. The first part includes the amounts of identified occurrences without economic value in the foreseeable future as have been calculated in several cases, e.g. for coal in the FRG and for all minerals in Hungary according to their official regulations. The second part of the resource base are the undiscovered occurrences. Of course the second part of the resource base can become resources through further exploration. And the whole amount of the resource base may--perhaps--be of ultimate benefit to mankind in a now unforeseeable future.

FINAL REMARKS

In summary, apart from semantic questions a tripartition of geologically estimated occurrences into reserves, other resources, and resource base, as in Figure 5 is much more suitable than the present separation into reserves and other resources, if the true realities of exploration of occurrences is to be complied with as well as the necessities and requirements of the economy and of the decision makers. The assumed total occurrences, therefore, should be assessed and established independent from economic considerations according to the geological availability, and then they may be divided according to economic factors into reserves, other resources, and resource base. A similar procedure should be adopted for all data on occurrences of usable raw materials in the Earth's crust and for their worldwide statistical assessment.

A forecast of resources in the sense discussed is more realistic, even if it may be difficult and accompanied by many

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*There are also differences between the author's idea of "total estimated occurrences" and the "resource base" of Schurr and Netschert. The latter can include the total physical amount of a material in the upper Earth's crust, or portions of it, without considering any possibilities of usage and can be calculated merely geochemically by means of average crustal contents and not be geologically estimating the contents of deposits as special accumulations as is necessary for calculating "occurrences".

uncertainties, than a resignation in this matter and sticking to the vague limits of an "eventual availability some day" of the calculated amounts. This fully agrees with the statement of D.B. Brooks from the Department of Energy, Mines and Resources of the Government of Canada [7]: "The greatest problem in dealing with mineral deposits as sources of supply rather than as geologic phenomena arises from the common failure to quantify them with appropriate economic dimensions. Perhaps it is hard enough to classify natural physical entities without introducing concepts from another field, but this is exactly what is essential if an inventory is to be meaningful!"

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QUALITY AND "BONITÄT" OF MINERAL OCCURRENCES AS FACTORS OF MINEABILITY

G.B. Fettweis

INTRODUCTION

According to suggestions of the author in another paper in this volume [13], identified occurrences can be divided depending on their economic value into resources, of which reserves are a part, and a resource base (or "other occurrences").

The important factors for inquiries on the economic value of occurrences of mineral raw materials can be divided into two main groups, each of which is important for the costs and proceeds of a mine assumed to be applied to the adequate deposit.

The first group may be summarized as the "geographic conditions" in the widest sense. This comprises all natural conditions of climate and topography, as well as the transportation situation and the local technical, economic, social, and political factors. Demand and market conditions are also included within this group. Many factors in the geographic conditions group are dependent on time. This paper does not deal with the geographical conditions.

The second main group of factors influencing the assessment of economic mineability of a deposit consists of the geological conditions of this deposit. Statements on the influence of geological conditions may be applied to all kinds of mineral raw materials and all kinds of mining, but here they are to be discussed in more detail for the example of coal deposits. Consideration can be restricted to the two kinds of coal mining in use today, namely, opencast and underground mining. No attention is paid to the mining through wells, unless especially mentioned.

TWO GROUPS OF GEOLOGICAL CONDITIONS

To discuss the problems of the economic assessment of coal resources it is useful to distinguish between two subgroups of geological conditions [11].

The first subgroup consists of factors concerning the quality of the coal as a raw material in a given deposit. This subgroup may thus be called the "quality" of a coal occurrence and it determines the income per ton of a mine and can influence the costs per ton too, by way of the costs for coal dressing. This influence on costs can be neglected for our purposes.

The second subgroup of geological conditions consists of factors connected with the geological body containing the coal and with the geological environment of this body. These factors determine the costs of extraction. To prevent misunderstandings I propose to call this group of factors in German the "Bonität" of the coal occurrence, an expression that is also used, for example, for the assessment of soils for agriculture.

Table 1 gives a survey of the most important factors of quality and "Bonität" of coal deposits. Some of these can only be assessed qualitatively and/or verbally (see also [3,16,17,20,22]).

The relationship between these factors and economic mineability is defined by technical parameters and thus depends on technical progress. This also means that the relative importance of the different factors, for example of the dip or the tectonic disturbance, is particularly defined by developments in the technical and economic field and thus correspondingly depends on time.

The interrelations may be very complex in detail. The determination of economic mineability therefore requires sufficient knowledge about the related technical fields, i.e. mainly the mining technique, the processing technique, and all methods of coal utilization, including an adequate knowledge of development trends.

The influence resulting from the "Bonität" factors on the economic mineability of coal deposits is very often more important than that of quality. The existing range of variation can be estimated by comparing the production costs of coal at different kinds of deposits in the same country--i.e. in comparable geographic conditions.

Thus in Germany the production of 1 m^3 of coal is twelve times more expensive in the Ruhr-coal district than in the brown coal district of the Rhine-Valley only a few tens of kilometers distant. The differences in depth, thickness of the seam, tectonic conditions, etc. are why generous opencast mining of the brown coal in the Rhine-Valley can be done while the hard coal of the Ruhr-District has to be mined below ground under a difficult "Bonität".

According to Astakhov the costs for mining in the projected large-scale opencast mines of Kansk-Achinsk in Siberia will only amount to 5% of the costs in the Donbass District with its difficult underground mining conditions [1].

But there are not only these big differences in costs between conditions suitable for opencast or underground mining. Also within either of these mining methods, the production costs for a ton or a cubic meter of coal in mines of the same country or within comparable countries can differ by a factor of 3 or even 4 and more.

Table 1. Main geological conditions influencing mineability of coal occurrences.

Quality factors of coal occurrences

(a) Rank
- Moisture
- Volatile matter
- Fixed carbon
- Energy value

(b) Grade
- Content of ash in coal
- Content of sulfur in coal
- Content of other deleterious constituents in coal
- Content of partings (including fall) in the seam

(c) Coking quality (different tests)

(d) Continuity and regularity of the quality factors

Factors of the "Bonität" of coal occurrences

(a) Geometric conditions
- Areal extension of seams
- Depth of seams
- Number of seams
- Intervals between seams
- Thickness of seams
  - Coal
  - Partings
  - Fall
  - Total
- Strike and dip of seams
- Tectonics of seams with regard to folding and faulting, small scale and big scale
- Intrusions
- Continuity and regularity of the above geometric conditions

Geometric continuity and regularity of the factors of quality (these can belong to Bonität with regard to the eventual necessity of selective mining causing increased costs).

(b) Geomechanical conditions

Sheeting, cleavages, foliation, strength, hardness, abrasivity, permeability, etc., and their continuity and regularity with regard to
- the seams (coal, partings, fall)
- the immediately underlying and overlying strata
- the overburden strata

Rock pressure (including the danger of rock bursts)

(c) Geochemical conditions
with regard to spontaneous combustion

(d) Geothermal conditions

(e) Hydrogeological conditions

(f) Conditions concerning natural gases
(e.g. CH_4-outflow, danger of outbreaks of gases)

In comparison the energy values which are the most important characteristic for the quality of steam coal differ by a factor of 8 (e.g. lignite, Megalopolis Mine, Greece, about 4100 kJ/kg; low volatile bituminous coal, about 33500 kJ/kg).

TECHNICAL PROGRESS AND MINEABILITY

Progress in mining techniques need not necessarily mean a quantitative extension of economically mineable occurrences, apart from technical developments in the field of consumption. In underground coal mines, a generally contrary development could be seen during the last decades: a mainly worse adaptability to nonuniform and particularly unforeseeable changing conditions found in the principally discontinuously and unhomogeneously formed crust of the Earth as they very often can be seen with highly developed technologies. "With highly sophisticated mechanized deep mining, extremely simple geological conditions are essential", Dunham stated during the discussions at the First IIASA Conference on Energy Resources [4].

In fact large portions of coal deposits have become economically and sometimes also technically unmineable in many coal fields with modern techniques of coal mining while with the earlier prevailing hand mining methods which were the more flexible ones, winning had been possible. This particularly refers to thin and disturbed beds.

The Ruhr coal mining industry with its huge coal bearing strata and numerous seams mined by proceeding to a greater depth may be taken as a well authenticated example of the restriction on the amount of usable coal in the Earth with the technical development of past decades [6,7,8,9,11,12,15].

Figure 1 shows the development of the degree of exploitation since the beginning of this century.* The total percentage refers to all the coal principally regarded to be mineable within the mined sedimentary strata of the coal fields according to a limitation made in the 1930s (> 0.60 m thickness, < 30% by vol. partings). The reduction in exploitation between 1961 and 1970, has, however, technical and economic reasons.

Figure 2 also refers to the Ruhr District. It compares the distribution of seam thickness of existing coal, which has remained practically unchanged in the coal bearing strata mined during the past few decades, and the distribution of coal production from seams of different thicknesses in the years 1929 and 1974. In 1929, when mining was nearly completely done by

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*Recovery of and exploitation are differentiated here by leaving the recovery more to the primarily technically or legally unavoidable losses whilst exploitation also considers losses due to purely economic factors.

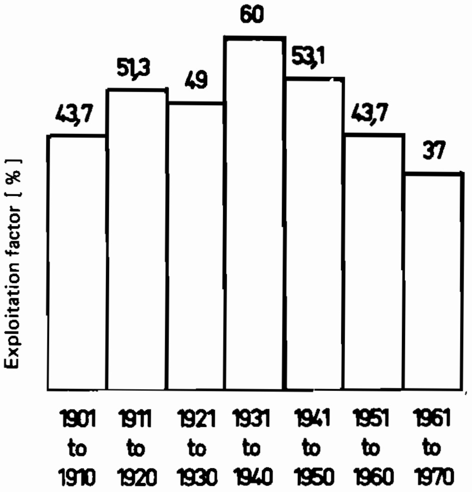

Figure 1. Degree of exploitation (%) in the Ruhr coal mining industry 1901 to 1970 due to technical and economical reasons.

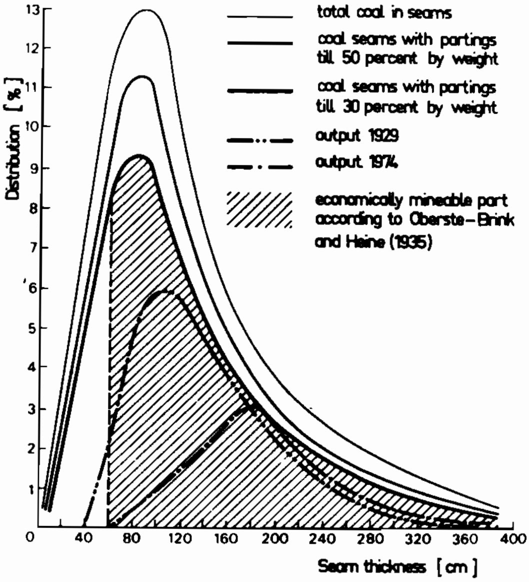

Figure 2. Distribution of the reserves in situ and of the output of the Ruhr coal mining industry 1929 and 1974 according to seam thickness including partings.

pneumatic picks or blasting and with wooden supports, a remarkably higher proportion of the coal in the strata could be exploited than in 1974. Those portions of coal in the Earth that meanwhile have become unmineable with mechanized methods are particularly the thin, faulted, and folded seams. The increase in the mining of thicker and impure seams can be observed, but this cannot compensate for the losses.

Similar examples are also known in other branches of the mining industry and in other parts of the production from nature. In ore mining nonuniform and disturbed thin vein-type deposits with bad roof conditions have also become economically unmineable with recent technical development, even if the percentage of metal in these veins is comparatively high [10]. In rocky agricultural areas, e.g. in the Alps, modern machinery cannot be used for effective farming work. However, compared with the mining industry conditions are more favorable as the irregularities are already known.

"Bonität" can set limits for coal mining that may not only be of an economic but also of a technical nature for the foreseeable developments of technology also. With regard to technical restriction the most important specific factor of the "Bonität" is without doubt the depth of a mine. Considering the prevailing geothermal and geomechanical conditions in the coal-bearing sedimentary basins it will probably technically not be possible to exceed a depth of about 1500 m in underground coal mining in the foreseeable future. Labor-hygienic and ergonomic conditions, and more importantly mine safety conditions are important factors, e.g. with regard to the danger of rock bursts. These dangers would continue to exist even in a fully automated colliery.

An essential removal of the depth limitation would be possible by mining through wells, i.e. mainly by underground gasification. So far, it has not been found out whether the geomechanical problems prevailing at such depths can be controlled, apart from other unsolved problems of underground gasification.

In addition to depth, further factors of the "Bonität", mainly in combination with other ones, may also result in technical restrictions, e.g. low seam thickness, especially if the seams are tectonically disturbed.

RESOURCES AS A FUNCTION OF MINEABILITY

It is commonly known that occurrences of mineral raw materials are not at all homogeneous as to their quality and "Bonität". This is particularly true with larger occurrences. It is also true that known occurrences in general are mined from the better to the poorer geological conditions and this means in order of decreasing efficiency.

In the McKelvey diagram and also in the similar diagram of the author's in another paper in this volume this grading is shown in the correspondingly divided axis of economic feasibility.

By using the terms quality and "Bonität", it is possible to make a further step and divide the axis of economic feasibility into two dimensions, taking the identified resources as a whole. By means of a graphic model the existing connections are illustrated more clearly, as is shown in Figure 3. A scheme of this kind gives only an incomplete picture of reality and should be considered only qualitative, not quantitative. The correlations that exist in principle for all mineral raw materials will be discussed below with coal.

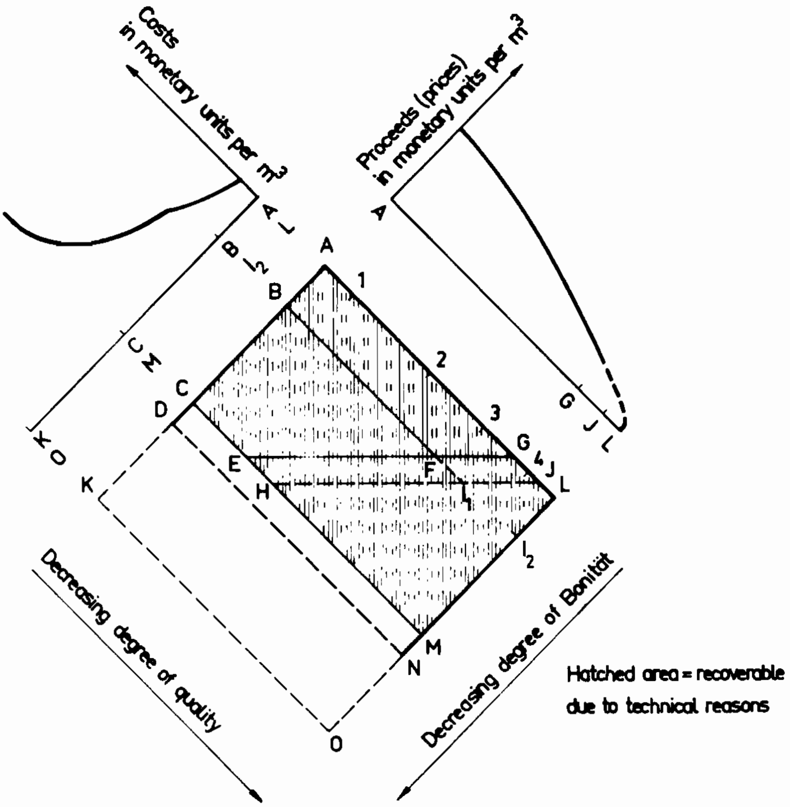

Figure 3. Scheme of resources as function of mineability.

In Figure 3 the area AKOL represents the total identified coal occurrences in place. From A to K the "Bonität" of the occurrences decreases, while A to L shows a reduction in the quality of coal. Within the total area some subareas may be distinguished according to their mineability in technical and economic respects now and in a foreseeable future. The limitations of these areas and thus of the subareas in question will depend, as already mentioned, not only on naturally based factors like "Bonität" and quality, but also on a large number of external technical-economic factors such as technical progress, wages, etc. Therefore these limits are not fixed but flexible.

In Figure 3 the portion of the occurrences in place that are technically exploitable lies above the boundary CM. As a result of the elimination of thin and disturbed beds with the technical and social development of the last decades from the number of technically mineable occurrences in place, this line has moved from DN back to the present line.

While the technical mineability now and in the future depends only on the "Bonität" of the occurrence, the economic mineability now or in the future depends on the relation between costs and proceeds and therefore is a function also of the quality of coal. In Figure 3 economic resources in place (reserves in place) are symbolized by the area ACEG. The line CE limits economic resources in place (reserves in place) by technical possibilities, while line EG depends on economic factors only.

Line BF divides economic resources in place (reserves in place) into those of opencast mining (area ABFG) and those of underground mining (area BCEF). The boundary is based on economic factors only. It lies where, because of a given relationship between depth and thickness of the coal seam, underground mining would be less expensive than opencast mining.

Subeconomic resources in place, which may become economically mineable in a foreseeable future, are illustrated by area EHJG. This area can continue into area CDH if a displacement of the technical restrictions may be expected. The determination of the boundary between subeconomic resources and identified not economic occurrences is only a question of what can be assumed to be economically mineable in the foreseeable future. According to the author's suggestions in another paper in this volume, subeconomic resources must have a probability of at least 10% of becoming economically mineable in a period of about 60 years.

From the technically mineable occurrences and thus from the economically and subeconomically mineable resources in place, only a part is really recoverable. In the process of mining a further percentage remains in the Earth's crust because of technically unavoidable losses; for the same kind of reasons another portion gets lost during beneficiation. This effect is marked in the figure by hatched lines: only the hatched areas illustrate the truly recoverable and therefore usable quantities. In opencast mining the recovery factor is higher than in underground mining.

The technical recovery factor, too, is a function of technical progress and thus dependent on time. At present it is mostly calculated to about 50% for the average coal resources on the Earth [11].

This recovery factor is restricted to technically caused losses only within those parts of the occurrences that are subject to the mining (stoping) process. Of course, there are relations between these losses which are a function of the layout and stoping method of a mine and the amounts of economically mineable occurrences in place. In general the costs per ton of recovered mineral decrease in mining with increasing losses, mainly for strata control reasons. In the actual process of planning and running a coal mine, these interrelations arise at a later stage so that for clarification of the primary interrelations the simplification of the graphic model seems useful and justified.

Figure 3 also illustrates the fundamental curves for proceeds depending on the quality of the coal and for costs depending on the "Bonität" of the occurrences. Of course the descending line of the proceeds curve and the rising direction of the cost curve as a function of the quantity of the occurrences can also show a repeatedly changing gradient. All curves refer to free pithead coal and are based on a certain state of technology.

The steeply ascending part of the cost curve in Figure 3 is of special importance. It shows the approach of technical limitations. These limitations are in no way set only by an exhaustion of the coal itself, but by other factors, particularly depth, thickness, and degree of tectonic disturbance. The steeply ascending cost line not only corresponds to the common rules of decreasing profit with worsening production conditions, but also agrees with the experiences of the mining industry. (Strictly the cost functions according to the quantity of reserves in a mining industry are U shaped. The descending line at the beginning of the curve is only important when considering individual coal mines, but has no effect on the discussion in this paper.)

Figures 4 and 5 show cost as a function of tectonic disturbance and of the thickness of seams. The examples are taken from the Ruhr-District and are based on thorough studies. In this connection, the estimates of coal resources in the USA as a function of coal prices and thus of costs are informative. They are taken from American data for 1956 and 1970 and presented in Figure 6 [18,21,23].

Since the economic mineability at present or in a foreseeable future depends on both groups of geological conditions, quality and "Bonität", the fundamental relation between costs and proceeds is shown in Figure 7. The numbers 1 to 4 refer to the different coal qualities of Figure 3.

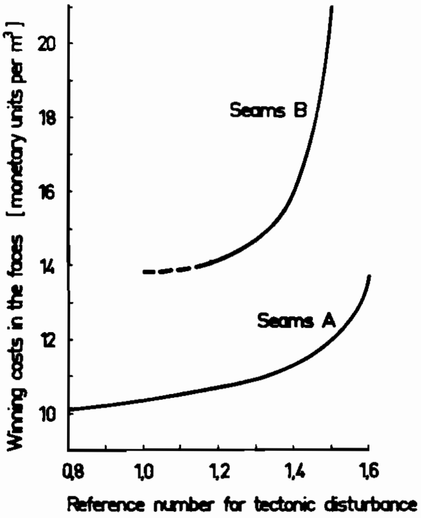

Figure 4. Costs per unit in longwall faces of the Ruhr coal mining industry as a function of the grade of tectonic disturbance according to Ehrhardt.

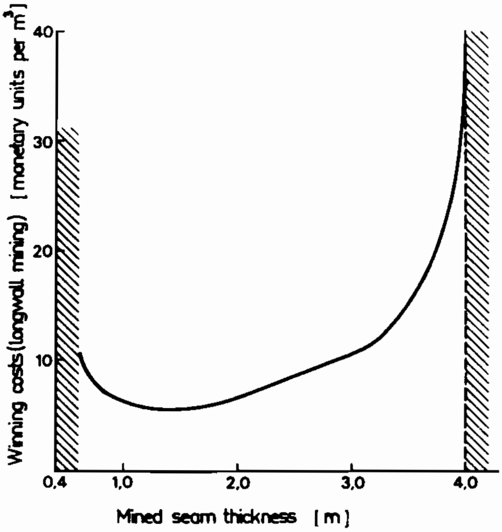

Figure 5. Costs per unit in longwall faces of the Ruhr coal mining industry as a function of mined seam thickness in single-slice mining according to Steinbauer.

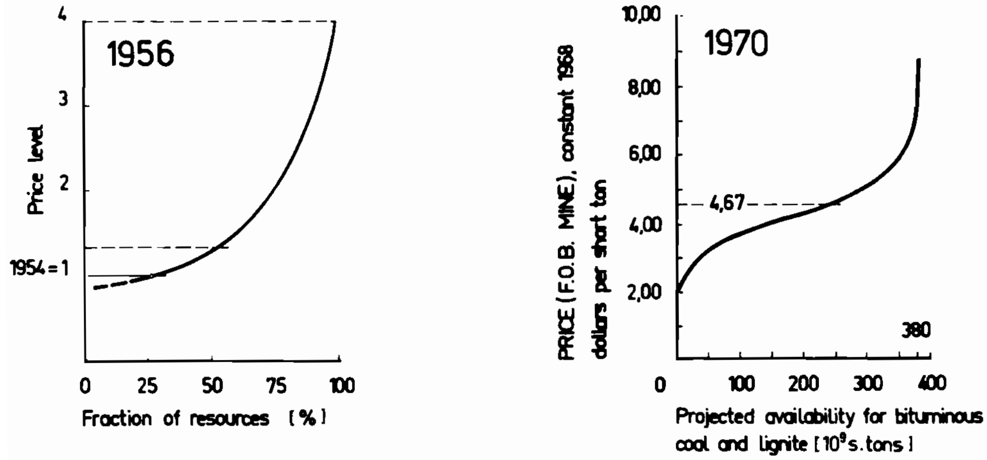

Figure 6. American estimates of the coal resources of the USA as a function of coal prices in 1956 and 1970.

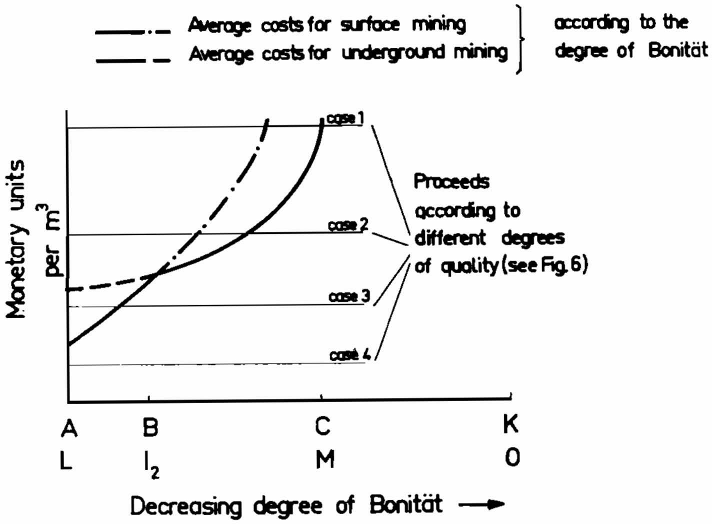

Figure 7. Economic mineability as a function of geological conditions (quality and Bonität) according to Figure 3.

In the case of no. 1 quality, the proceeds reach such a point that the limit of economic mineability coincides with technical mineability. In cases nos. 2 and 3 only a part of the technically mineable resources are also economically mineable, case no. 3 referring only to opencast mining. Case no. 4 shows that the possible proceeds are much too low to permit economic mineability.

The proceeds per unit free pithead are determined by the market prices for coal at the place of coal consumption and by the transportation costs from the pit to the consumer. Figure 7 shows that an increase in proceeds caused by changes of the two factors mentioned above can increase economically mineable resources only to the limit of technical mineability.

A remarkable change of the occurrences considered as resources is furthermore possible by a modification of the cost curves due to economic and technological developments. In Figure 8, c_1 shows the cost function of a more old-fashioned, mainly manual mining technique, while c_2 shows the cost function of a modern, highly mechanized technique. With the dotted lines c_{1b} and c_{2b} the level of wages is higher than with the curves c_{1a} and c_{2a}. Both groups of curves represent the development of the past few decades in some coal basins discussed earlier.

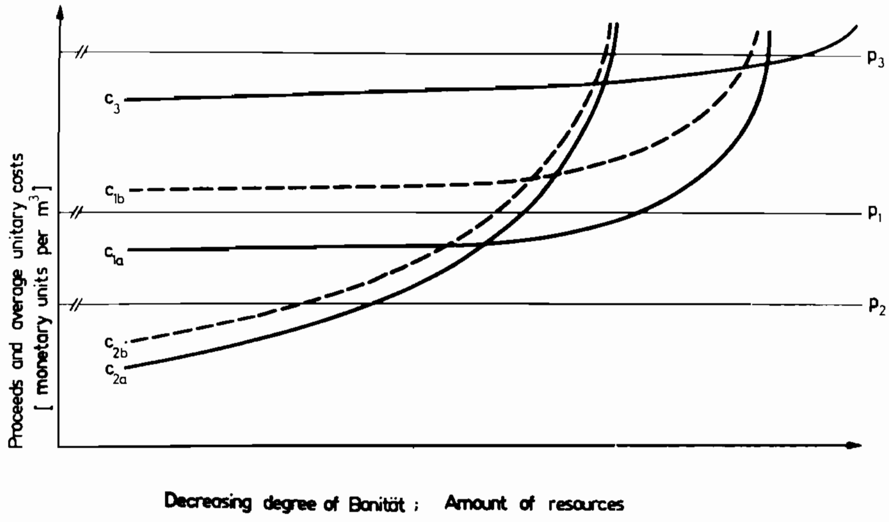

Figure 8. Cost functions of different mining technologies.

Curve c_3 should be taken as an example of a technology that could perhaps result in an extension of resources, e.g. underground gasification. The values c_{SM} and c_{UM} in Figure 9 represent the fundamental cost functions for opencast and underground mining, based on present techniques. The other curves show possible developments of cost functions of a new, at present not sufficiently known technology, such as underground gasification [11].

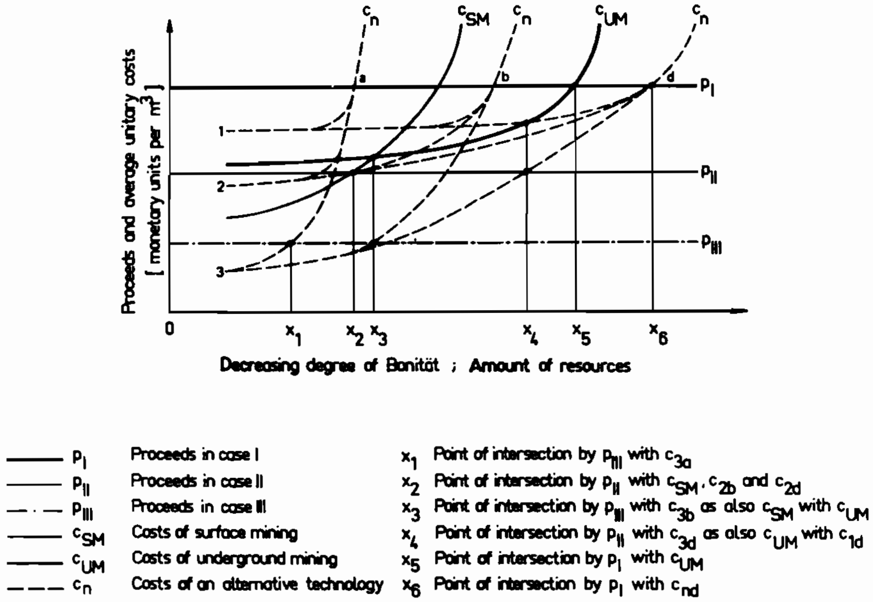

Figure 9. Cost functions of surface mining and underground mining and possibilities for cost functions of other technologies in relation to today's technologies.

EVALUATION OF IDENTIFIED OCCURRENCES

The first step towards an economic evaluation of identified occurrences in place lies in the differentiation between the presently economically mineable quantities (reserves) against the subeconomic resources, in place and recoverable. The specific geographic conditions that have to be taken into account are known. And since the geological conditions of identified occurrences have either been sufficiently proved or at least assumed with sufficient certainty, it is also possible to make feasibility estimates or even studies for costs and proceeds that can be expected for mining these occurrences with a suitable high degree of evidence. In fact this is the procedure carried out in many cases.

In countries with centrally planned economies, evaluation of economic resources, i.e. of balance resources, are generally made by means of centrally established conditions to which occurrences have to correspond; for coal these are depth, thickness, energy values, etc. In countries with market economy too, empirical values are very often used. All these conditions must be based on continuous, newly established analyses of economic mineability under currently prevailing conditions, if proper results are to be obtained.

Much more difficult, of course, than the delimitation of identified economic resources is that of identified subeconomic resources, in place and recoverable. As shown in Figure 3, this means a decision about whether and to what extent the limits of the technical and economic mineability will possibly be displaced in the foreseeable future and thus also a forecast of future cost and proceeds aspects. Thereby the economic interrelations between the two values (cost and prices) are to be considered. An estimate about future recovery has also to be made.

In the case of coal the proceeds free pithead that can possibly be obtained in the future from occurrences will only be estimated together with general considerations on energy economics, as well as by taking into account all means of transportation and their future costs. From such considerations an order of magnitude of subeconomic resources can be gained, if the limits of technical mineability of Figure 7 and those of the presently prevailing economic mineability are taken into account.

For the future development of cost functions as given in Figures 7 and 8, two main possibilities, the further development and "finalization" of the existing technology, and the change to completely new technologies have to be considered. The first case is the easier one. Estimates can always be made for alterations of cost functions during an increasing completion of the various techniques. It must be remembered, however, that such completion of the technique can also restrict the limits of technically or economically mineable resources, as experiences during the past few decades have taught (see Figure 8).

More difficult is whether new technologies will be developed in the future and what the cost functions for the occurrences in question will then be. This consideration should therefore only include new technologies, if the technological change is, at least partly, genuinely foreseeable. "Decisionmaking can only take place within the realm of the foreseeable" [19].

For coal the only probable alternative to the common technologies of underground and opencast mining in the foreseeable future will be underground gasification [5,14]. The author has discussed possible consequences of this process on the world coal resources in the above sense in other papers, based on the present state of knowledge and on foreseeable developments [11,12]. It is at least an open question whether underground gasification will increase the resources in the foreseeable future beyond what are now called economic or subeconomic even by the common techniques. It is much more likely that it will be possible under favorable geological conditions to extract those resources in future more economically by underground gasification which, according to the present and foreseeable progress of the common techniques, are to be treated as resources too. However, unforeseeable changes of technical development must not be excluded. But they may fail to take place.

The division of the identified occurrences into economic and subeconomic resources can leave quantities for which--according to suggestions in another paper in this volume--a chance of less than 10% is assumed for becoming economically mineable within the next 60 years. These occurrences are therefore to be assessed as not being economically mineable in the foreseeable future and included in the resource base.

Of course the economic evaluation of the identified occurrences in whole regions cannot be done in the same detailed way as is necessary for feasibility studies of individual coal mines. For such an assessment neither the required detailed data nor the necessary time are available. Therefore the present considerations can only be approximative. This seems, however, better than the open ended and misunderstandable alternative of resigning in this matter.

For the technical and economic assessment of identified occurrences prognostic methods of various kinds can be used, and these are developing scientifically very fast. Moreover the more than 10 years of experience with the economic assessment of uranium ore resources show that specific considerations are possible for sufficiently well known occurrences.

It is advisable to develop a study of deposits with regard to their economically relevant geological conditions more intensely than at present and to establish patterns of the influence of geological conditions of a deposit on the possibilities of its technical and economic exploitation. This refers particularly to the development of cost functions in relation to "Bonität" which then may be applied for the evaluation of occurrences. This should be the main target for research.

For the evaluation of identified occurrences with regard to their technical and economical mineability, one has to consult people who have a first hand knowledge of the problem in question and who are also well informed about the trends and developments of their special branch. The evaluation of identified mineral occurrences, therefore, is a typical example of the fact that in view of the specialization of sciences, certain problems can only be solved in cooperation with specialists of various disciplines. In this respect the author completely agrees with the statement of Brobst and Pratt that "Economic evaluations of a specific mineral deposit have become a complex task for a team of specialists, including not only geologists, but also mining engineers, ore dressers, metallurgists and economists" [2]. Every step must therefore be taken in that direction.

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A COAL DATA SYSTEM: ITS PURPOSE AND VALUE

C. Masters

INTRODUCTION

This paper concerns the development of a coal resource data system and a discussion of its geological and geochemical capabilities. A few statistics will emphasize the enormity of attempting to evaluate and assess the quality and quantity of the vast coal resources in the USA.

- The estimated remaining coal resources in the USA on January 1, 1974, were nearly 4×10^{12} short tons.
- These resources underlie roughly 460,000 mi^2 (1,250,000 km^2) or about 13% of the land area of the USA (Figure 1).
- The coal-bearing rocks occur in 39 of the 50 states and span 4000 miles (6400 km) from northwest Alaska to Alabama in southeast USA.
- The coal deposits range in rank from lignite to anthracite.
- The coal beds considered a resource are of varying thickness ranging from 14 inches (0.35 m) to more than 100 ft (30 m). Overburden thickness ranges from 0 to over 6000 ft (1800 m). The ash, sulfur, energy, and major, minor, and trace element contents are quite variable.

The vast quantity, variability, and extent of US coal deposits present immense problems in collection of data and their storage and analysis by conventional methods. In addition to quantity, information on quality must be analyzed and made readily available to the public to promote optimum development of the coal most suitable for each end use.

The relationships between coal quality and quantity factors are depicted in Figure 2. This diagram illustrates that geological mapping and sampling programs are the foundation from which are derived the geological, geochemical, geophysical, and geographical factors necessary for coal resource assessment. The quantitative factors such as thickness, distribution, and amount of coal are derived from stratigraphical, sedimentological, and structural research, which form the basis of geological mapping.

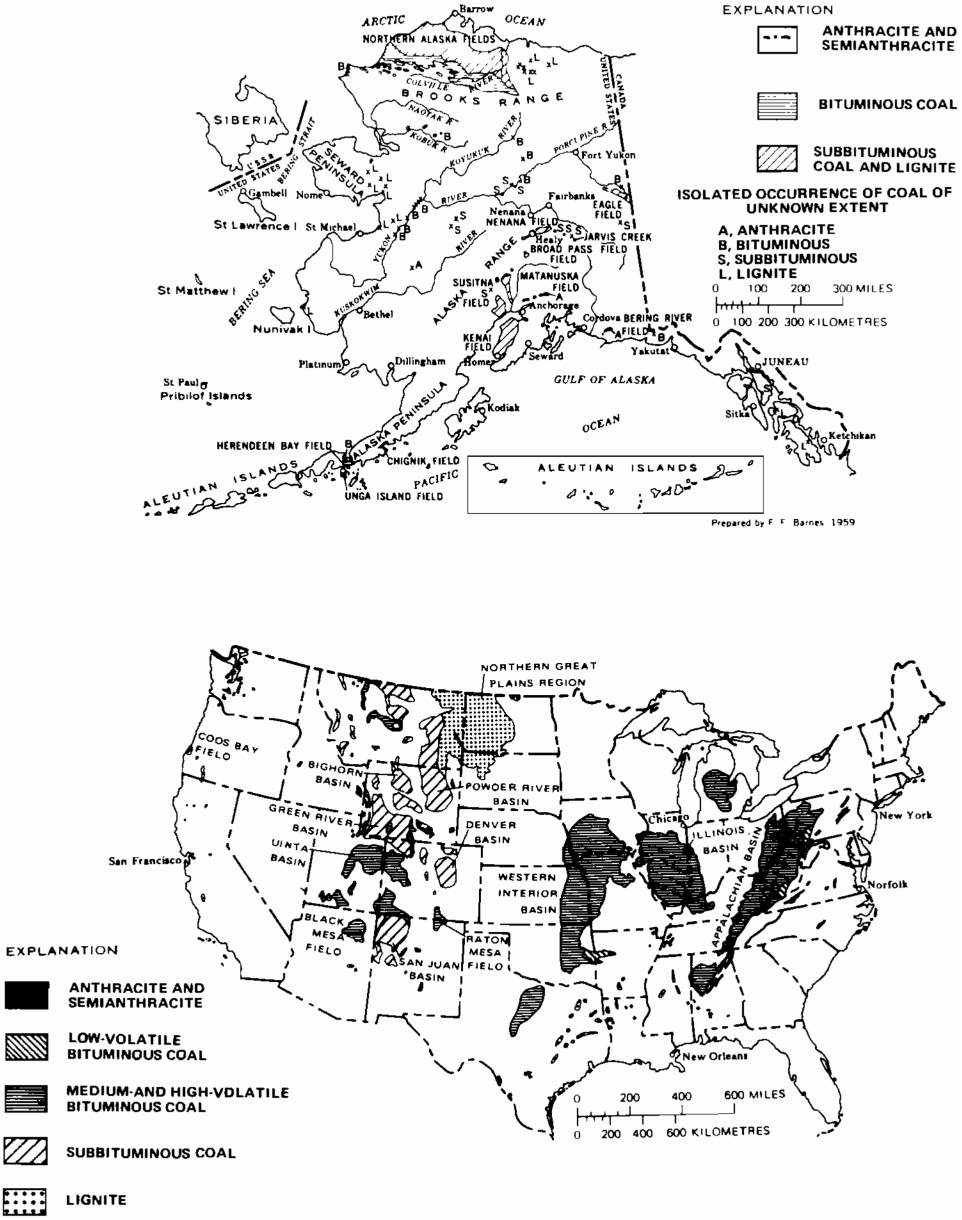

Figure 1. US coal fields in the conterminous states and Alaska.

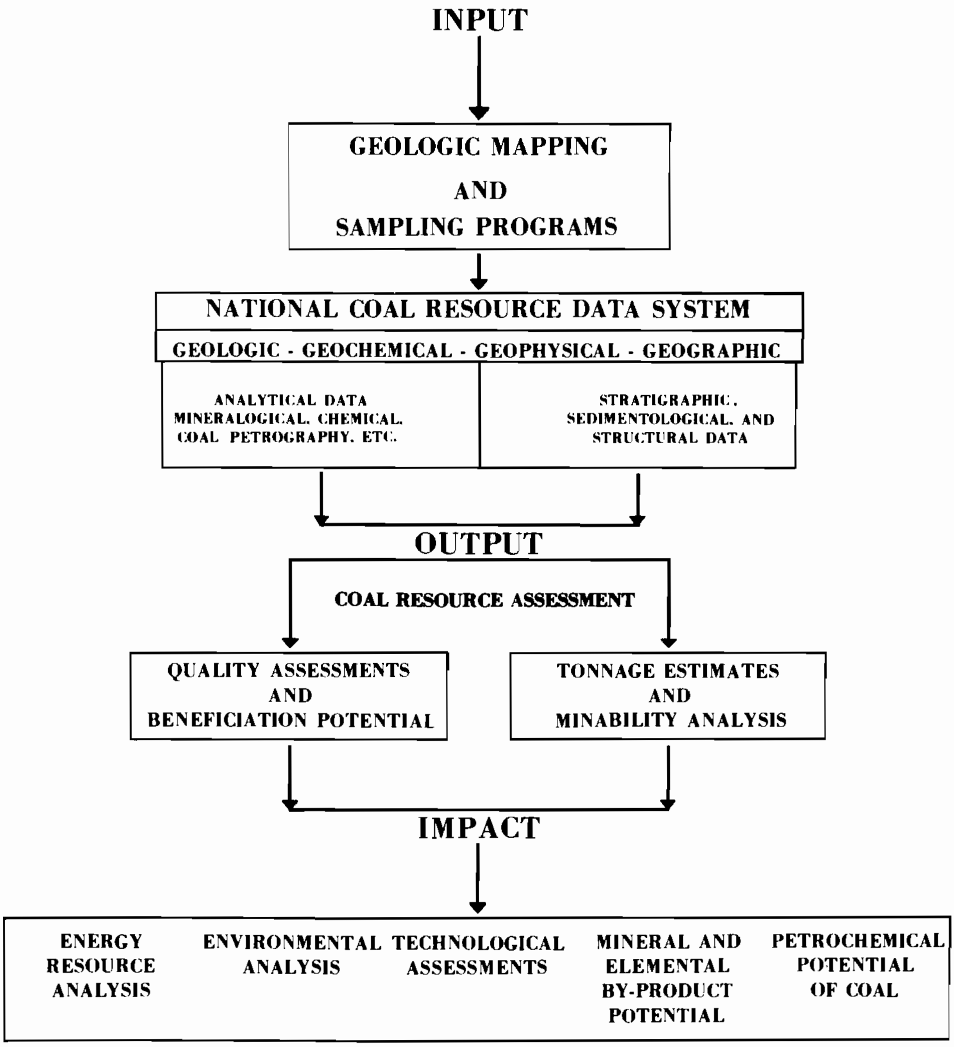

Figure 2. Flow diagram depicting the interrelationship of geological mapping, sampling, National Coal Resources Data System, and coal resource assessment and subsequent impacts on coal quality, quantity, and utilization.

Qualitative studies involve the derivation of such analytical data as mineral-matter mineralogy, coal chemistry, and coal petrography. These studies are a natural extension of the geological mapping and sampling programs and logically accompany such investigations. In order to adequately combine, compare, manipulate, and interrelate the geological, geochemical, geophysical, and geographical qualitative, and quantitative data, an efficient computer data system must be available. The output of this data system allows for rapid coal resource assessment and provides a basis for decisions on quality assessments. This resource assessment affects every present and future aspect of coal utilization such as environmental analysis, technology assessment, mineral and by-product recovery, petrochemical potential of the coal resources, and the classification of energy resources in terms of best usage.

In order to allow rapid retrieval as well as ease of update and analysis of data on coal quantity and quality, a computer-based coal-resource data system has been developed by the Branch of Coal Resources within the US Geological Survey. This interactive conversational query system allows access to the data by an interested party, either on request through the Geological Survey or by independent remote access through telephone connection with any standard computer terminal.

Development of the system has been in two phases to accomodate the availability and complexity of the data.

NATIONAL COAL RESOURCES DATA SYSTEM

Phase I consists of areal data from publicly available sources (such as published reports or open-file material) on coal resources and standard chemical analyses (i.e. proximate, ultimate, and energy content). Phase II contains point source data from borehole, field observation, or sample analysis including geological, geochemical, geophysical, petrological, engineering, and topographical information.

As illustrated in Figure 3 the areal resource data may be reported by state and by county (the patterned area). When sufficient additional data are accumulated in the point data files for an area, new coal resource estimates using the parameters of the US Geological Survey (USGS) and US Bureau of Mines (USBM) coal classification system can be generated by the computer to update and verify the coal resource quantities and coal quality data stored in the areal file. Thus, the US coal resource inventory can be constantly updated and trends in coal quality identified and analyzed.

All of the data stored in both the areal and point data files may be retrieved and aggregated for statistical, tabular, or graphic display.

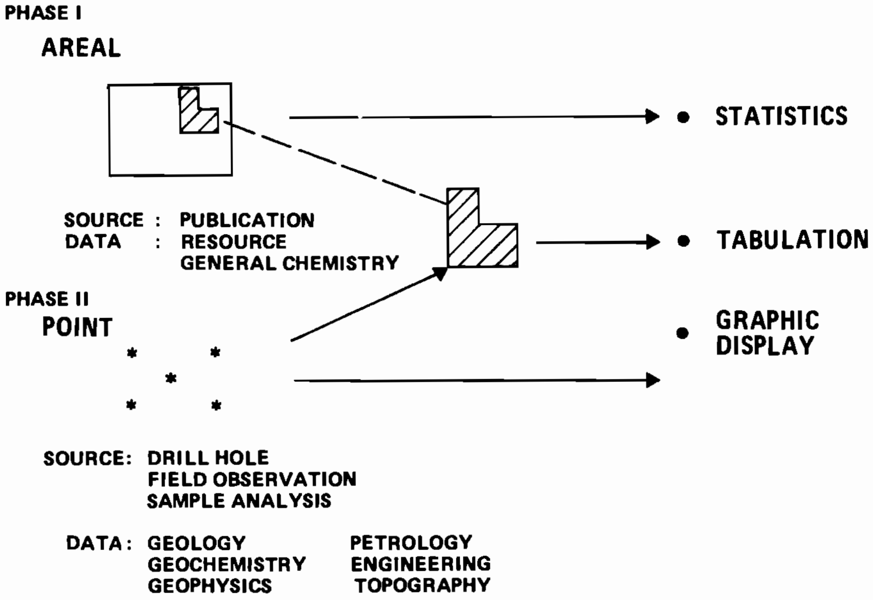

Figure 3. Interrelation of Phase I areal data and Phase II point data elements.

NATIONAL COAL RESOURCES DATA SYSTEM - PHASE I

Phase I (containing the areal data) is currently operational with 90% of the data base entered and validated (Figure 4). It involves the computerization of existing US coal resource quantities and chemical data compiled from published sources. The coal resource quantity estimates are based on state summary reports prepared from approximately 1500 USGS detailed reports and maps and perhaps an equal number from state geological surveys and USBM. The chemical analyses are primarily from USBM sampling and analysis programs. Data on production and loss in mining will be entered into the system as they become available.

Phase I output may be in tabular or graphic format but will always be reported in *areal* units. At present the smallest reported area is a township (generally 36 mi^2 or 94 km^2), which is the standard reporting area in most of the western USA. In the future, estimates may be by section (1 mi^2 or 2.6 km^2) or even smaller units. However, currently the smallest common area for national comparison is the county.

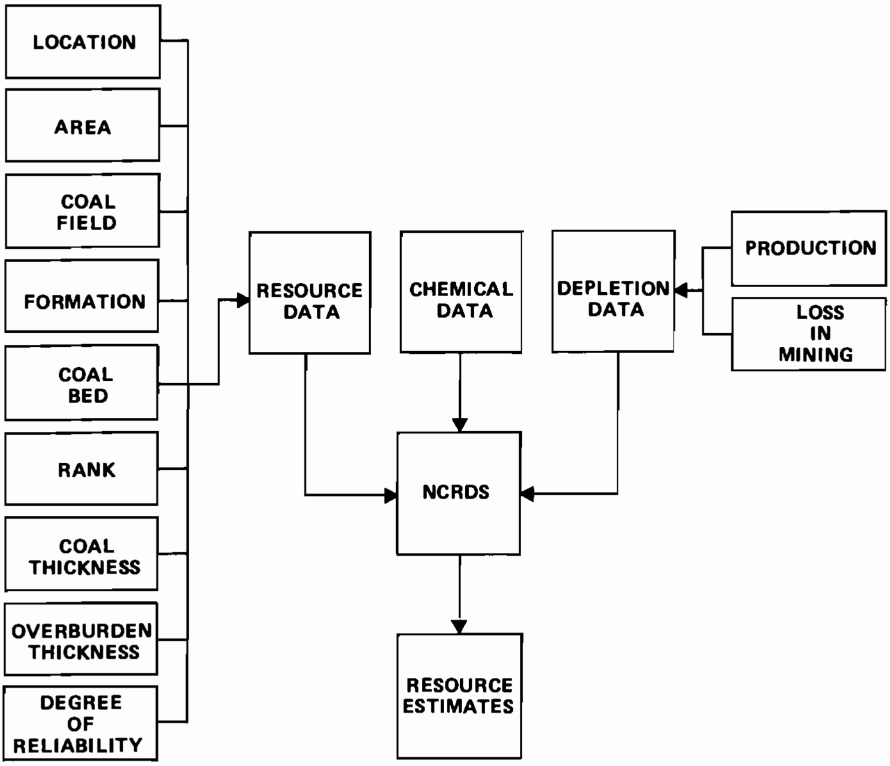

Figure 4. Flow diagram displaying various data categories in Phase I of the National Coal Resources Data System (NCRDS).

Phase I Resource Data Elements

The Phase I resource data base includes location information such as state, county, township; AAPG province code for comparability with other energy resources; coal province, region, field, and district; and 7.5" quadrangle (Table 1). Coal bed information includes bed name, formation, geological age, rank, thickness of coal bed and overburden, reliability of data, and quantity in millions of short tons to two decimal places.

The base year category indicates whether the resource estimate is of the original coal in the ground or of the coal remaining as of that date (for example; 72 indicates remaining resources on January 1, 1972; 00 indicates that the estimate is of original coal resources). Data source and year of publication are also included.

Table 1. Resource data elements in Phase I of NCRDS.

State	Formation
County	Coal Bed
Township	Geological Age
Section	Base Year
AAPG Province Code	Source
Coal Province	Thickness Code
Coal Region	Overburden Code
Coal Field	Reliability Code
Quadrangle	Rank
District	Tonnage

Phase I Analytical Data Elements

The same basic location and coal bed descriptors that are in the resource file are included in the analytical data file (left-hand column in Table 2). The items shown in the column on the right are the standard chemical analyses performed by USBM including proximate and ultimate analyses.

Table 2. Analytical data elements in Phase I of NCRDS.

State	Analysis ID
County	Lab Code
T, R, and SEC	Sample Type
AAPG Code	Analysis Type
Province	Number of Samples
Region	Trace Element Data (Y or N)
Field	Grindability
Quadrangle	Other Tests (Y or N)
District	Btu
Formation	Ash Temperatures
Bed	Free Swelling Index
Geological Age	Proximate Analysis
Source	Ultimate Analysis
Rank	Forms of Sulfur

The chemical data can be aggregated into the same areal units as the resource estimates so that for any given area, a quantity can be retrieved along with a general chemical analysis for coal in that area.

The primary objective of Phase I is to collect, store, retrieve, calculate, and tabulate coal resource and basic chemical data by area on a local, regional, and national scale. Simple arithmetic functions can be applied to the data such as addition, subtraction, totalling, averaging, and standard deviation. This inventory can be added to and modified continuously as new coal resource, production, and chemical data become available. In brief, Phase I enables questions to be answered more rapidly and based on data that will be constantly updated with increasingly greater detail.

NATIONAL COAL RESOURCE DATA SYSTEM - PHASE II

In contrast to the areal aspect of Phase I, Phase II of the NCRDS is based on point data. The major portion of Phase II software development is approaching completion. Data entry has begun. Implementation of Phase II consists of entering several hundred different criteria into the system for each field observation, borehole record, or sample analysis. Input data, as shown in Figure 5, are grouped into seven broad categories.

- Physical data include the thickness, location, identification, and relative density of the coal bed, its altitude, and the extent and type of mining, if any, at the data point.

- Geological data include character and thickness of the overburden, detailed description of the coal bed, location of the outcrop line, slope angle of the land surface, cleat orientation measurements, and hydrological observations.

- Topographic data will be entered into the system in the form of digitized land terrain, including associated items such as drainage, cultural features, and political boundaries.

- Borehole records include location, source, elevation, and unit thickness, lithology, color, grain size and shape, mineralogy, bedding characteristics, fossil content, jointing, and contact with overlying and underlying rocks.

- All coal geochemical data derived from major US coal beds will be stored in the data system to allow rapid synthesis and prediction of the major, minor, and trace element distribution characteristics and coal quality. Coal quality parameters include energy, sulfur and ash content, mineral matter mineralogy, coal macerals, and the major, minor, and trace element concentration.

- Geophysical and petrographical characteristics of coal beds, which are being studied in current USGS projects, will be entered into the system in the near future.

Output data retrieval in Phase II will fall under five broad categories: resource estimates, maps and cross sections, tables and graphs, analysis and model development, and regional studies. In the first category, the data system can be used

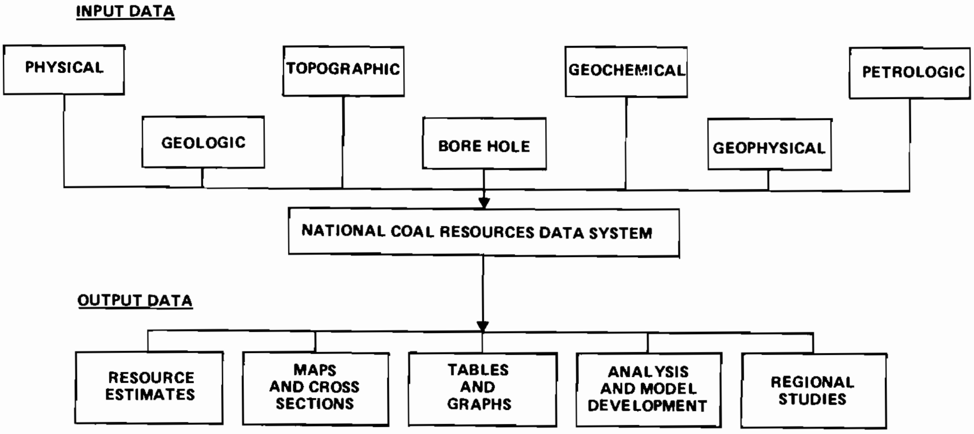

Figure 5. Flow diagram showing data categories for Phase II of NCRDS.

primarily to delineate coal quantity and quality in any area, coal bed, or sequence of coal beds, for any combination of factors, such as sulfur, ash, trace element, and energy content, distribution and reliability of data, and coal bed and overburden thickness. The second category involves the display of data for visual interpretation such as structure contours, isopach maps of coal and overburden, isoline maps of chemical elements, and ratio maps between various coal-bed properties. The third category is designed to retrieve and display computerized data as tables or graphs. The fourth category involves development of models to project the location of coal resources having specific quantity or quality parameters. In the fifth category, all data stored in Phase II may be aggregated for regional and national or interdisciplinary studies with other systems.

A fundamental goal of Phase II is to provide the geologist with a working tool to assess a larger amount of more detailed information in determining the quantity and quality of the total coal resource for an area or particular utilization. Examples of use of this tool in pilot areas are demonstrated in the following discussion.

Figure 6 depicts a computer-drawn structure-contour map of the base of the Red Ash coal bed in the Jewell Ridge quadrangle in southwestern Virginia. This map was produced from digitized data points from the geologist's work map. The map shows several anomalies, indicating possible erroneous points, but more importantly, it compares very favorably to that drawn by the geologist and was produced with a considerable saving of time. Similar maps could be produced to show overburden, coal-bed, and interval thicknesses.

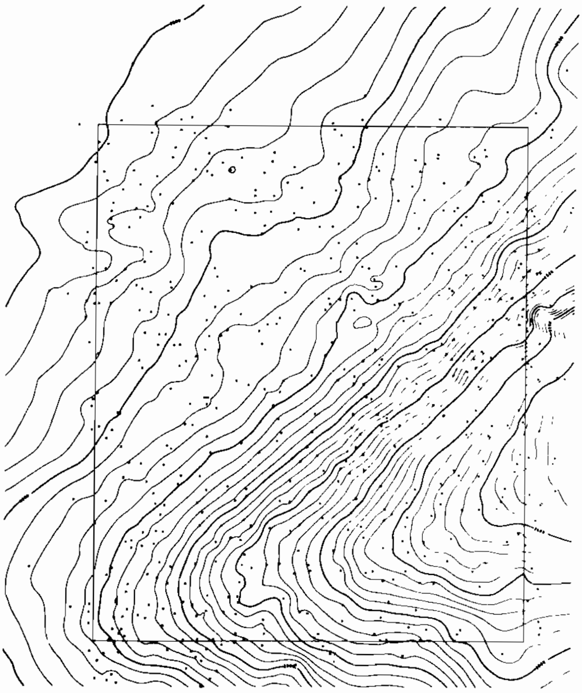

Figure 6. Structure contours at base of Red Ash coal bed, Jewell Ridge 7.5″ quadrangle, Virginia.

COAL QUALITY DATA

Commonly a need exists to appraise a larger area for the chemical and physical characteristics of the coal beds. This need may be related to assessments for environmental concerns, process technology efficiency, by-product recovery options, and the development of geological predictability of element/compound distribution.

Figure 7 demonstrates such a capability of the computer and the ability of the computer to compare multiple data items for possible correlations or anomalies. In this example the computer plotted isolines of the pyritic sulfur and arsenic distributions in coal in a 250 km^2 central Appalachian project area. The similarity of the patterns illustrates the expected direct correlation. Although the data shown represent several coal beds, the principle will be applied to individual coal beds for areal analysis of coal petrography, mineral-matter mineralogy, and other chemical and physical data such as ash fusibility and free swelling indices.

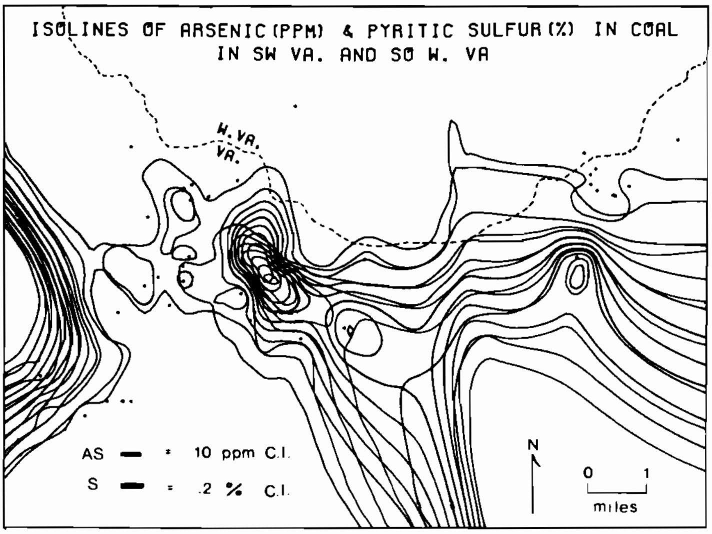

Figure 7. Computer plotted isolines of pyritic sulfur and arsenic distribution in coal beds in southern West Virginia and southwestern Virginia.

Another example of the planned data system capability is shown in Figure 8. The schematic map illustrates how the computer may delineate an area meeting multiple conditions. In this hypothetical case the computer is directed to outline an area in which the coal-bed thickness is greater than 42 inches (1.06 m), sulfur concentration is less than 1%, ash content less than 2%, and mercury concentration is less than 0.1 part per million. The computer will isopach the coal, isoline the chemical components, and overlay the derived data to delineate the area (pattern) which meets all the conditions. Obviously further conditions could be added such as structure contours and level terrain data to derive the amount of overburden and subsequently coal resource estimates. These computer techniques are estimated to provide an approximately tenfold saving in costs and a 30-fold saving in manpower over the current manual coal resource calculation technique.

Other ways of analyzing and interpreting coal geochemical data for by-product recovery potential is by studying computer derived and statistically treated element concentrations. An approach is the use of element enrichment in coal and coal-related rocks as compared to the Earth's crust.

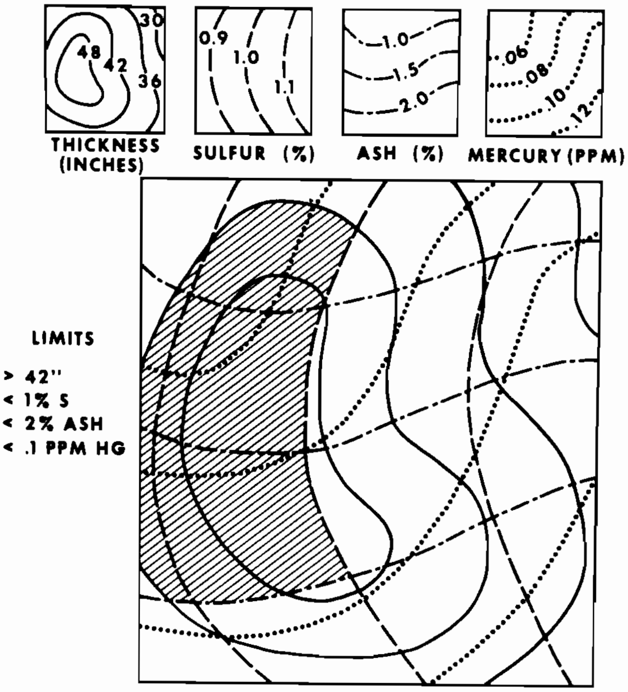

Figure 8. Diagrammatic map constructed by computer.

A convenient way of comparing element enrichment for a particular material is by calculating factors derived from an element's average composition in the Earth's crust. The unit concentration for any element in the Earth's crust has been called a Clarke. This Clarke value is divided into an element's concentration in, for example, coal and coal-related rocks to obtain the enrichment factor. Table 3 displays Clarke values for 30 accessory elements found in coal and coal-related rocks from the major and selected coal provinces of the USA.

Only As, B, Ba, Sb, and Se are consistently enriched in all coals and coal-related rocks. Selenium enrichment ranges from 12 to 128; the highest factors in Gulf Coast lignites and coal-partings from the Appalachian and Eastern Interior provinces. Antimony enrichment ranges from 1.5 to 9; the highest is in Alaskan coal samples. Boron enrichment factors range from 1 to 27.5; the highest is in coal-partings from the Eastern Interior. Arsenic enrichment ranges from 1.1 in Rocky Mountain coals, to 12.8 in coal-partings from the Eastern Interior province.

Table 3. Elements enriched in coals and coal-related rocks. Samples are from Anthracite (Anth.), Appalachian (Appal.), Interior, Eastern Interior (EI), and Gulf Coast (GC). Geometric mean concentration used in the calculation of enrichment values.

	Coal							Floor Rock		Partings		Roof Rock	
Element	Anth.	Appal.	Interior	GC	N. Great Plains	Rocky Mt.	Alaska	GC	EI	Appal.	EI	EI	GC
Ag	-	-	-	-	-	-	-	2.8	2.8	2.8	10.0	15.7	4.3
As	2.2	6.1	6.6	3.1	1.3	1.1	1.6	1.6	4.3	3.5	12.8	6.7	2.7
B	1	2	5	10	7	7	7	8	13	10	27.5	10.8	7
Ba	-	-	-	-	-	-	-	1.5	1.3	1.2	-	1.1	1.6
Be	-	-	-	-	-	-	-	1	2	1.5	4	1.5	1
Cd	-	1.5	-	1	-	-	1	1.6	1.8	1.2	5	6.0	1.4
Co	-	-	-	-	-	-	-	-	-	1.3	-	-	-
Cr	-	-	-	-	-	-	-	-	1	-	1	1.2	-
Cu	-	-	-	-	-	-	-	-	-	-	1.5	-	-
F	-	-	-	-	-	-	-	-	-	-	-	-	-
Ga	-	-	-	-	-	-	-	1.5	2	2.1	2.3	1.8	1.1
Ge	-	-	-	-	-	-	-	-	-	-	58.	-	-
Hg	1.4	1.7	1.2	1.6	1	-	2.5	-	-	-	2.3	1.1	-
La	-	-	-	-	-	-	-	1.3	2.2	1.4	2.2	2.1	1.7
Li	1.2	-	-	-	-	-	-	2.5	4.5	6	4	2.2	2
Mn	-	-	-	-	-	-	-	-	-	-	-	-	-
Mo	1	1.3	1.3	-	1	1	1	-	4.0	2.0	17.3	26.7	-
Ni	-	-	-	-	-	-	-	-	-	-	2	-	-
Pb	-	-	1.5	-	-	-	-	-	3	2	3.6	1.6	-
Sb	3	4	4	3.5	2	1.5	9	4.5	5.5	4.5	8.5	5	4
Se	54	70	56	116	12	24	18	40	26	102	128	42	26
Sn	-	-	-	-	-	-	-	-	-	-	-	-	-
Sr	-	-	-	-	-	-	-	-	-	-	-	-	-
Th	-	-	-	-	-	-	-	-	1.4	1.6	1.2	1.5	1.1
U	-	-	-	-	-	-	-	1.3	1.6	1.6	1.7	3.2	1.3
V	-	-	-	-	-	-	-	1.1	1.1	-	-	1.1	1.1
Y	-	-	-	-	-	-	-	-	1.1	-	1.3	1	1.1
Yb	-	-	-	-	-	-	-	1	1.7	1.7	1.7	1.7	1.7
Zn	-	-	-	-	-	-	-	1.1	1.2	-	1.5	1.7	1.9
Zr	-	-	-	-	-	-	-	1.1	1.5	-	1.3	1.2	1.8

Further insight into element enrichment can be obtained by analyzing the minimum and maximum values for the various elements as well as comparing the geometric and arithmetic means to the maximum elemental concentrations. By doing this, anomalous areas can be recognized and targeted for further study.

CONCLUSIONS

In conclusion the development of a coal resource data system allows:

- Savings in money and manpower;
- An integration of coal resource quantity and quality data;
- The storage, manipulation, retrieval and display of voluminous coal data in many contrasting formats;
- Comprehensive coal resource assessments to be made concerning utilization, environmental concerns, technology efficiency, by-product recovery, and the development of the ability to predict chemical, physical, and geological changes locally, regionally, and nationwide.

THE APPROACH OF IEA COAL RESEARCH TO WORLD COAL RESOURCES AND RESERVES

K. Gregory

INTRODUCTION

It has been recognized for many years that world assessments of coal resources and reserves, such as those published by the World Energy Conference (WEC) (1974) have a high level of built-in inaccuracy. This is because individual countries assess their resources/reserves in their own way, taking into account the economic and mining factors relevant to the country at the time of assessment. These economic and mining factors change from time to time, as does a country's level of knowledge of its resources/ reserves, although assessments of resources/reserves are not necessarily updated. Thus any world aggregations, based on a series of differing national assessments, can only be of limited value. However, with coal projected to play an important part in the world's long-term future energy supplies there is a clear need for better international assessments of coal resources and reserves.

This need for better assessments, together with the inherent problems, has been recognized by the International Energy Agency (IEA) in taking the initiative to set up the World Coal Resources and Reserves Data Bank Service (as part of IEA Coal Research). This paper describes the problems of assessing coal resources and reserves in more detail and then goes on to describe the approach of IEA Coal Research to these problems.

THE DISTINCTION BETWEEN RESOURCES AND RESERVES

The two terms, resources and reserves, are used to mean two quite different things in this paper. Consequently, two approximate definitions are given here (the author recognizes that there are many other definitions--which is one reason why the World Coal Resources and Reserves Data Bank Service was established):

- Resources may be defined as concentrations of coal, the extraction of which may be feasible now or in the future.

- Reserves may be defined as those quantities of identified coal resources that are considered economically recoverable at the time of assessment.

THE PROBLEMS WITH COAL RESOURCE AND RESERVE ASSESSMENTS

The problems of making international assessments of the world's resources and reserves of coal can perhaps best be illustrated by studying how the published figures have changed in one country (the UK). The figure for physically workable resources has increased steadily with increasing knowledge and now stands at 160 gigatonnes (Gt; 10^9 t) (Clarke, 1977). On the other hand, the figure for proved reserves has fluctuated from 101 Gt (Royal Commission on Coal Supplies, 1905), down to 3.9 Gt (WEC, 1974) and now stanas at 45 GT (Clarke, 1977; Evans, 1977). The figures are presented graphically in Figure 1. In order to understand the fluctuations in these figures one must first understand the definitions and the economic and mining environment on which each figure was based.

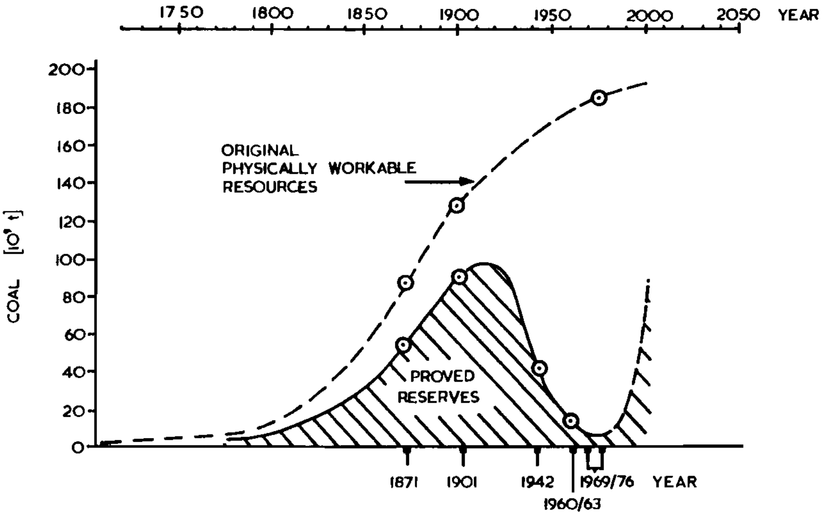

Figure 1. Proved reserved and estimated physically workable resources in known British coalfields.

Source: Clarke (1977) and Evans (1977)

In 1905 coal had no serious competitors and it was reasonable to assume that if a coal deposit was physically workable, then sooner or later it would become economically workable. In addition, the hand methods of mining allowed a 70-80% recovery of seams being worked. The combination of these two facts gave the figure of 101 Gt which represented a high proportion of the physically workable resources.

In looking forward from 1905 to 1974 one must first subtract the total production for that period (15 Gt) and also add on any newly proved reserves. The net result would have been an increase in the figure for reserves--using the 1905 criteria. One must therefore look to the changing economic and mining environment to understand the dramatic fall in the UKs coal reserves. The main change, of course, was the arrival in the energy market of large quantities of cheap oil. This had a twofold effect. It forced the mining industry to develop and implement mining technologies that gave higher productivity/lower cost at the expense of recoverability, and it made mining in many areas uneconomic. Thus in considering the 1974 figure of 3.9 Gt (produced by the UK National Coal Board (NCB) for the WEC before the oil crisis) the NCB had to take into account the following three points:

- The extraction percentage for seams, when worked, was about 45% (Clarke, 1977).
- Not all seams at collieries were economically workable even if they were physically workable.
- The demand for and price of coal did not justify the opening of any new deep mines.

Consequently, the figure for reserves represented only a fraction of the physically workable resources and covered only existing collieries. However, this vast reduction in the published size of reserves, which took place in other countries as well as the UK and which was due almost entirely to the competition from oil, led to speculation that "coal is not so abundant" (see, for example, Fettweis, 1975).

In considering the latest figure for the UK reserves of 45 Gt, the main change that has taken place since the previous assessment has been the sharp rise in energy prices coupled with the increased realization that oil and gas resources are running out. This has made large areas of coal once again potentially economically extractable and has led the NCB to produce their revised figure.

In summary, it may be seen that the figures for coal resources and reserves in the UK have been revised from time to time and that the figure for reserves has varied by a factor of 25 or more in the recent past. However, one might also note that the economic and mining environment, which changed through time to produce these varying assessments, can also vary from country to country. It is easy to understand therefore that if different countries were to assess the same deposit of coal, they could easily come up with radically different values for the reserves--depending on the criteria that are relevant to the individual countries as well as on the date of assessment. Consequently, the assessments produced by individual countries of their own resources and reserves are not generally compatible with one another and direct aggregation of the figures to produce world assessments will have inherent limitations.

THE APPROACH OF IEA COAL RESEARCH

The approach of the IEA World Coal Resources and Reserves Data Bank Service to the problems of assessing the world's resources and reserves of coal can essentially be divided into three parts:

- Data collection,
- Data translation, and
- Reserves assessments.

The bulk of the work is being carried out by IEA Coal Research in London whilst a Data Bank Facility is provided by the United States Geological Survey (USGS).

Data Collection

Data on resources and reserves are being collected by the Service's team of geologists initially from published sources, and secondly by direct inquiry in individual countries. The exercise is geared to the quantity and quality of data available on any coalfield and may be divided into three parts:

- The collection of the best available published summary data on each of the world's coalfields--so that the Service has a basic amount of information on every coalfield (there are over 2000 coalfields in the world).
- The collection of more comprehensive published data, where these exist.
- The collection of unpublished comprehensive data by direct inquiry in individual countries.

These detailed data, from either published sources or direct inquiry, include both block data, covering parts of coalfields, and point data (e.g. bore hole data) which will allow the Service to make its own assessments of the resources of an area, using the USGS data bank system, as part of the validation procedure. The third part of the exercise is obviously possible in member countries of the Service but it is hoped that other countries, particularly those with a high coal export potential, will co-operate. All the data, when collected and validated where possible, are banked on the US computer using the USGS data base system PACER (a version of GRASP) (Cargill et al., 1976; Bowen et al., 1975). At the time of writing a bureau computer, housed in Chicago, was being used and accessed from London via the bureau's data transmission network, INFONET. However, the system is to be shortly moved to a USGS in-house computer and will be accessed from London via TYMNET. The resource/reserve data files for the system are shown as part of Figure 2.

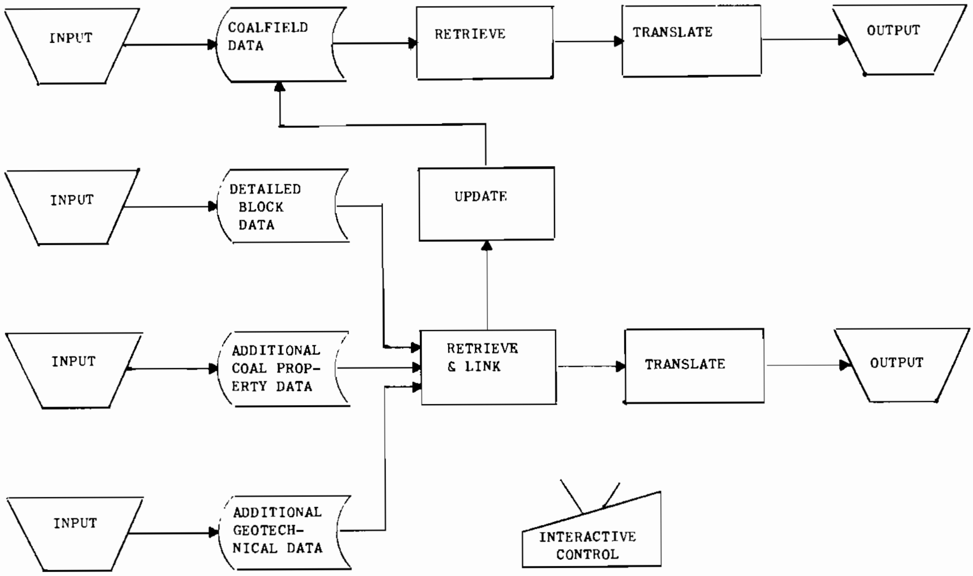

Figure 2. Flow diagram for simple data storage and retrieval.

Data Translation

After the data have been collected and banked, the next phase of the operation is to translate data to a common basis so that meaningful comparisons and summations can be made. Data translation can be divided into three types:

- Straightforward translation of units.
- Translation of bracketed data. For example, data may be given in depth brackets: 0-100m, 100-300m, 300-1200m for country A; 0-200m, 200-500m, 500-1500m for country B. Again the translation is fairly straightforward and involves some interpolation.
- More complex translations of processed data. This section includes data expressed by coal ranking systems (i.e., systems that express quality or suitability for end use) and also data expressed by resource/reserve classification systems. For the former and in the absence of supporting data, they may involve a statistical comparison of the various coking and caking tests. For example, some countries use the Gray-King coke test as part of their coal ranking system; others use the Roga test. The relationship between the two tests may perhaps be best expressed as a probability function and this leads to approximations in translation.

The latter case--i.e. the translation of data expressed by resource/reserve classification systems--is the most important part of the whole translation process. Resource/reserve classification systems normally use a degree of geologic certainty as the prime means of distinguishing between different categories. In addition they generally take some cogniscence of economic and technological certainty and of recoverability, and also specify cut-points for seam thickness, depth, and quality. Thus using these factors it is possible to translate from one system to another although the accuracy of translation depends both on the degree of sophistication of the relevant systems and perhaps also the availability of supporting data.

In summary, therefore, one can see that data translation is feasible, but that on many occasions it involves approximations. This factor has influenced the design of the overall data system. Translations involving approximations are carried out as a post-banking operation to avoid degrading any of the banked data. This ensures that data, which may be outputted in different forms to different member countries of the Service need only be translated once, thus minimizing the number of approximations required. Figure 2 illustrates the flow diagram for data banking, translation, and retrieval.

Reserves Assessments

One of the main purposes of carrying out any assessment of reserves at the national or international level is to provide input for the derivation of long-run supply curves. This is reflected in the approach of the Service, which is undertaking studies to provide alternative assessments of the world's reserves based on a range of possible assumptions.

Any assessment of reserves depends not only on the knowledge of their existence, but also on location, geologic setting, mining technology, recoverability, productivity, production costs, local availability of manpower, capital and services, relative influence of environmental and social constraints, coal quality, utilization technology, demand, price, and transport cost to existing or potential markets. Some of these factors are interrelated and most will vary through time. Figure 3 shows a simplified flow diagram for the assessment of reserves from resource data taking into account the above factors. The system is currently under development.

The starting point for the calculations is the detailed resource/reserve data files shown in Figure 2. The data used include resource tonnage and location plus available geotechnical and coal property data such as seam thickness, depth, level of tectonic disturbance, and coal quality. The first part of the process is simply to eliminate resources that are not extractable for environmental or other reasons. The revised data are then processed through the two main parts of the system, the mining module and the marketing module.

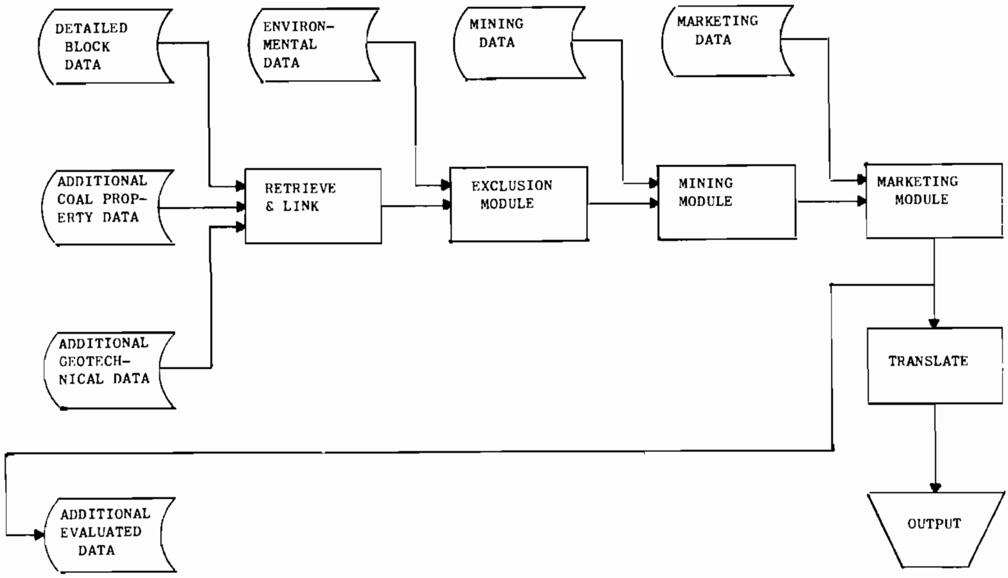

Figure 3. Flow diagram for the evaluation of resource data.

The mining module is geared up to use whatever data are available. A typical equation used in the module to give the operating cost (C) of underground longwall mining is:

$$C_j = [(A + f(S_j) + f(D_j) + f(T_j) + f(G) + f(R_j) + \cdots)LW + M_j]$$

where j is the subscript for different seams, A is a constant, S is the seam thickness, D is the depth, T is the level of tectonic disturbance, G is the dip (gradient) of the seam, R is the rank, L is any local productivity factor, W is a local wages factor, and M is the cost of materials. The different seams, j, in any block of coal under study, then have to be considered together when calculating capital charges. Some of the early work on the derivation of the various functions f(S), f(G), etc., is given in the paper by Gregory et al. which appears elsewhere in these Proceedings. Other mining cost models, dealing with surface mining, other conventional types of underground mining, underground gasification, etc., are being developed together with models dealing with recoverability. Each type of mining can then be tried by the system and the most appropriate one chosen.

The main output of the mining module is a type of supply function giving recoverable tonnage against cost of mining. Ancilliary output includes the type of mining, the desired maximum output and the recoverability factor.

The second main part of the system is the marketing module, which is essentially geared to calculating the potential pithead price. This price may then be used as a cutoff point on the relevant reserves supply function and a figure for the "reserves" established. The potential pithead price will depend initially on the price of coal in any market that the coalfield could serve. This is turn will depend on the overall world energy price and on a number of local market factors related to quality, end use, demand, competing fuels, etc. A series of potential pithead prices may then be calculated by subtracting transport costs from each of the potential market prices. The highest pithead price is then used for the cutoff point, provided that the demand from the prospective market is significant.

The system as a whole is designed to provide a basis for comparing reserves on an international basis, taking into account any local factors that may influence the likelihood of mining and using a range of alternative assumptions. A number of time dependent variables can be incorporated into the system as alternative assumptions and the potential effects of any of these on reserves assessments can be calculated. For example, the system could incorporate alternative equations covering new technologies of mining or utilization and the effects of these could be calculated. More importantly, a range of possible world energy prices (taken as an extrinsic variable for this purpose) could be used so that the influence of this on reserves may be calculated and long-run supply curves derived.

CONCLUDING REMARKS

The IEA has recognized the problems of trying to assess the world's resources and reserves of coal and has taken the initiative in forming the World Coal Resources and Reserves Data Bank Service as a part of IEA Coal Research.

The approach of the Service can be divided into three parts: the collection of resource/reserve data both from published sources and by direct inquiry; the translation of data such that comparisons and aggregations can be made; and additional work on reserves assessments in particular taking into account different world energy prices.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution of the other members of the IEA World Coal Resources and Reserves Data Bank Service to the preparation of this paper. However, the views expressed are those of the author and are not necessarily those of the Service as a whole.

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GEOLOGICAL ASPECTS FOR THE ASSESSMENT OF RESOURCES AND RESERVES

THE EFFECT OF THE PHYSICAL PROPERTIES OF COAL RESERVES ON DEEP MINE PRODUCTIVITY IN THE UK

K. Gregory, L. Lock, and R.J. Ormerod

INTRODUCTION

Productivity is one of the major contributing factors to the cost of extracting coal reserves from deep mines and yet in the past it has proved to be very difficult to predict with any degree of accuracy. This paper discusses some of the problems that have been encountered in a recent attempt to build a model of face productivity for the UK deep coal mining industry that is based on the physical characteristics of the reserves. Similar studies have been undertaken in the FRG [1], USA [2,3], and the USSR [4]. The work referred to here is concerned only with productivity at the coal face and only longwall advancing faces. Face productivity was used in this first exercise since it is probably more closely related to some of the physical characteristics of the coal than is overall colliery productivity. Longwall advancing faces represent the main method of working in the UK at present. Other methods are used, principally longwall retreating faces, but insufficient data were available on these methods to make a detailed statistical analysis worthwhile.

The main reason for this productivity study is to develop measures by which one might compare the "value" of different deposits of coal both within the UK and, if possible, within areas of coal with similar geological features in other countries. Such measures must, of course, be derived from more than just the analysis of past data described here. Productivity in other parts of a colliery, alternative methods of working, technical innovations, increased capital spending, and better designs for new collieries will all have an impact on future overall productivity and mining costs, and hence on the "value" of deposits. Thus the work referred to in this paper represents only the first step towards the development of these measures.

BACKGROUND TO THE UK COAL MINING INDUSTRY

In the UK, the National Coal Board (NCB) is responsible for almost the whole of the output of the coal mining industry (122 Mt in 1976). About 10% of the production comes from opencast mining, whilst the remaining 90% comes from deep mining. The NCB operates 239 deep mines and the bulk of the output of these mines comes from about 720 major longwall faces. The distribution of faces by depth and seam thickness is given in Figures 1 and 2. About 86% of these faces are advancing faces whilst 14%

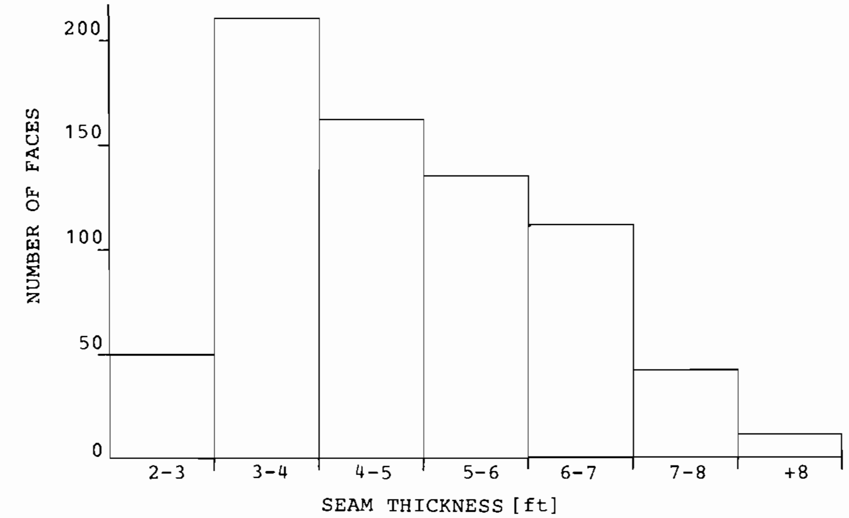


Figure 1. Distribution of faces by depth.

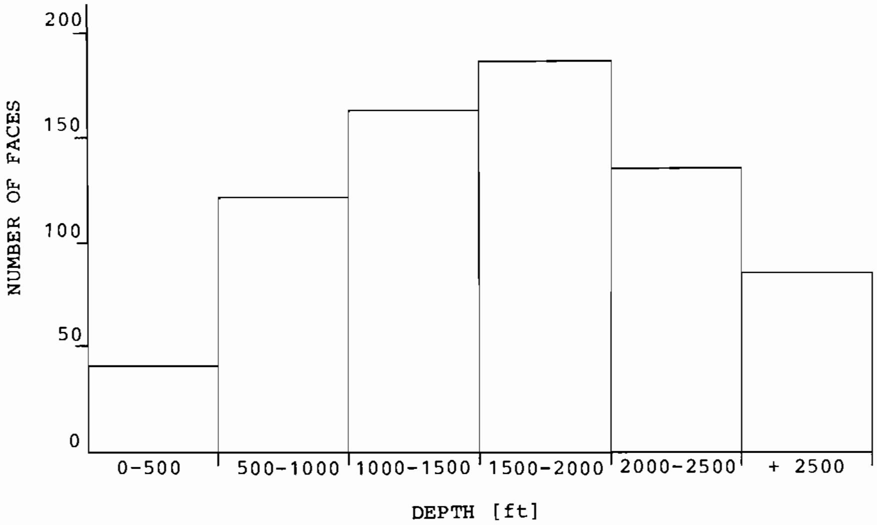
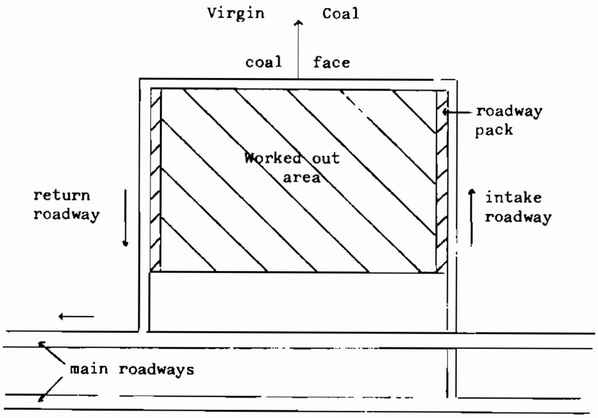
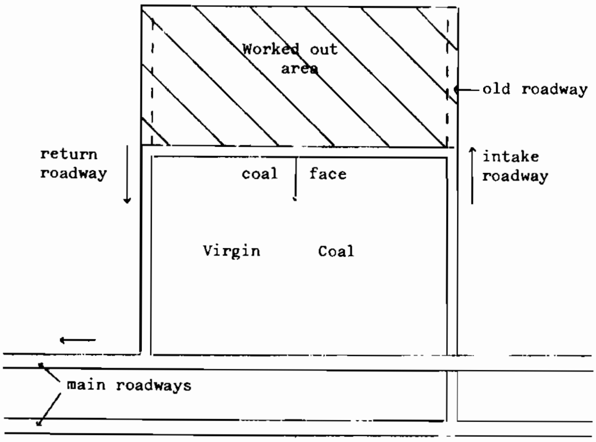


Figure 2. Distribution of faces by seam thickness.

are retreat faces. Figure 3 illustrates the main differences between these two types of mining. (There are a number of types of retreat mining--only one is shown here.) The essential difference is that with advancing faces, part of the mining operation is to build roadways at each end of the face--for access, ventilation, coal clearance, and incoming supplies. With retreat faces the roadways are pre-driven.



EXAMPLE OF A LONGWALL ADVANCING FACE



EXAMPLE OF A LONGWALL RETREATING FACE

Figure 3. Examples of longwall advancing and retreating faces.

All of the UK output is hard coal taken from the Upper Carboniferous Coal Measures. The system used to classify these coals is based on their volatile matter content and on the coking properties. The highest ranks (rank 100s--anthracite) are assigned to coals that have undergone the highest degree of coalification and have the lowest volatile matter. The main types of coal produced are:

- Rank 100s	Anthracite (high rank)
- Rank 200s	Low volatile steam coals

- Rank 300s	Prime coking coals
- Rank 400s-600s	Coking coals
- Rank 700s-900s	High volatile steam and house coal (low rank) (general purpose coal).

PROBLEMS WITH THE DATA

Which Factors to Use?

Undoubtedly there are many factors that influence productivity at the coal face. The choice of which to include in any model will depend upon the purpose to which the model is to be put and the availability of the data. From this point of view the factors can be divided into four categories:

- Those that are almost impossible to measure even in retrospect, e.g. workers' attitude/aptitude and management efficiency;

- Those that are not defined until mining is about to start, e.g. length of face and face machinery;

- Those that are not usually measured before mining starts or that, at present, do not have a useful standard of measurement, e.g. roof and floor conditions and degree of faulting; and

- Those factors that are known (to a large extent) before mining starts.

Factors in the first category are, by definition, of little value in this type of analysis. Those in the second represent the results of decisions by mining engineers, and are influenced by the physical characteristics of the coal seam and the host strata as described in the last two categories. The factors in the third category are generally thought to be important in the UK. In the FRG some progress [5] has been made in the forecasting of tectonic disturbance, but its application to the UK must await further research. It is thus only those factors in the fourth category that were included in the analysis. The choice of factors was, of course, influenced by the availability of data; the ones included in the analysis were:

- Seam section: This is the thickness of the seam that is extracted. We would expect low productivity from a face with a thin seam section since working conditions will be more cramped and less coal will be cut each time the machine traverses the face.

- Coal rank: The rank of the coal may affect productivity indirectly in several different ways; these are discussed later in the section on problems.

- Depth: The depth is more likely to affect the overall productivity of the pit but even at the face it may have some effect since increase in depth will mean an increase in working temperature; and increased problems from strata pressure.
- Dip: If the seam is on a steep gradient then working conditions will be worse.
- Distance inbye: The distance of the face from the shafts. This is more likely to affect the overall productivity of the pit. Nevertheless, at the face, a greater distance inbye will mean more travelling time and so less time at the face. The average distance inbye will, of course, be influenced by the area of "take" of the colliery, which will be known during the planning stages of a colliery.

Unfortunately, even with these items, the values have not been recorded or have not been recorded frequently enough at some faces to give a comprehensive set of data. Some other factors (region, face length, and type of coal cutting machine) were considered after the initial analysis to attempt to explain the remaining variance in the data.

Bias

Any model that has been based upon past data must necessarily be biased, since for one reason or another someone decided that the coal that was extracted was more desirable than the coal that was not extracted. So the data will not be a representative sample of all deposits of coal. If, in the future, the coals that are mined are similar to those presently being mined, then this bias may not be important. However, if there is some substantial difference, then the bias in the model may well be important. During the past thirty years, with increasing competition from other sources of fuel, many of the less economically viable collieries have closed. This suggests that the coal currently being mined in the surviving collieries is "better" in some sense than coal previously mined at the collieries that are now closed. Such changes may also occur in the future, but this may not necessarily be a continuation of the same process.

Data from a total of 538 faces were used in the analysis. This represents 61% of the total output of the period considered.

PROBLEMS WITH STATISTICS

The problems that arise from applying statistical techniques to the available data are vast and will depend upon the type of model that is being built.

Which Type of Model?

There are many different types of statistical models that can be used but broadly the decision is between time series and cross-sectional, and between regression and analysis of variance. The first choice is basically whether to include time in the analysis. Over the last 30 years there has been a considerable change in productivity (Figure 4). Work within the NCB has illustrated that this change can largely be explained by the increase in the level of mechanization aided by capital expenditure on colliery reconstructions and the closure of some less economic pits. A time series approach was used in this work, and may well be useful as a basis for estimating the effect of future changes in technology. However, the aim of the work described here was to relate productivity to the physical properties of the coal reserves and a cross-sectional analysis seemed more appropriate. The data used for this model were summaries for one quarter from longwall advancing faces. Longwall retreat faces were left out of this early analysis firstly because it was thought that the physical characteristics of the coal would have a different effect on retreating faces than on advancing faces, and secondly, since there were insufficient data to construct a separate model.

Figure 4. UK deep mine productivity.

The second choice in the type of model depends on our prior belief in the effect that each of the factors will have on productivity. Linear regression assumes a linear relationship (e.g. 20% increase in seam section will cause double the increase in productivity of a 10% increase), and polynomial regression assumes more complex relationships. (Coal rank cannot be considered in this way since it is not measured on a linear scale.) The alternative is to use analysis of variance techniques. This approach is more flexible since no assumption is made about the relationships with productivity, as in regression analysis. However, the data must be banded (for example, the seam section has been banded into (feet): 3, 3-4, 4-5, 5-6, 6-7, and over 7) introducing some loss in accuracy. Also, apparent inconsistencies can occur, as we shall see when we consider the results. Many books on statistics, such as *The Analysis of Variance* by Sheffe, explain the theory. In the following sections on the statistical assumptions and the results, we have referred only to the analysis of variance approach. The results from the regression analysis are broadly similar.

Statistical Assumptions

Having decided upon the form of the model that we want to build, we can derive the numerical estimates of the parameters arithmetically. The questions that we want the analysis to answer are:

- Which of the chosen factors are sufficiently important to be included in the model, and which of these are the more important factors?

- How accurate are the estimates of the parameters used in the model?

The usual assumptions for the application of analysis of variance techniques to answer these questions are:

- Each band should have the same number of observations.

- The distribution of productivity within each cell (each combination of one band of each factor defines a cell) should be normal.

- The variance of the productivity in each cell should be the same.

The available data do not fully satisfy any of these three criteria. Firstly, if all five factors are included, there are 15,876 cells, but only 538 observations. Hence, on average, there is just one observation for every 30 cells. In theory, however, the first assumption can be relaxed to at least partially accommodate this situation (although in doing so the complexity of the arithmetic is greatly increased). Secondly, the distribution of productivity in many of the cells may be skew (for example, those included within the 7 ft and over band of seam sections), and thirdly, in these cells the variance may be greater than in the more "central" cells.

Therefore, any confidence estimate may be very inaccurate. However, some attempt can be made to determine the importance of each of the factors.

Goodness of Fit

No model of productivity in terms of the physical characteristics of the face has yet been found that gives a good fit to the data, and, as we shall see in the next section, this model is no exception. Statistically, this suggests that there are many other important factors that have not been included. Such factors may be the degree of faulting, the roof and floor conditions, and other geological factors. At present, they cannot be measured or forecast in a manner suitable for use in this type of analysis. When making use of a model that does not have a good fit for the data, we must always bear in mind that changes in factors other than those used in the model may cause major changes in productivity not estimated by the model. Hence, any forecasts are likely to be more accurate for large areas of coal rather than for individual faces.

RESULTS

The statistical analysis shows that rank and seam section are very important (significant well above the 99% level). This result is so clear that all the errors in the analysis are unimportant. Rank, alone, explains 18% of the variance in the data, and rank and seam section together explain 27%. Distance inbye and gradient of dip are marginally significant (at the 95% level). This result is very susceptible to the errors in the analysis. Finally, depth is insignificant.

The model that uses these four most important factors (i.e. excluding depth) is given in Table 1. This model explains only 31% of the total variance. Thus, distance inbye and gradient of dip together have only explained an extra 4% of the variance in the data. This figure of 31% is very low and clearly shows that many important factors have been excluded from the model. The introduction of face length, region, and type of coal cutting machine each individually improve the model, explaining 10%, 6%, and 4% of the residual variance respectively.

Table 1. Face productivity model.

$$\begin{array}{l}\text{FACE PRODUCTIVITY} = 196.1 + \\ \text{(cwt*/face manshift)}\end{array}
\begin{array}{c}\text{RANK}\\ \left[\begin{array}{r}-71.4\\-109.9\\-75.6\\-8.3\\11.9\\4.4\\26.2\\40.2\\44.5\end{array}\right]\begin{array}{l}\text{100s}\\\text{200s}\\\text{300s}\\\text{400s}\\\text{500s}\\\text{600s}\\\text{700s}\\\text{800s}\\\text{900s}\end{array}\end{array}
+
\begin{array}{c}\text{SEAM SECTION}\\ \left[\begin{array}{r}-57.1\\-26.2\\6.3\\32.1\\39.4\\31.2\end{array}\right]\begin{array}{l}< \text{3 ft}\\\text{3-4 ft}\\\text{4-5 ft}\\\text{5-6 ft}\\\text{6-7 ft}\\\text{7+ ft}\end{array}\end{array}
+
\begin{array}{c}\text{DISTANCE INBYE}\\ \left[\begin{array}{r}30.3\\9.0\\-4.5\\8.3\\-19.0\\-15.8\\-23.5\end{array}\right]\begin{array}{l}< \text{2000 m}\\\text{2000-3000 m}\\\text{3000-4000 m}\\\text{4000-5000 m}\\\text{5000-6000 m}\\\text{6000-7000 m}\\\text{7000+ m}\end{array}\end{array}
+
\begin{array}{c}\text{DIP}\\ \left[\begin{array}{r}-33.6\\-17.2\\6.8\\3.3\\4.2\\10.2\end{array}\right]\begin{array}{l}\text{1 in 2-5}\\\text{1 in 6-9}\\\text{1 in 10-17}\\\text{1 in 18-25}\\\text{1 in 26-33}\\\text{1 in 34-level}\end{array}\end{array}$$

*1 cwt ≃ 50 kg

Example of use: Face productivity for rank 500, seam section 5-6 ft, distance inbye 2000-3000 m, and dip 1 in 6-9 = 196.1 + 11.9 + 32.1 + 9.0 - 17.2 cwt = 231.9 cwt.

PROBLEMS IN THE INTERPRETATION OF THE RESULTS

We discussed earlier the problem of bias in the data introduced by the fact that we can only include data on the productivity of working coal that has already been extracted. This naturally will influence our interpretations of the results. For example, depth was found to be not significant--but this may be partly because faces are only worked at great depth if the other factors are favourable. In addition, while the influence of depth on face productivity may be apparently small, it may be reasonable to assume that certain other aspects of productivity or overall cost of mining may be influenced by this factor.

A second source of bias may be that we have only considered one type of mining technology (longwall advancing faces). The results suggest that there is little difference between faces over 5 ft thick. This may be true, but alternatively it may be argued that the better faces are worked by using retreat methods and that the results do not fully illustrate the value of thick faces.

The second main problem is the interpretation of the significance of coal rank. It may be more than the geochemical properties of the coal that cause rank to be an important influence on productivity. There are at least three ways in which it could be important:

- Some ranks of coal can be sold at a higher price than others hence more money can be spent on extracting the coal and still make a profit, i.e. it can be mined in worse conditions. In general, in the UK, the higher rank coals fetch a higher price and this does seem to be reflected in the results.

- It may be true that, because of the geological history of coal, the rank of the coal may be linked with the level of tectonic disturbance of the seam.

- The rank of the coal is related to the hardness of the coal. Soft coals may yield closer to the face to give poorer working conditions. They may also be more difficult to cut since the coal clogs in the machine reducing working speed.

The third problem is that there are apparent inconsistencies in the results. For example the estimated parameter for 3000-4000m inbye and 6000-7000m inbye appear to go against the general trend. These apparent inconsistencies have occurred since we have not constrained the parameters to adhere to any prior beliefs that we may have. If we had wished to avoid this problem linear or polynomial regression type models would have been used.

FINAL REMARKS

This paper discusses some of the problems that affect any estimate of likely future productivity from an analysis of past data. The analysis reported here indicated that only 31% of the variance in face productivity might be explained by factors that would be known before mining began. More refined analysis may improve this figure but the importance of several as yet unquantified factors will probably prevent it rising above, say, 50%. The most important of these is probably roof and floor conditions which vary considerably in the UK and which are difficult to predict at the pre-mining stage. In addition, there is the level of disturbance to the coal seam which affects overall productivity and mining costs rather more than it does face productivity. However advances are being made in the detection of underground faults from the surface by seismic reflection methods and this factor may become less important in the future. Further major factors are the quality of management and the attitude/aptitude of the men. These are bound to vary from colliery to colliery and through time and are not easy factors to measure or predict. Finally, the analysis reported here covers only one type of coal mining technology. With the level of effort currently being applied to mining research it is hoped that new developments may lead to higher productivity/lower costs for this type of mining together with the development of alternative technologies.

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The views expressed are those of the authors and are not necessarily those of either the NCB or the IEA Coal Research.

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SURFACE SEISMIC PROFILING FOR COAL EXPLORATION AND MINE PLANNING

J.B. Farr and D.G. Peace

INTRODUCTION

The basic seismic reflection method is well established in the petroleum industry and has a long record of success in finding favorable geologic structures that contain hydrocarbon deposits. As the larger structures have been discovered in many areas, the petroleum industry has started to turn to smaller structures and, more importantly, to stratigraphic traps which require a far greater precision and fineness of detail to locate. This redirection resulted in improved equipment design, field recording techniques and processing procedures, which means the geophysicist is now able to look much more closely at the shallow near surface strata of interest in coal exploration and mine planning. Although this paper specifically concerns applications to coal mining, for which the technique is highly suited, high resolution seismic profiling may be used in other mining investigations such as for uranium or in associated fields like engineering and construction surveys.

The low density and conduction velocity of coal, compared with its enclosing rock, produces a very strong seismic reflection. This means that a coal seam should be easily identified through the background noise. However, while this is generally true, in some areas of very thin coal seams and high seismic noise levels it may only be possible to identify to the nearest coal cyclotherm. This should not significantly affect the interpretation or reliability of the data, because when a coal sequence is disturbed, perhaps by a fault, the effects will be noticeable over a greater area than just the thin coal seam itself.

Although the use of seismic reflection techniques for coal exploration and mine planning purposes is still in its infancy the preliminary results are encouraging. As shown on Figure 1, the use of seismic profiling in the mining industry increased quite dramatically after 1973. After a relatively low value in the 1972-1973 period an increase of more than ten to one is noted in 1975-1976, which is the latest time period for which statistics are available. Seismic profiling figures for coal are available in A.M. Clarke's 1976 paper on seismic surveying and mine planning [1]. For the entire mining industry the statistics can be found in the annual activity reports printed in *Geophysics* [2-6]. While the mining expenditures are small compared to those for petroleum exploration, these figures show a substantial and increasing dedication to seismic data acquisition by the mining industry. Clearly, seismic profiling is a geophysical tool that should be carefully considered by the mining community.

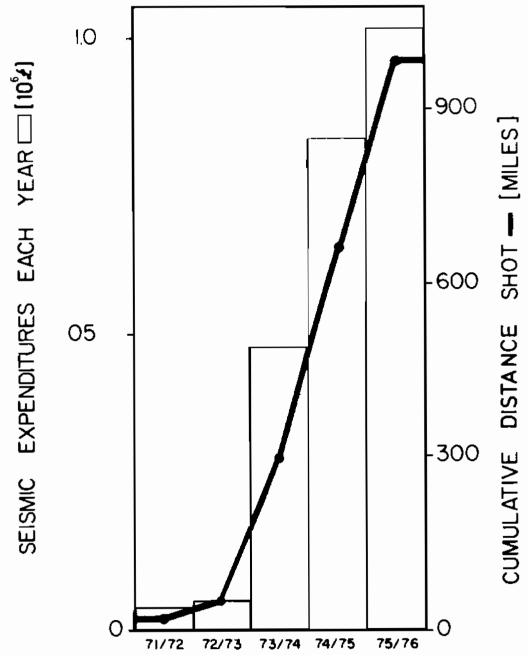

Figure 1. Graph showing increasing use of seismic reflection profiling in the mining industry. The jump in activity after the 1972 to 1973 period coincides with improvements in seismic resolution capabilities.

Source: [1]

HOW DOES THE NEW SYSTEM WORK?

Figure 2 shows an idealized field seismic layout, consisting of a small drill, a portable digital recording unit, cables, and downhole detectors. Also shown are some subsurface disturbances, such as faults, channels, and pinchouts, that are problems in coal extraction and thus the principal targets of the seismic survey.

At a precisely known time, acoustic energy is sent into the ground from a very small dynamite charge buried in the same shallow bore hole previously used for the detector. This energy radiates through the earth until it reaches a suitable reflector, i.e. a density and velocity contrast at a change in rock type

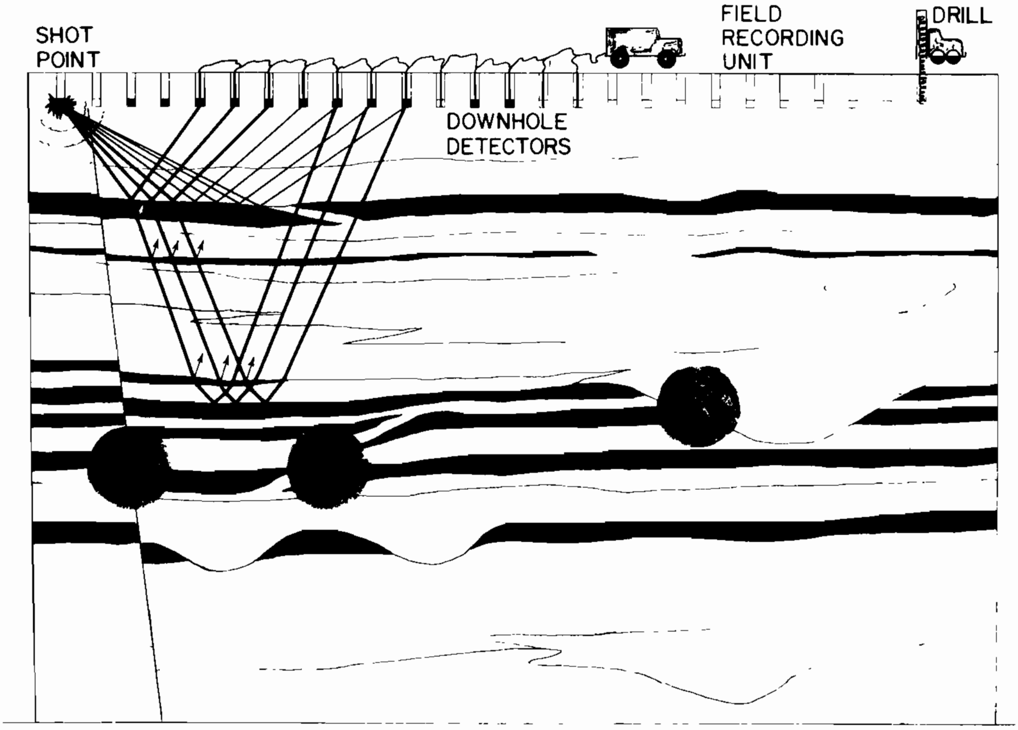

Figure 2. Diagrammatic cross section showing fundamentals of reflection profiling and type of field equipment used. Also illustrated are typical subsurface disturbances such as faults, sand channels and seam pinchouts which can present problems in the extraction of coal.

where, following Snell's law, some of the energy is reflected back to the surface where it is recorded. The remaining energy passes further down into the earth to follow the same procedure at deeper and deeper interfaces. The energy returning to the surface is recorded in terms of travel time from the shot to the subsurface interface and then back to the detector. This acoustic energy information is stored in digital form on magnetic tape. The field crew then moves 5-10 m further along the traverse and repeats the process, removing one detector at the near end of the spread and adding a new detector at the far end. This roll-along procedure continues until the traverse is complete.

These raw field recordings are then processed in a digital computer center to enhance the recorded signals, while reducing unwanted noise to a minimum. The computer processing also compensates for variations in rock conducting velocity and corrects the data for irregularities introduced by changes in near surface geology and elevation along the traverse. When the digital processing is complete the net result is a seismic section display as shown on Figure 3. This seismic display must be interpreted by the geologist or mining engineer before it is of value in coal exploration or mine planning.

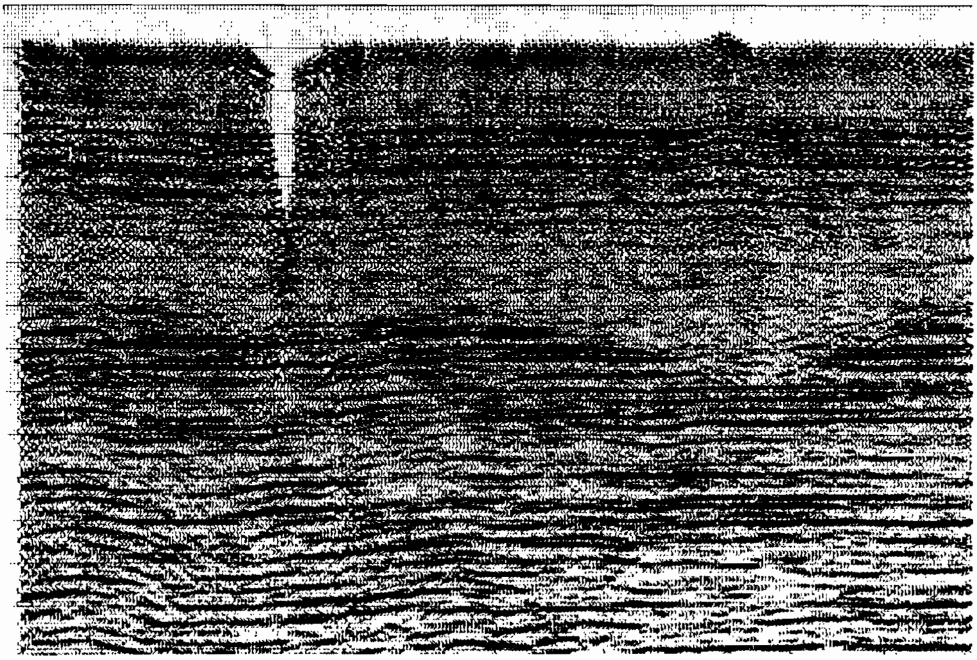

Figure 3. An uninterpreted seismic cross section display after computer processing has been completed. This cross section was obtained using the new high resolution techniques outlined in the text with coarse 10 m (0.5 ms) sampling interval.

At first glance, the seismic section is merely a mass of light and dark bands intermixed with wiggly lines. However, as seen in Figure 4, when some shading is applied over the black and white display an interpretation is generated. In this case, for illustration purposes, a number of geological features that would be expected to disturb typical coal seams are interpreted, although the information was not recorded in a coal province. To see the interpretation more easily, it is repeated without the seismic data background on Figure 5. Note the small fault is clearly identified by the displacement of reflections, while the old river channel is evidenced by the cutting out of reflection bands. In addition to the obvious fault and sand channels, a wide variety of other features such as unconformities, areas of lensing, and seam splitting can be detected with high resolution seismic data.

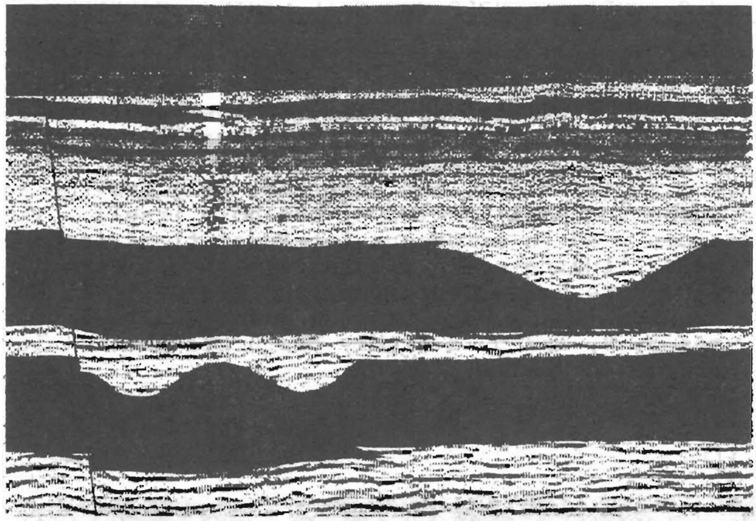

Figure 4. Seismic cross section display of Figure 3 superimposed on illustrative interpretation showing geological features which could be expected to disturb typical coal beds.

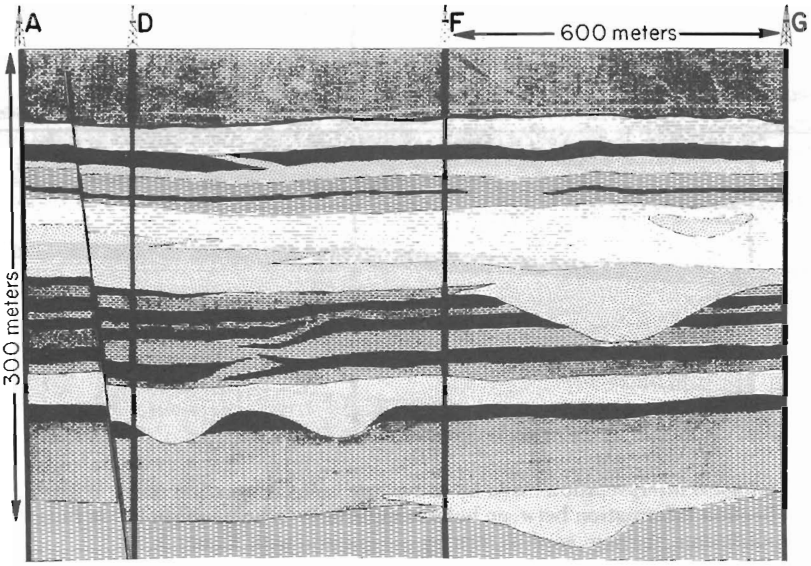

Figure 5. The interpretation derived from the seismic data in Figure 3 with patterns representing different geological formations. Core holes have been added representing a hypothetical coal drilling program which just misses all disturbing features.

HOW CAN SEISMIC PROFILING HELP THE COAL MINING INDUSTRY?

Very simply, seismic profiling can help by defining more precisely the subsurface geology in the coal seam and allied rock. This is now done by sinking bore holes at close and regular intervals. While bore holes are essential to actually prove the existence and thickness of coal seams they are expensive, relatively slow in proving a coal field, and then they only provide accurate information about the small radius of the hole itself. This can in many instances lead to erroneous interpretations in disturbed coal fields. As illustrated in Figure 6, simple interpolation between the four bore holes would lead the geologist to believe that undisturbed coal beds were present while, in reality, as seen in Figures 3, 4, and 5, a highly disturbed section lurks undetected between the holes.

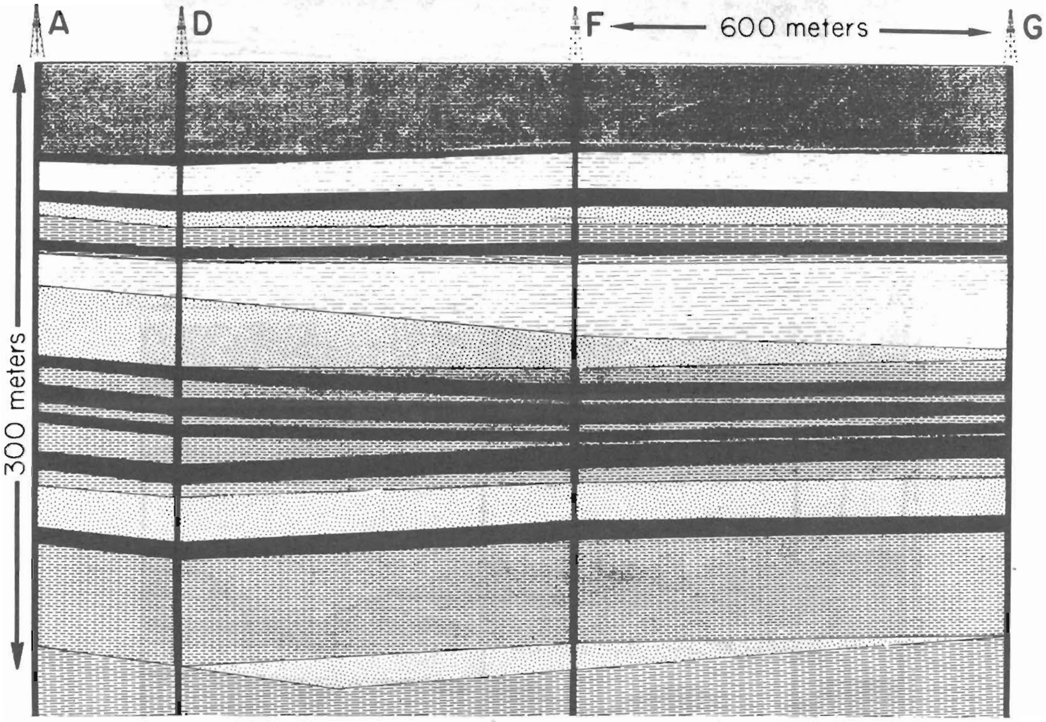

Figure 6. Geological interpretation made by using core hole information only. Without seismic reflection information between holes, simple hole to hole interpolation fails to reveal troublesome problem areas as seen by comparison with Figure 5.

Miscorrelation or misidentification of coal seams in bore holes has contributed to misinterpretation of coal fields more than any other single factor. Only through knowledge of the stratigraphy of coal-bearing strata can consistently accurate correlations result. It is by supplying this stratigraphic information between bore holes that high resolution seismic profiling can benefit the coal mine operator. Seismic profiling can be used to fill in between, or extend out from, bore holes or other control (i.e. underground workings) to provide an accurate picture of subsurface disturbances.

ACOUSTIC IDENTIFICATION OF SPECIFIC COAL SEAMS

The structural information derivable from the seismic displays includes, in addition to the location of faults, sand channels and partings illustrated on Figures 3, 4, and 5, such information as the unique identification, thickness, and lateral persistence of particular seams. All these factors are of utmost importance in economic evaluation of virgin areas, as well as planning mine operations once an area has become active.

Coal seams are best identified by their relationship to associated strata such as roof slates, cap rocks, underclays, underlimestones and the like. In addition, persistent partings or bands within the coal seam itself can aid in identification and lateral correlation of specific seams. For example, one seam of interest may rest on a 1-3 m underclay above a nodular limestone and have no limestone cap rock. Other seams in the same area may be characterized by roof slates or have a limestone cap, or have no underclays.

While the coal seams remain unchanged, the acoustic response will differ in each of these cases permitting seam identification from the seismic reflection data. The differing acoustic properties (i.e. density and velocity changes) across the upper and lower seam interfaces will cause the seismic reflections from essentially identical coal beds to have different amplitudes and frequencies. Provided the source signals are sufficiently broad band, these changes in the shape of the individual reflection wavelet can be used for unique seam identification even when trace-to-trace time correlations are absent due to interruption or cutout over wide areas.

The identification and study of rock types by seismic wavelet characteristics has been called "seismic petrology" and is an extremely useful supplement to the more familiar structural aspects of seismic profiling. It can provide the coal geologist with valuable regional information as to basin edges and depositional environments.

Obviously, seam thickness variations will affect the economics of coal extraction by automated methods. Clay or rock partings within a given seam will also present serious mining and quality control problems. Some partings, so thin as to present no problems at one point, can rapidly and unexpectedly increase in thickness to the point where mining is so difficult as to be uneconomic.

MAPPING THE THREE DIMENSIONAL DISTRIBUTION OF FAULT ZONES AND CHANNELS

Small faults or slips if closely spaced can cause serious problems in mining or loading of coal. Highly inclined clay seams which traverse both the coal bed and caprock are often associated with these small faults. Both the clay seams and vertical displacements of the coal bed can cause considerable difficulty, both in underground and surface mining. In underground mining the seam is often lost across these faults and the roof is weakened. In surface mining the uneven surface causes difficulty in cleaning the coal surface during stripping, resulting in the loading of much shale with coal. Segments of the coal bed that have been faulted downward so as to protrude into the underclay cannot be loaded, thus reducing coal recovery. Where thin seams are being worked, very little such loss can be tolerated.

The three dimensional distribution of small faults is not readily detectable even by closely spaced drilling. Many times the fault throw is so small as to be overlooked in correlation between bore holes. It is in this area that the high resolution seismic profiling can prove of great help in mine planning and economic evaluation.

"Wants" or buried stream channels containing sand, glacial deposits, or other detrital material dissect and replace coal seams in many coal fields. Even where no seam dissection is evident, overlying channels can produce severe safety problems in underground workings. The stream channel patterns are difficult to reconstruct in three dimensions from drilling alone, as shown in Figure 7 where only one of six wells encountered a branch sand channel. Also, all of the core holes missed the small fault. With core hole information alone a coal bed could be misinterpreted, as shown in the upper portion of Figure 8, while in reality the lower representation is correct. Clearly, the mine planning and economics of coal extraction will differ depending on which interpretation is available.

This difficulty can be avoided by shooting the seismic lines as shown on Figure 7. Seismic cross section displays can then be prepared, as shown in three dimensional idealized form on Figure 9. With such seismic displays prepared in both east-west and north-south directions, dissected channel areas which heretofore have been difficult to identify and localize can now be economically worked. Also, small throw steeply dipping faults can be localized and avoided in mining operations.

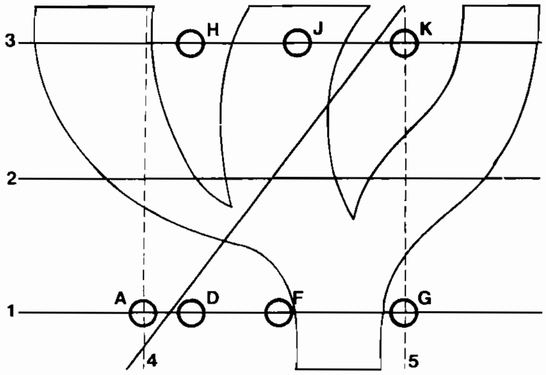

Figure 7. Map of core hole locations, sand channels which dissect coal and fault which displaces seam. Note that only single core hole encounters coal cutout by sand channel and no holes encounter the fault.

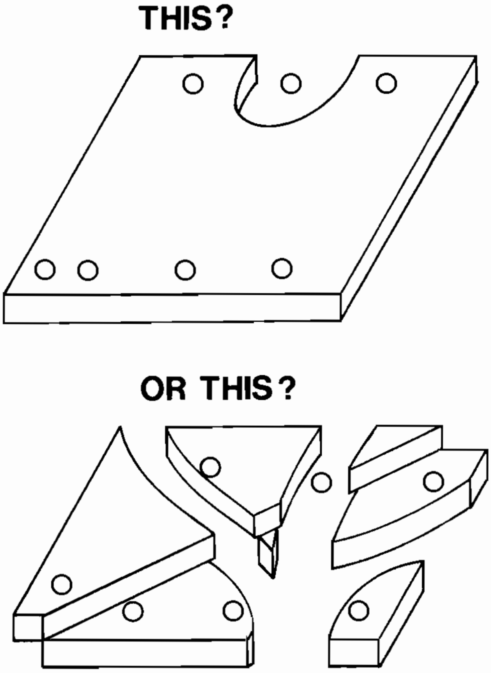

Figure 8. Map of core hole locations relative to high resolution seismic lines which reveal the fault and channel locations to within 5 m. Such lines can effectively reduce the number of core holes needed by optimizing locations relative to disturbances.

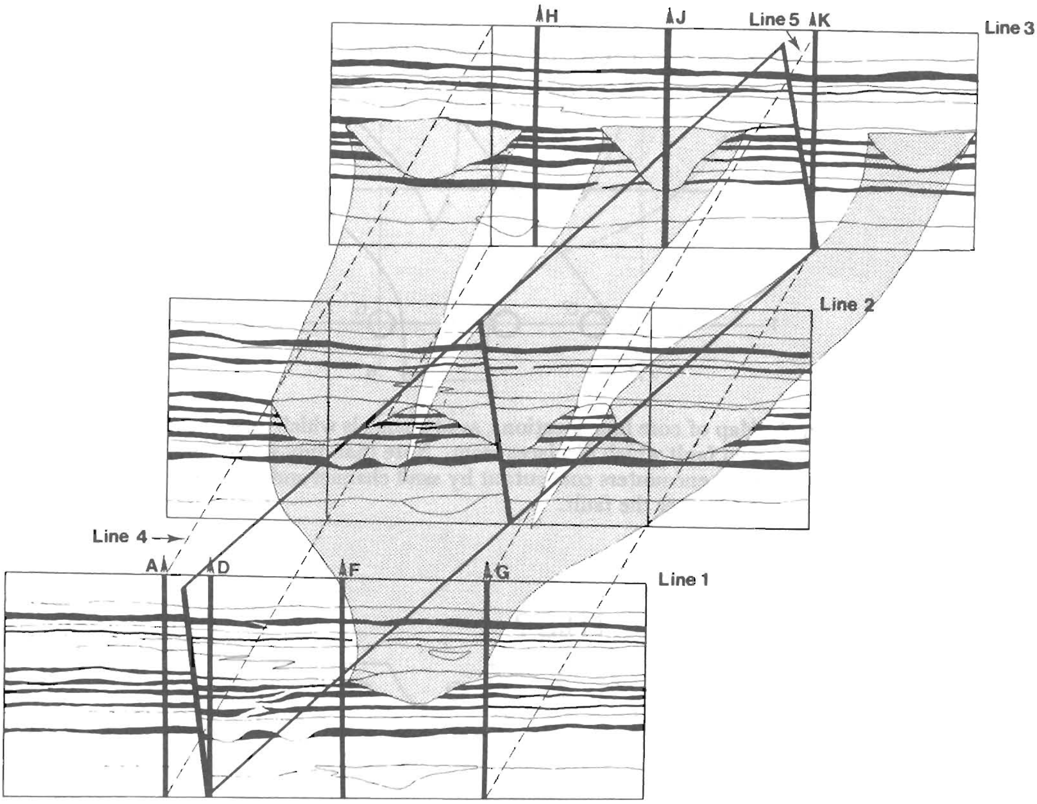

Figure 9. Three dimensional drawing illustrating how seismic cross sections permit tracing of fault planes and sand channels. For clarity only east-west lines are shown, but north-south lines would appear in similar manner fixing subsurface locations.

DELINEATING STRUCTURAL FEATURES AFFECTING COAL RECOVERY

Anyone working with coal geology soon appreciates the error of the popular notion that coal beds are exemplified by flat lying layer cake geology. Anticlines, synclines, and nondescript troughs and basins are found throughout many coal regions. In many areas such structures can lower thin coal seams beyond the reach of economic stripping operations. Lack of structural information in the primary stages of coal exploration can result in much wasted time and effort spent drilling bore holes in the middle of anticlines where the target coal seam has been removed by erosion. Another common drilling error is the failure to drill deep enough to reach the target seam in the center of synclines or basins.

Structural features of much smaller scale can also be very troublesome in certain mining operations. Irregularities in the top and bottom of seams are known as roof rolls and horsebacks, respectively. Roof rolls are merely a thickening of roof strata accompanied by a corresponding thinning of the coal seam. Roof rolls may be caused by tentacles of shale projecting down into the top of the coal. Also they may be related to channel deposits or in some instances to small slips or faults permitting slippage of the roof rock downward into the coal seam.

Horsebacks are rolls in the floor that intrude upward into the coal seam. They also may be associated with small faults. The net effect of both roof rolls and horsebacks is to reduce seam thickness and introduce foreign matter into the seam which, of course, affects the mining economics.

Provided the seismic reflection frequencies are high enough, each of the features discussed above can be identified directly or indirectly on the seismic displays by carefully tracing each coal bed and noting the intervals along the line where the reflection vanishes, undergoes a change in character, or is displaced in depth. While there is no substitute for core drilling to determine the absolute depth, thickness, and quality of coal seams, seismic reflection data can provide invaluable supplementary information regarding relative depths and thicknesses, as well as the detailed geology on a very fine spacing.

Seismic traces, while not as detailed as bore hole logs, are obtained every 2-5 m apart in typical coal surveys. Even the most ambitious and detailed coring programs never approach this density!

WHEN IS SEISMIC PROFILING MOST USEFUL IN A COAL RECOVERY PROGRAM?

There are two broad phases in coal operations where seismic reflection profiling can be employed. The first is the premining or exploration phase, where one needs to know if there is any coal in the area, if there is enough coal present to be interesting, and if the geological conditions are such that the coal can be economically handled in the mining method selected. In relatively undisturbed tectonically inactive basins the geologist can measure the outcrop and perhaps with a few core holes, adequately define the area. Clearly under such situations seismic profiling is unnecessary. If, however, the basin is poorly defined and tectonically disturbed, then a seismic survey would be able to define the basin more accurately by locating its edges and center of deposition, and hence the most favorable location for the exploratory core holes. This could save core holes being placed at a locally disturbed, and hence possibly unrepresentative area of the basin.

After the coal exploration phase has been completed and the decision made to begin mining operations, the high resolution seismic system can provide additional information useful in developmental planning and maximization of the yield from a particular mine operation. This second or coal exploitation phase can greatly benefit from the very detailed information available from high precision seismic reflection sections obtained from areas immediately in advance of mining operations. Careful attention to coal geology, fault and channel locations, and general seam thickness and structural attitude in advance of mining can help understand and overcome many of the difficulties encountered in developing old as well as newly discovered coal areas.

The geological objectives of seismic profiling in both exploration and exploitation phases are essentially the same. It is merely the scale or degree of fineness that differs. Resolution that is dependent on temporal and spatial sample intervals is merely an economic factor that must be optimized in planning seismic line locations and detector intervals in exactly the same manner as the spacing between core holes in a drilling program. In both cases, closer spacing and hence higher costs are necessary where more detailed information is required.

WHAT SEISMIC RESOLUTION IS REQUIRED IN COAL WORK?

The prime seismic target is the coal seam itself so one can immediately ask how thin a coal bed can be detected in a matrix of country rock?

The ability to acoustically "see" a coal bed or, more specifically, to seismically detect whether the coal is present or is missing is a function dependent not only on the bed thickness and its conduction velocity, but also on the local noise and the predominant reflection frequency. Even reflections from very thick coal beds may be obscured by high level noise. Since the noise varies in both frequency and amplitude from place to place, any statement regarding the thinnest observable coal bed, and thus the resolution, will also vary.

This variability dilemma can be resolved by considering a definition of resolution that compares the thinnest observable bed with a single interface seen under the same signal to noise conditions. Assuming that the local signal to noise ratio is such that a vertical incidence reflection signal from the single interface is just visible above the noise, resolution may be defined as the dimension of the thinnest single coal bed that will have a vertical incidence reflection signal equal in amplitude to the signal from the single interface.

This is a relative definition; when the noise level increases or decreases, the detectability of the single interface will go up or down, as will the ability to see the thin bed. It is a realistic definition since, if the seismic reflection method works at all (i.e. if any reflections are seen above noise) one is assured of seeing a coal bed at least that thick.

Lord Rayleigh [7] developed the exact equation for reflection from a single embedded thin layer. Widess [8] developed an approximation of Rayleigh s equation for the geological acoustic contrasts normally encountered. This approximation gives the resolvable bed thickness in terms of single and composite reflection frequency. Widess's formulation gives the detectable coal bed thickness as the predominant seismic wavelength in the coal divided by 12.6. The predominant seismic wavelength is derived from the coal velocity and predominant reflection frequency.

While coal beds as thin as one twelfth of a wavelength can be detected, to position the upper and lower interfaces accurately is more difficult. Widess points out that a different reflection character exists only for signals returned from beds greater than one eighth of a wavelength in thickness. Others claim one sixth or even in the worst case one quarter of a wavelength bed thicknesses are required for upper and lower interface resolution.

When a typical sound conduction velocity of 2300 m/s is taken for the coal bed, a minimum detectable bed thickness can be established for each predominant reflection frequency, as shown in Figure 10. If the predominant frequency is a "conventional" 20 Hz, the minimum detectable coal bed will be nearly 10 m thick in the best case or 30 m thick in the worst case. On the other hand, if the predominant reflection frequency can be boosted to 200 Hz, then a bed only 1 m thick can be detected. Clearly for coal exploitation studies, frequencies above 100 Hz are essential, and those up to 800 to 1000 Hz most desirable!

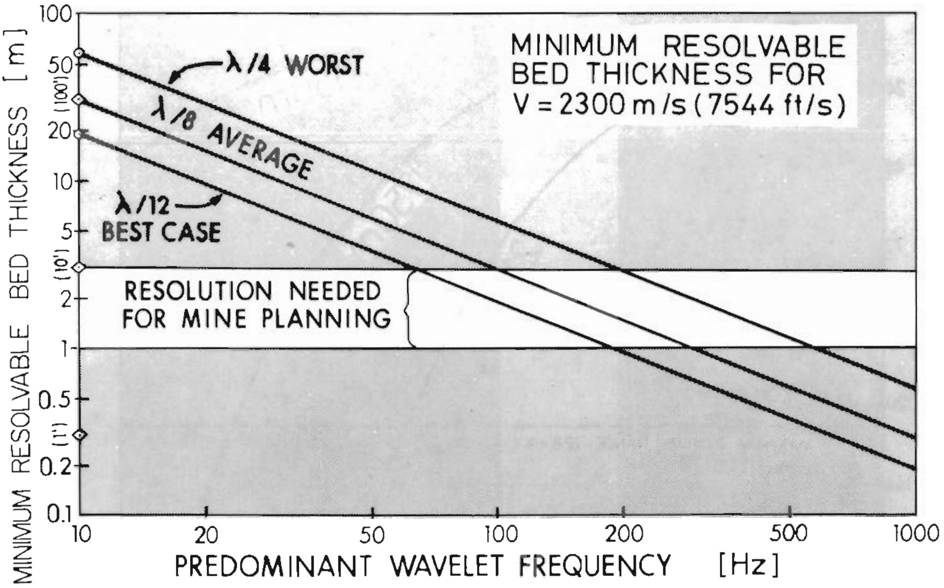

Figure 10. Minimum resolvable coal bed thickness as a function of predominant reflection frequency. Resolution needed for coal mine planning and high quality exploration studies is between 1 and 3 m. For the average one-eighth wavelength detectability criterion this means frequencies between 100 and 300 Hz are required.

As well as a better detectability and resolution, reflection "character" always improves as the upper frequency limit is raised. Resolution and character together determine the overall effectiveness of the seismic reflection method, particularly when used with bore hole logs and samples. Thus, for coal investigations the effectiveness and therefore the value of seismic profiling improves directly with increasing frequency.

SEISMIC SIGNAL ATTENUATION IN COAL SEQUENCES

It is known that the low seismic frequencies used in petroleum exploration are transmitted more easily or, conversely, are less attenuated by the earth than the high frequencies needed for effective coal investigations. A number of field and laboratory studies of wave energy losses in rocks have shown the signal attenuation (in dB per unit length) increases almost linearly with frequency. Thus the high frequency signals needed in coal exploration will be much weaker than the conventional reflection signals used in common profiling. In a given rock type the attenuation at each frequency is directly proportional to distance traveled, or depth of the reflecting bed. For an average constant conduction velocity rock the attenuation can be plotted as shown in Figure 11 where the high frequency losses are seen increasing with greater and greater depth.

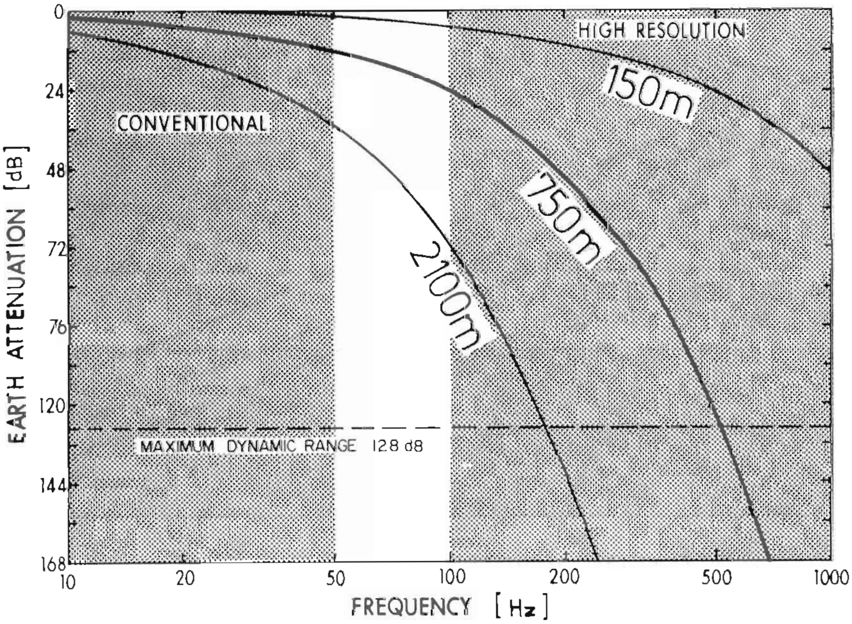

Figure 11. Earth attenuation as a function of frequency for an average geological section. It can be seen that as depth increases, attenuation reduces the signal levels to a point where dynamic range is exceeded, thereby eliminating higher frequency components in the reflection signals. V = 3050 m/s; $\alpha = 0.5$ dB/λ.

Existing seismic amplifiers, designed for the "conventional" frequencies, are limited in their dynamic range. Since the decay rates are much greater for high frequency signals, a much greater dynamic range is needed to adequately record signals in the high resolution 100 to 800 Hz band needed for coal exploration.

The typical coal province is not comprised of a single average rock type, but is a series of alternating layers, each with its own unique acoustical characteristics. Such parameters as grain size, porosity, permeability, as well as the elastic properties of the grain and pore materials, all affect the attenuation of seismic waves.

The seismic attenuation of different rocks has been measured by Hamilton [9] who has summarized the work of many earlier investigators along with his own measurements, as illustrated on Figure 12. Various sediment types, ranging from coarse sand through silt to clay are shown along the horizontal grain size axis, while attenuation is represented by the vertical height of the bars. The average attenuation value of 0.5 dB per wavelength, used for the curves on Figure 11, is also plotted. Attenuation values for coal were not measured by Hamilton in this study.

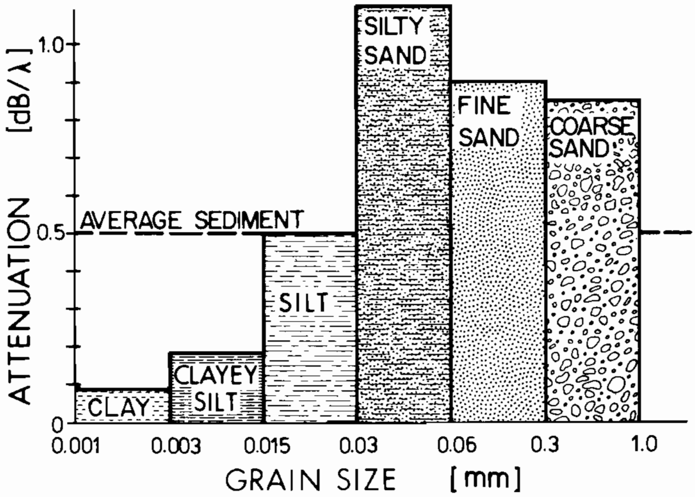

Figure 12. Attenuation as a function of sediment type from Hamilton's 1972 work on water saturated sediments. The 0.5 dB/λ average sediment attenuation value is shown. The seismic signal amplitude is halved every 5 wavelengths traveled in silty sand but it will travel 60 wavelengths or 12 times further in clay before reaching the same level.

Source: [9]

The attenuation increases more than 50% when the mean grain size in a sand decreases from a typical coarse sand to a very fine sand. After reaching a maximum of 1.2 dB per wavelength for very fine grain sand, the attenuation then decreases over 90% as the grain size further decreases from fine sand through sandy silt to clay. Stated another way, the seismic signal amplitude is halved every 5 wavelengths traveled in fine sand while it must travel roughly 12 times further, or 60 wavelengths in clay before dropping to the same level.

Within the near surface weathered layer, an exceptionally large attenuation of 13.1 dB per wavelength has been measured. This high attenuation means that only 25% of the 200 Hz signal will get through a typical 30 m weathering layer. This is approximately 100 times greater than the attenuation found in subweathering materials. Clearly, these high losses must be avoided wherever possible by locating both the seismic source and detectors beneath the near surface weathered layer in bore holes.

HOW IS A CONVENTIONAL SEISMIC REFLECTION SYSTEM MODIFIED FOR COAL USE?

The fine detail and resolution required in coal exploration and mine planning dictate field electronic system designs approximately 10 times more sensitive and higher in frequency response than "conventional" systems used for petroleum work.

The lowest usable frequency of 100 Hz is established by the average coal seam thickness of 2 to 3 m. Certainly resolution of at least 2 m must be achieved if the seismic system is to be useful in the majority of coal investigations. The upper frequency limit should be as high as possible since the finest possible detail is desired. However, factors such as seam depth, type of country rock, number of overlying coal seams, type of near surface soil material and a variety of other field conditions will limit the upper frequencies. The three octave bandwidth from 100 to 800 Hz is about the best response that can be achieved by a high resolution system in very good areas. This bandwidth produces a maximum resolution of 20 to 30 cm under extremely favorable low noise conditions. Under more typical field environments, one could expect upper frequencies of only 200 to 400 Hz and hence average resolutions of 1 m under most conditions.

The first field system modification involves redesign of the seismic wave detectors to compensate for earth attenuation before the signals reach the recording system. Conventional moving coil geophones used in petroleum exploration have a response that rises to peak at the resonant frequency and then remains relatively flat with increasing frequency beyond that point. This flat high frequency response means that the received signals from a given coal seam will very rapidly decay in accordance with an attenuation curve similar to one shown on Figure 11. On Figure 13, the 750 m curve from Figure 11 is reproduced to show the attenuation to one particular target.

Over the "conventional" 10 to 50 Hz band only a 6 dB difference is noted from the highest to lowest frequency. However, as the frequency increases, the signal amplitudes decay far more rapidly, increasing from 24 dB per octave between 100 and 200 Hz to 96 dB per octave in the region beyond 500 Hz. The ideal detector would have the "desired perfect inverse" on Figure 13 that exactly compensates for the "earth attenuation curve" producing reflection signals with a flat "perfect response". Actually, such an "ideal" detector response curve is not easily obtained and in reality is undesirable since, rather than the single "earth attenuation curve" shown on Figure 13, many different attenuation curves will be found from location to location, depending on the particular country rock type and on the depth to the target coal beds. Detectors with the "achievable detector response", shown in Figure 13, have a 42 dB per octave increase in amplitude with frequency and produce a reasonably uniform (within ±18 dB) amplitude input to the field recorder.

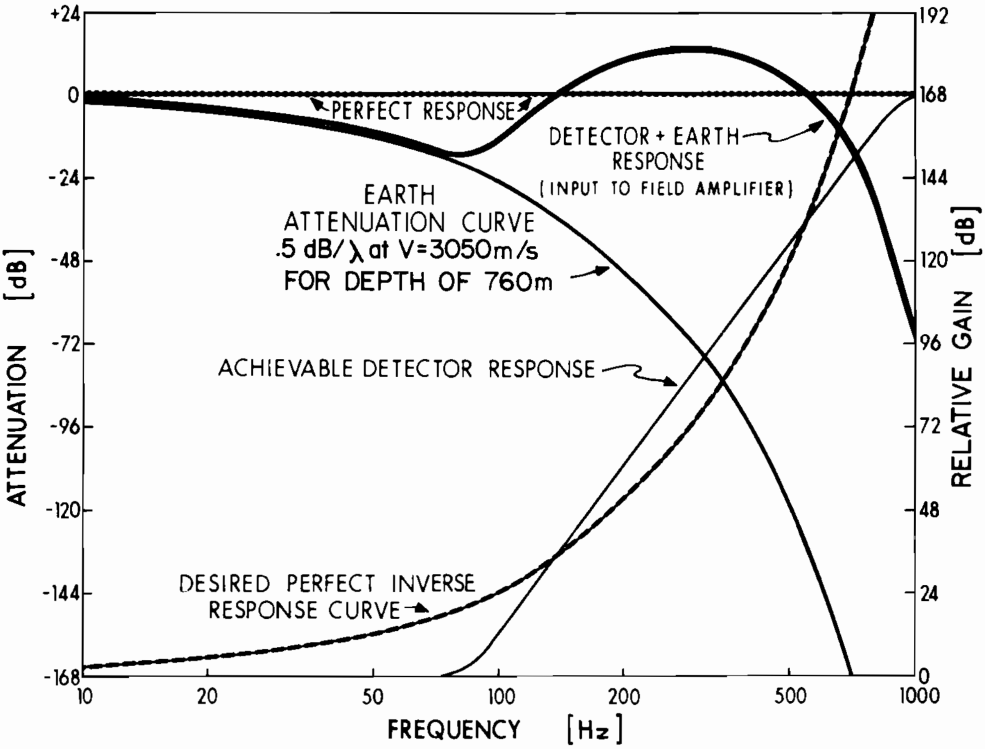

Figure 13. The single earth attenuation curve represents only one of many possible sediment types and depths. If a detector had the "desired perfect inverse response" the combined earth and detector response would be flat, as indicated by the dotted "perfect response" line. By using the "achievable detector" approximation up to 800 Hz, the overall earth-detector response remains within ±18 dB of the perfect flat response which is within the dynamic range capabilities of existing electronic equipment.

The particular high resolution detectors used in shallow coal exploration and mine development have an amplitude frequency characteristic that produces output signals with only slight variations across the critical 100 to 800 Hz band. The electrical signal produced by a typical flat response moving coil geophone used in petroleum work can drop more than one million times over the same range.

A typical tractor mounted small drill can put a hole down every few minutes. Deeper weathering depth, of course, slows down the drilling speed. Typically, 5 m hole spacing will be used with 0.25 ms digital sample rates for detailed coal exploitation or mine planning surveys to maximum depths of 800 to 1000 m. For deeper exploitation surveys, 10 m "spatial" and 0.5 ms "temporal" sampling has been found satisfactory. For basin reconnaissance and coal exploration surveys the sample spacing can be extended to whatever distance fits the economics involved. However, coarsening the sampling will invariably lower the precision of the survey and each investigation requires a balancing of survey cost per unit distance and the value of the data recorded.

A comparison of two different sample intervals on the identical line is shown in Figure 14. This line was first done at an economical 10 m spacing and then repeated a few days later with twice the sample rate to get improved resolution. At 5 m spacing the second line took twice as many holes, twice as many dynamite charges and generally cost just about twice as much as the first line, but achieved much greater detail in location of subsurface features. Figure 14 shows that the fine reflections from the angular pinchouts or, more precisely, acoustic discontinuities, are entirely missing on the coarsely sampled data.

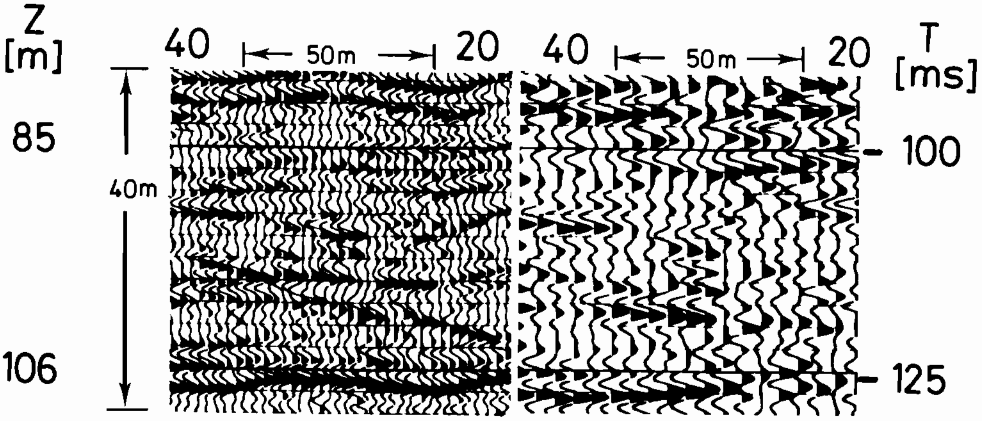

Figure 14. The increased resolution obtained when temporal and spatial sample rates are doubled. Note reflection periods of approximately 1 ms (1000 Hz) on data to left.

Fine partings within coal seams or small channels or faults can just as easily be missed if in the interest of economy a too coarse sample interval is employed. On every investigation a balance must be achieved between costs and detail or resolution needed.

The time sampling of 0.25 and 0.5 ms refers to the digital time sampling interval used in the field recording apparatus. The shorter this interval the higher the frequencies that can be recorded. A field recorder can be configured to work at 0.25, 0.5, or 1 ms sampling.

DIGITAL COMPUTER PROCESSING OF HIGH RESOLUTION SEISMIC DATA

Digital computer processing is essential to retain and enhance the weak high frequency seismic signals needed to see thin coal beds, small faults, roof rolls, and small channel sands on the cross section displays. To show the necessity of such processing, only one of many such computer correction procedures will be used as an illustrative example. This particular procedure corrects the reflection times for lateral changes in velocity along a given profile line. Such lateral velocity changes may be caused by varying geology, soil conditions, or water levels, among other factors. Changing rock properties cause the velocity and therefore the arrival times of the seismic reflections to vary, thereby masking the true subsurface structure if not corrected in the computer.

The bands seen on Figure 15 above the section are a cross sectional plot of equal velocity zones. The horizontal scale of the graph is approximately the same as the section shown below. Each band represents a velocity change of roughly 70 m/s ranging from the 1700 m/s at the top to 2100 m/s at the bottom. Velocity changes of 10 to 20% are seen laterally along the line. Without computer correction, the reflection times and thus the structural position of a given coal bed could be 20% too shallow or too deep.

On the right the low velocity trough coincides with the old river channel, as would be expected from a channel filled with the low velocity unconsolidated material. To the left a velocity anomaly is seen to be associated with the shallow fault zone which also is expected from the ground disturbances and water flow associated with this type faulting. These two geological features generally correspond to the right and left velocity changes but leave the largest anomaly in the center unexplained!

Regardless of the causes, such geologically related velocity anomalies must be identified and used for dynamic correction if essential high frequency components are to be retained. All electrical signal summation must be avoided unless all such corrections have been applied.

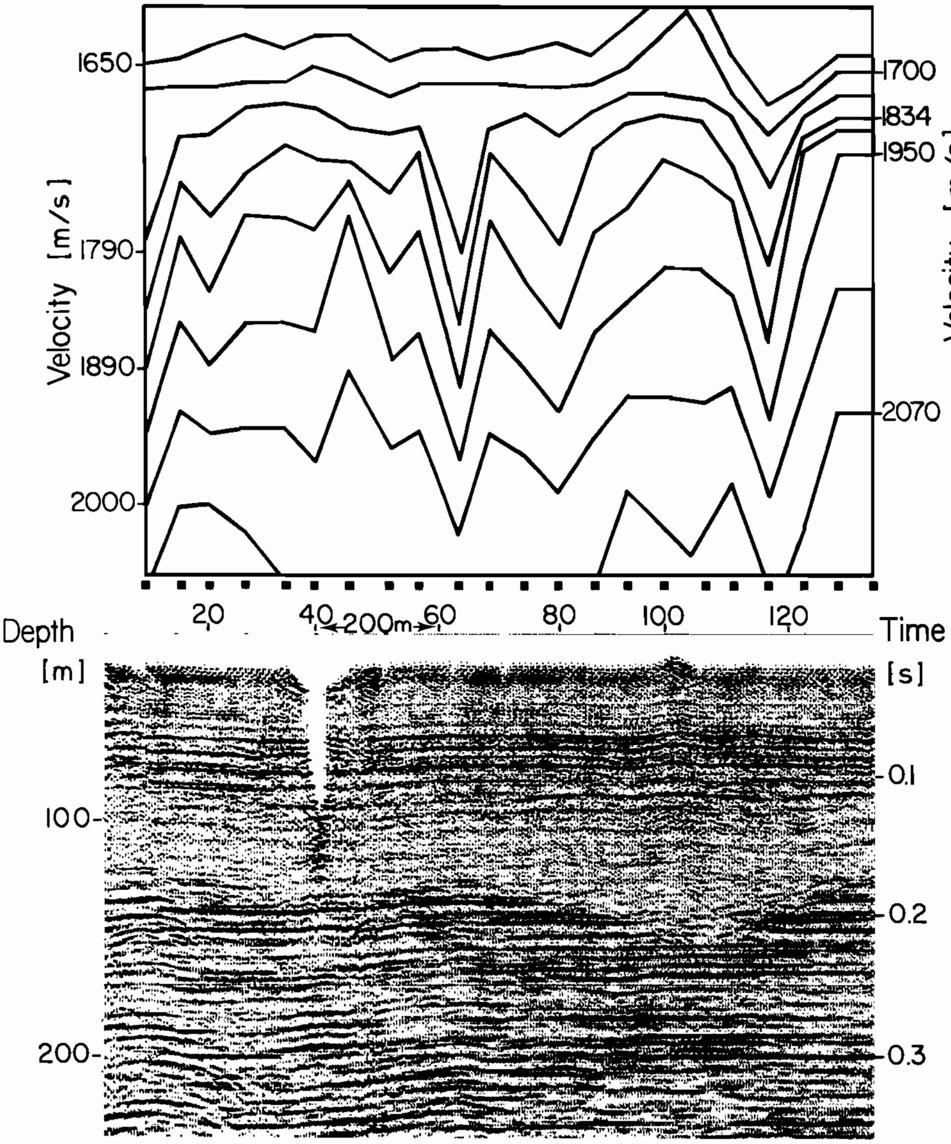

Figure 15. Constant velocity graph positioned over data from which it was derived. Horizontal scales are approximately the same for both graph and section. Note correspondence of low velocity anomalies and old river channel as well as near surface fault.

EXAMPLES OF HIGH RESOLUTION SEISMIC CROSS SECTIONS

A recent field example taken with the high resolution techniques developed is shown in Figure 16. This area was shot using the "coarse" 10 m sampling. Note that the small fault can be traced to within 50 m of the surface. A 5 m fault displacement is clearly seen, as are reflection wavelet periods of 3 to 4 ms, indicating predominant frequencies in the 200 to 300 Hz range which are about the highest anticipated when coarse sampling is employed.

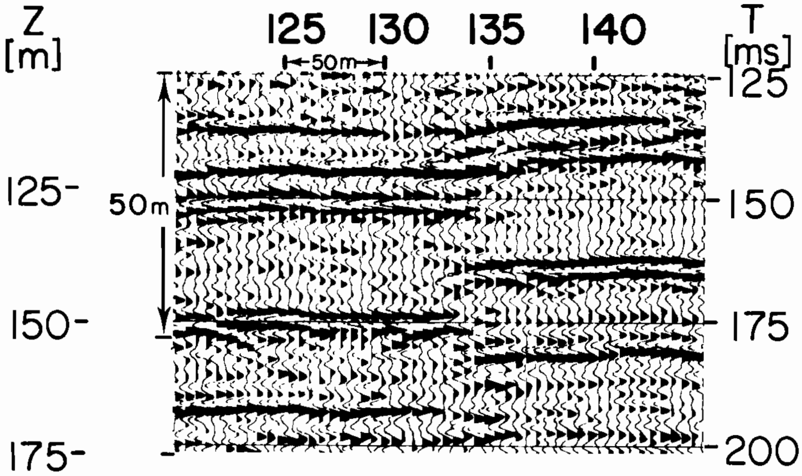

Figure 16. Enlarged portion of "coarsely" (1/2 ms, 10 m, 33 ft) sampled data. Note the easily identified 5 m fault displacement and the somewhat smaller bed thicknesses.

A second field example is from an area shot by using the finer 0.25 ms - 5 m sample intervals (see Figure 17). The fine reflections from small acoustic boundaries within the cross bedded depositional pattern can be seen: the fine sand shale interfaces or partings produce reflections that can be correlated over large distances. It is this type of fine geological detail that is the objective of the new high resolution seismic techniques. The horizontal timing lines on Figure 17 are 1.25 ms apart, which represent a vertical distance of 1 m at an average coal section velocity. Events are seen with periods close to that interval, showing frequencies of 700 to 800 Hz have been recorded and preserved in the computer stacking process.

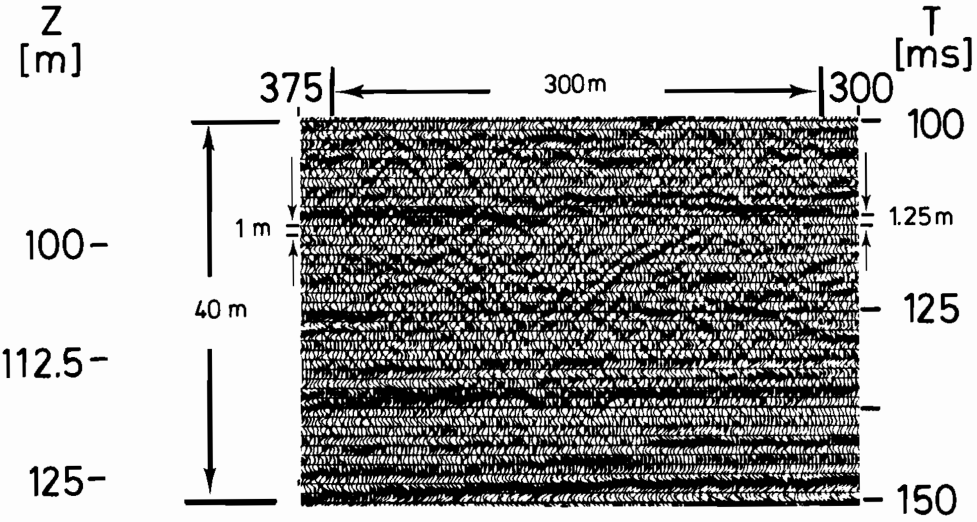

Figure 17. Example of high resolution data from the new techniques showing fine stratigraphic detail within individual beds. Temporal sampling is 1/4 ms while spatial sampling is 5 m, or 16-1/2 ft. Horizontal lines are approximately 1 m apart at typical coal section velocities.

EARTH LIMITATIONS ON ACHIEVABLE RESOLUTION

Figure 18 compares two coherence spectra graphs from two locations (SP 610-650) 200 m apart. At location point 650 the reflections have a broad box car spectrum with a sharp cutoff at 650 Hz. At shot point location 610 only 200 m along the line, the reflection pass band is seen to be abruptly narrowed to one third its previous width! This abrupt change is entirely due to changes in near surface soil conditions and well illustrates the limitation imposed by the earth itself on the upper frequency limit and thus the maximum achievable resolution.

Coal exploration and especially mine planning requires seismic waves with frequencies above 100 Hz. To typical coal seam depths the earth is transparent to these waves and the improved field equipment and procedures needed to record them are now available. Computer processing of this data can provide cross section displays that, when interpreted by a qualified coal geologist, can greatly improve coal exploration and mine planning. The highest usable frequency, and thus the maximum achievable resolution, will be limited by the near surface geology which will vary from location to location.

Although expensive when compared to other geophysical methods, seismic reflection profiling can be cost effective in a large number of coal areas when used in a combination drilling-shooting program. An overall cost saving can be realized since fewer deep core holes are needed when seismic profiling is employed. When compared to a typical coring program the very much greater information density obtained with short interval seismic profiling enhances the overall evaluation program. Admittedly, a seismic trace is not the full equivalent of a bore hole log, but it also costs a great deal less. Besides, can you imagine drilling bore holes every 2 to 5 m over the entire area to be mined!

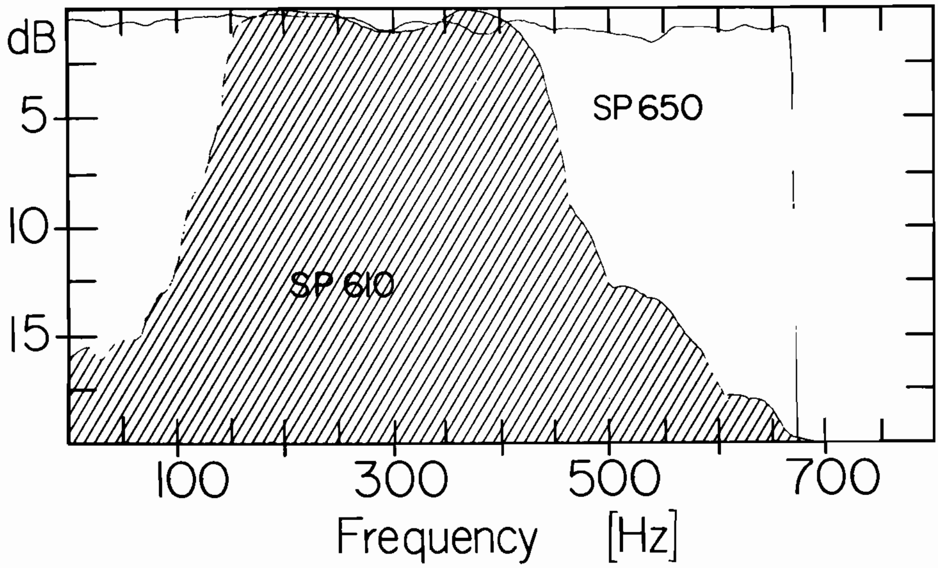

Figure 18. Comparison of coherence spectra between two shot point locations 200 m apart along one seismic profile. Severe narrowing of useful energy passband is due to localized near surface conditions.

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MINING TECHNOLOGY

TECHNOLOGICAL POSSIBILITIES AND SCIENTIFIC TASKS FOR MINING IN THE NEW CENTURY

I. Evans

INTRODUCTION

The present paper arose from a question posed by the Chairman of the UK National Coal Board (NCB), Sir Derek Ezra. In effect he said: "We know what we are aiming for at the moment in terms of our mining research effort, but mining will undoubtedly change. How will it change towards the end of the century or beyond? What new techniques or devices will be employed? If we can guess at them now then we ought to be instituting immediately the research that will bring them to fruition in due course". Sir Derek emphasized that he was thinking not of "evolutionary" but of "revolutionary" technologies, such as might be required to operate in order to exploit deeper or more remote coals, or in a social context that might not countenance any longer large bodies of men going underground.

Technological change can be forecast in terms of known knowledge, but technological revolution is quite unpredictable. A military scientist of the early middle ages would have concerned himself with improvements in armour, and quite missed the import of gunpowder. In the early 19th Century transport scientists would have forecast better roadways and more efficiently sprung carriages, and missed the railway. Later generations would have missed discoveries or inventions ranging in scale from the electron to the aeroplane. Every revolution is unforeseen except to a few sages who unfortunately, at the time, are hardly to be distinguished from those who make wild and improvident guesses. This thesis provides no comfort to those who look forward in mining. Reasonable extrapolations from a known base can again be made, but we must face the likelihood that the revolutions, if they are feasible, can in prospect be only too easily missed.

If there is anything new, then we are more likely to find it outside the coal industry. The new findings could at the moment be the academic curiosities in a field of research quite unrelated to coal mining. There is unfortunately no way of deliberately stimulating the brilliant inspiration that, owing nothing to rational thought, can still overtake the painstaking advances of logical development. But it was felt that by surveying other fields of endeavour, and consciously attempting to relate their developments to possible mining systems, novel techniques might be perceived that otherwise would never be noticed or at least long delayed.

Hence the team charged with this task, under the chairmanship of the author of the present paper decided to embark upon a survey of the new work in the scientific field. Facilities were sought to visit the major research establishments in both the public and the private sectors in the UK. These included such places as the National Physical Laboratory and the Royal Signals and Radar Establishment in the public sector, and firms involved in such diverse activities as chemicals, oil processing, electronics, mechanical engineering and constructional engineering in the private sector.

The immediate information obtained from the establishments was used as the raw material for writing the individual chapters in the report finally presented to the NCB. The main points in these chapters are summarized in the ensuing sections of the present paper.

COAL FOR FUTURE EXPLOITATION IN THE UK

Any method of working coal must be examined in the light of the reserves of coal that might be exploited by the particular method. One of the first tasks is therefore to obtain an estimate of reserves, and this is no easy task.

Within the limits of known coalfields the total amount of physically recoverable coal is a fixed quantity. The amount of this judged to constitute the coal reserves cannot be designated by a fixed figure. The amount considered available, and the workable part that might be mined is dependent upon changing economic factors, the major items of which are the demand for energy, the cost of extraction, and the cost of alternative fuels. Throughout this century, stated reserves have varied according to fluctuation in these factors.

In the UK "deep" mining is carried out at depths which are less than 1200 m. While this limit is to some extent an arbitrary one, it is one beyond which problems such as strata control and maintenance of an equable underground climate would become greatly exacerbated.

Shorn of detailed arguments, the forecasts for reserves of coal suitable for deep mining as just defined are as follows:

By 2000 AD, current mines that survive and projected new sinkings are likely to offer reserves of 45×10^9 t. At an output of 150 Mt/year these would suffice for 300 years. The average depth of extraction will increase at the rate of about 100 m per decade. The area of exploitation for individual mines will also increase, with all that that means in terms of technological, environmental, and other problems. Several hundred further years of reserves exist in as yet unexploited areas of the UK, offering about the same problems in mining. Several hundred more years exist in coal which is too deep for present methods of extraction.

These estimates do not include coal which is under the North Sea at distances which prevent it being accessible from land at the present time. North Sea coals are deep, ranging from 1000-3000 m below the bed of the sea. In view of the bountiful supply of coals under the mainland, undersea exploitation would have to be relatively easy to be economically competitive.

Thus the picture for mining in the new century is primarily for mineral extraction as at present under the mainland. We cannot preclude however a climate of public opinion arising that would not countenance men going underground any longer. In this event methods of in situ conversion of coal into gaseous or liquid reactants would have to be employed. If North Sea coals are ever to be exploited, the physical problems of access by men, and the remoteness of the epoch from the present day in which the exploitation is likely to be made, would seem to make highly unlikely the employment of other than in situ conversion methods.

MECHANICAL CUTTING

At the present time the bulk of coal extraction by the NCB, and indeed in the world as a whole is done by mechanical means, whereby a tool such as a cutting pick or a plough blade is used to break lumps of coal from the solid face. Much research has gone into the process, and now picks, pick arrays and cutting heads on machines can be designed with the expectation that the machine as a whole will be effective. One standpoint for gauging the effectiveness is the amount of power used: the lower the power for a given mass of material broken from the face, the more efficient the cutting, this precision being manifest in a number of ways such as least production of dust and least emission of methane.

Coal can be regarded as an engineering material having certain attributes of strength and elasticity. The minimum energy required to break it can be calculated from the corresponding data, and there is therefore a theoretical standard from which a practical process can be judged and to which it may attain as an ideal limiting value. The breakage of coal by the best mechanical means, e.g. by plough or shearers employing the tenets of recent research in blade type and disposition, is quite effective.

The point is that mechanical breakage, at its most effective, sets a certain standard of efficiency superior to that of other more indirect methods, e.g. where force is produced by the destruction of fluid momentum, as in hydraulic mining. There is therefore an incentive to promote mechanical breakage to its highest potential by developing suitably hard materials. At the moment tungsten carbide sintered in a cobalt matrix is the standard hard facing for cutting coal. It fails against the harder rocks in that it is too easily abraded or chipped. Various harder materials have been suggested from time to time, e.g. nitrides and borides, and we were told at the Fulmer Research Institute of benefits that can accrue to metal-cutting from their use. The snag is that the harder a material gets, the more brittle it is likely to become, and nitrides and borides tried experimentally in the rock-cutting role have always shown excessive chipping. Tungsten carbide is a remarkable material in that it combines a good level of abrasion resistance with good resistance to chipping, but on both counts "good" is not up to the level of the ideal, or nearly ideal requirement. NCB work at the moment is aimed at extracting as much extra duty from tungsten carbide as can be obtained, by care in specification and fabrication, the concept of "fracture toughness" being very relevant to the studies. Surface hardening by laser beam heat treatment is also relevant. This activity should go on while we endeavour to find, by encouragement to specialist laboratories such as Fulmer, a hard material that will supplant it.

Research into the best use of tools equipped with hard facings continues. The mechanics of pick behaviour in cutting coal are well enough understood, but there is still something to be learned in rock cutting. The Transport and Road Research Laboratory (TRRL) will pursue further their investigations into the efficiency of cutting by discs. This is thought by some, including the present author, to be inherently less efficient than pick cutting. TRRL do not subscribe to this view and will endeavour to use discs in an effective way.

Use of Explosives

Explosives are still used underground to a great extent as the only reliable means of breaking harder rock. The technique is mechanically efficient, explosives breaking about the same weight of material per unit of energy supplied as mechanical cutting. The drawbacks are the hazards, and the labour-intensive nature of the operations, which do not lend themselves to easy mechanization.

One must take note here of the potential of peaceful nuclear explosion (PNE). The Atomic Weapon Research Establishment has a unit devoted to PNE, and its leading scientist, Dr. K. Parker, has made a special study of its possible use in coal mining. The use of PNE for producing craters for, say, exposing measures for opencast exploitation is somewhat academic so far as mainland Britain is concerned. The most relevant use would be for measures below the bed of the North Sea. Dr. Parker points out that at depths below the sea bed greater than a calculable value the explosion will be contained and result in an enclosed hole. The coal measures in the vicinity would be broken up and possibly become more amenable to in-situ conversion. This will be discussed in more detail in the section on underground gasification and solvent extraction. There are many problems related to surface damage to structures, which may be caused by the explosion, and to radioactive contamination of the product. There could not be any application to processes where men would be required to have subsequent access to the working area.

Cutting by Pressurized Water

A technique of breaking coal and rock which has attracted increasing attention of recent years has been that of water jets. It has been the subject of two recent international symposia, and over 300 references are given in a bibliography compiled by the British Hydromechanics Research Association. A high velocity water jet suddenly arrested produces force by virtue of the destruction of momentum, and the approximate force can easily be calculated from the simple equations of hydraulics. It appears that the force may equal the compressive strength of coal and rocks, though the harder materials require such a high velocity that very great pressures need to be induced at the jet.

Coal is commonly found in the strength range of 5 to 35 MPa, and this does not pose a difficult problem for jet cutting. Hydraulic mining of coal has been tried in many countries and practiced successfully in some. In most cases the water pressure has been less than 35 MPa. In a sense the coal is "washed from the face" by these relatively low water pressures.

For cutting rock much higher pressures have been used, up to 1500 MPa. At such pressures the jets are almost needle-like in appearance, and the water issues at velocities of the order of thousands of feet per second. Under the impact of the jets, narrow slots can be cut in materials such as concrete and rock. The process is inefficient, the consumption of energy per unit mass of material removed being about ten times that for mechanical cutting. There are various environmental benefits, such as freedom from the sparking hazard associated with cutting picks, and, it has been suggested, lessened production of dust, though the last point is by no means proven.

Relatively small amounts of rock are removed in cutting narrow slots, and various ideas have been propounded for increasing the product. One is to remove the lands between the slots by mechanical breakage which is that much the easier because of the relief granted by the slots. Another idea derives from research by the Safety in Mines Research Establishment: it has been found that if the jets are pulsed instead of being continuous, large slabs of rock may come away from the face. The mechanics of this process, and the range of rock to which it is applicable, are not fully understood.

The incorporation of jets into a machine involve many problems, e.g. the dangers attendant upon the use of very high hydraulic pressures, the difficulty of providing traversing and rotating mechanisms, and the fragility of the jet nozzles themselves, exposed as they are a very short distance from the rock surface, and the erosion which they may suffer in consequence of the water pressures used. The development of a suitable machine would be a major step from the essentially laboratory devices which have so far been described, but a decade of development work would no doubt produce a usable device if it were needed.

Drilling

In the sense that drilling is a kind of cutting, much that has been said about possible developments in cutting apply to drilling as well.

It seems likely that future mining techniques will rely very much upon rapid and accurate drilling, whether for underground gasification or solvent extraction, or access to holes blown by nuclear explosives, or for prior degassing of strata for conventional mining. At the moment the real expertise in the subject seems to lie with the big oil companies and to have its centre in Texas and other oil-associated States of the USA. The prospects for new developments in drilling and their relation to coal mining should be urgently considered with a view to applying research and development effort to the most promising.

Mole and Telechiric Mining

The idea of having coal extraction carried out by mechanical moles instructed from the surface is a very seductive one, especially for relatively inaccessible coal, e.g. that under the North Sea. A number of schemes have been described by various authors. While they make fascinating reading as a form of science fiction they are almost worthless from the engineering point of view as they do not tackle rigorously the many scientific, engineering, and organizational problems. For example, they are apt to leave out of account such essential matters as support for the tunnels made by mechanical moles, the tractive forces required to haul cables, ducts, etc. behind them, and the maintenance of equipment that will be essential in a rigorous environment.

In the UK more attention is being given to a limited form of robotry for which the name "telechir" has been coined. The telechir is a robot device that carries out quasi-manual operations when instructed by a remote human operator, whose appreciation of the situation is brought to him by closed-circuit television. One telechir, when instructed by a succession of operators of different skills has the abilities of a veritable superman. Telechirs could take over the operation of something like a conventional long-wall face and carry it on without human intervention on the actual site. There are possibly jobs like routine maintenance to power loader and supports that could be done in this way, or manipulations under circumstances that would spell danger for human operators.

The NCB in the UK has commissioned a study of the possible evolutionary approach towards a "telechiric" technology.

METHODS OF IN SITU ENERGY EXTRACTION

Beyond the year 2000, as we have already seen, our coal reserves will be mainly in two categories:

- Seams of the kind now being worked by conventional mechanical means, but gradually getting deeper as the "best" (i.e. shallower) areas are extracted

- Seams below 1200 m in depth. There are extensive reserves of these under the mainland, and more under the North Sea.

The first category of coals can be won by known techniques, albeit with greater difficulty and more expense. The second category of coals will, apart from the problems of access, have existing difficulties exacerbated by high strata pressures and temperatures. For both categories, the time may come when it is unreasonable and uneconomic to expect men to work underground, and in situ extraction methods will have to be considered. This section considers the possibility of such methods.

Operations Involved

All operations would require access to the seam by accurately placed boreholes in order to supply extraction media and to remove the products. The extraction techniques that seem at the moment to be feasible can be divided into two categories:

- Those which produce a refined product, for example gas by underground coal gasification (UCG) or a clean liquid (by pyrolysis). The advantage of these techniques is that they bring to the surface a totally usable product; hence there are no problems associated with the disposal of waste materials.

- Those which produce coal or a modified coal material containing all the constituents, for example a digest of coal in a solvent oil. These techniques have the advantage of providing coal in a form that can be modified to suit market requirements, but the disadvantage of requiring surface installations for further treatment.

The various alternatives are now very briefly considered.

Underground Gasification

This is one of the few methods with some basis in proved technology on which research work is being carried out internationally. Field trials are going on, or being prepared, in the USA, Belgium, and West Germany, with the latter two specifically intended to investigate the problem of gasification at depth.

Pyrolysis

Basically this is a form of underground gasification where complete gasification reactions are not attempted and volatiles are driven off leaving a coke residue. Normally, this has been considered undesirable in underground gasification trials since tars get deposited in cracks and fissures in the coal, thus blocking the passage of gases. However, a test was carried out by Gulf Research in the USA with the object of producing higher hydrocarbons but the results are open to several interpretations.

Complete Combustion

Again a variant of gasification. It has been argued that instead of trying to halt the reactions involved at some intermediate stage, as with gasification, it would be simpler to allow them to go to completion. Inert combustion gases would then be produced and the sensible heat in them utilized. Laboratory experiments are currently being performed by the US Bureau of Mines, Pittsburgh. They have put this forward as a means of exploiting abandoned pillars.

Quenched Combustion

This is a technique employed in oil wells where an in situ oil deposit is fed with air and ignited, after which water is pumped in to pursue the flame front and generate steam.

Solvent Digestion

A number of processes for application to conventionally mined coal are being developed in the USA, the UK, and Europe based on the digestion of coal in a coal-derived oil, e.g. anthracene oil. In recent years interest has been shown in the application of this technique to in situ processing although no directly relevant work, even on the laboratory scale, is being carried out. Some of the possible processes involve hydrogen transfer to the coal by the addition of hydrogen gas or the use of a hydrogenated solvent oil, and it has been suggested that hydrogen could be produced by in situ gasification.

Aqueous Phase Liquefaction

This is an alternative liquefaction process in which high temperature water at or near its saturation temperature and synthesis gas would be circulated through the coal seam.

Supercritical Gas Extraction

This is a pyrolysis process in which removal of volatile matter is effected by a supercritical gas. The process is being developed for application on the surface but no plans exist for in situ development.

Chemical Comminution

A US patent exists on a process involving the use of materials such as ammonia and aqueous methanol which act as surface active agents and reduce interlayer forces at the natural interfaces present in coal and thereby cause the coal to fragment. The nature of the fragmentation apparently also assists in the subsequent separation of sulphur and other inorganic materials.

Microbiological Degradation

Coal, being an organic chemical, can conceivably provide a life support medium for a micro-organism. It is possible that in digesting coal some micro-organisms might produce a significant yield of low molecular weight degradation products. No micro-organism has yet been identified but apparently no detailed search has been made. The majority of micro-organisms are not affected by elevated pressure although most prefer temperatures less than 70 °C. It would be necessary to supply the organisms with nutrients--oxygen, potassium, calcium, etc.

Plans for a program of work on this subject have been put forward by the University of North Dakota. The Microbiological Research Establishment at Porton, UK considers that a potentially fruitful experimental survey could be undertaken for a relatively small financial outlay.

Problems Involved in In Situ Energy Extraction

It is beyond the scope of a short paper to discuss at all adequately the problems that might be met in in situ energy extraction. However some can be mentioned even if not taken at length:

- In many cases large numbers of deep holes would have to be bored accurately, speedily, and cheaply. Directional control would be required.
- In many methods, especially solvent techniques and biological decomposition, the coal seam would need to be highly fractured, as by the use of explosives or "hydrofraccing" techniques. The fractured bed should have a relatively uniform permeability where viscous liquids are used or produced. All problems are exacerbated with the high pressures at greater depths.

- Extraction whether by reactants, hydraulic, or mechanical means, would be taking place in distant unknown conditions. There will clearly be great problems of control of progress and direction of extraction. Improvements in the field of remote sensing are of great importance.

- Most of the chemical extraction methods would require the construction of a large infrastructure to provide the necessary reactants and to handle the products. In some cases, for instance at a site consuming in excess of 1 Mt of coal per annum by means of solvent digestion in anthracene oil, the requirement for extraction medium would exceed the present national production of the material.

- In terms of surface installations in situ methods would not necessarily be any more conspicuous than conventional mining. However, many of the processes would employ potentially hazardous materials, for example anthracene oil and ammonia, such that failure to contain the material, sometimes at high pressure, could have disastrous results. Therefore, such materials could only be used where the host rock is highly impermeable and away from aquifers. Also, explosive fracturing would have to be carefully employed to avoid major damage and permeation of the host rock.

Summary on In Situ Energy Extraction

The suggested methods range from underground gasification, with operational experience to back it, to some based on no more than laboratory experiments or even theoretical speculation. It is clear that much basic research and economic and technical analysis must be carried out to decide which methods are sufficiently attractive to warrant investment.

MECHANICS OF MINE WORKINGS

It has been mentioned that the average depth of workings will increase into the new century, and this will have implications on the problems of strata control, with the overburden stress in the vicinity of workings increasing in direct proportion to depth. While this will have implications in many ways, it will be particularly potent in relation to roadway stability. Even now, keeping roadways open and preventing excessive convergence in soft strata is a severe problem in the UK. In order to deal with the requirements of future workings an increasing understanding of the mechanics of mine workings will be called for, particularly the relationship between roadway convergence and strength and other characteristics of the surrounding rocks. Various means of strengthening weak strata will need to be developed. At present resin grouting is so costly that it can only be considered for specially important work. We look to the large chemical manufacturers to produce cheaper and even more efficient resins. The possibilities of high-pressure cement grout should also be explored.

We look forward to the total use underground of any dirt mined, this dirt being used in conjunction with cement to roadside packs by one of the various forms of "pump" packing now being perfected.

It is to be hoped that advances in concrete technology will bring about the introduction of concrete lagging, concrete beams, and concrete panels for roadway supports, replacing much of the steel and wood currently in use. Loose floor material will be stabilized with concrete or other binders to facilitate the use of free-steered vehicles.

THE ENVIRONMENT--REDUCTION AND MONITORING OF ENVIRONMENTAL HAZARDS

In Situ Extraction Methods

In conventional mining practice the underground environment is controlled primarily with the aim of maintaining safe, healthy, and comfortable conditions for men to work in. An essential feature of in situ methods of extraction would be that as far as possible men should not be required to work below ground. The underground environment would then be created to suit the extraction process; it would, in fact, be an essential and controlling feature of the process, and could not be considered apart from it.

Hence for each method of in situ extraction that is selected for further investigation the underground environment will have to be controlled and monitored as a unique requirement of that particular method.

Manned Underground Control Base

It might be necessary or desirable, for some in situ extraction systems, though probably not those operating at high pressures, to have a small number of men in underground control bases. These men would not be in intimate contact with the active zone of extraction, as is the present-day miner, and indeed the aim would be to isolate them as completely as possible from the potential dangers and pollution of the process they were controlling. On the other hand, consideration might have to be given to a wider range of hazards, in the form of, for example, high temperatures and chemical contamination from such processes as underground gasification, solvent extraction or chemical comminution.

The problem of providing a suitable environment for these men to work in would depend on the particular circumstances--the type of extraction process, the depth below the surface of the control base, access from the surface, etc. In the simplest case, something very like a conventional mine ventilation system might be both feasible and adequate. It would of course be on a much less massive scale than in a conventional mine, where the pollution that has to be diluted arises as a direct result of the mining activity--dust from the breaking and transport of mineral, heat from machinery and newly exposed strata, and firedamp from the relaxed strata around recent excavations. It would be reasonable to suppose that in the manned areas of an in situ extraction system, these forms of pollution would be much reduced. Thus, dust production should be negligible, heat emission from machinery low, and firedamp release from strata remote from the extraction area should be small. Where these considerations did not lead to acceptable conditions, then, rather than incur the expense of a high-volume ventilation system merely to dilute the pollution, it would probably be wiser to concentrate effort on suppressing dust at source, applying local refrigeration when and where needed, and undertaking a measure of firedamp drainage.

An alternative approach, at present being canvassed for use in conventional mining, is to recycle the ventilation air, i.e. to clean up the spent air and re-use it. Currently available techniques for removing dust, heat, and moisture from spent air are considered to be practicable for use with a recycling system for the ventilation air of a conventional longwall district, and would certainly be adequate for the underground control base. No means are yet available for removing firedamp from ventilation air, though possibilities exist for catalytic or microbial oxidation, as we have been informed by BP, ESSO and the Microbiological Research Establishment. These might well prove feasible for the relatively small volumes of air required to ventilate the control base. The alternative is to add sufficient fresh air to maintain an acceptably low concentration of firedamp. In this connection recent proposals (e.g. McQuaid, J, Paper to the 16th International Conference of Coal-Mine Safety Research, Washington DC, September 1975) for augmenting mine ventilation by the supply of compressed air through boreholes from the surface, may provide a convenient solution. This technique also offers the possibility of using the compressed air initially as a heat-free power source and, via an air-cycle cooler, as a convenient source of refrigeration.

Where particularly severe conditions were encountered it might prove necessary to isolate the control base from its surroundings by providing an air-conditioned enclosure. This would seem to be entirely practicable, because only a small number of men would be involved and, by its very nature, their work would not require from them either the physical effort or mobility of the present-day miner. In the limit, the problem might become one of providing a life-support system within a hostile environment, and here the techniques used in submarine or space-travel activities would have much to offer.

Travelling Roads

However safe and comfortable the men might be in their underground control base, it must be assumed that, if only for repair and maintenance work, they would be required at times to work away from it, otherwise the base would be better situated on the surface. They would also have to travel the underground roadways, for example when going on and off shift. Some form of conventional mine ventilation would therefore still be necessary.

For the simplest case, where a low-volume conventional ventilation system would be adequate for the control base, the same system would presumably suffice for the travelling roads as well. Where the environmental pollution was greater, the main problem would probably be in controlling firedamp concentrations. Then, in addition to using conventional forms of firedamp drainage, it would also be worth considering predrainage of the strata near the proposed manned areas, using surface (or underground) boreholes, stimulated by hydrofracture or microbial digestion of methane in the seam (Department of Industry Moscow Newsletter No. 2, December 1974). If these methods proved to be inadequate, consideration might be given to a method, proposed some years ago in the USA, for operating an entire new mine at a pressure of 2 bar. It depended on the fact that if the extra pressure were achieved by the addition of inert gases then men and machinery could work in complete safety, because no concentration of methane could form an explosive mixture in such an atmosphere. While the problems of applying such a technique to a mine producing by conventional methods would be formidable, the complete absence of coal transport, and the minimal amount of materials and personnel transport in the manned areas of an in situ extraction system might well make them relatively easy to solve.

The high temperatures encountered, for example, at great depth (strata temperature at 1200 m is about 50 °C) would be dealt with not by widespread refrigeration, which would be too wasteful and expensive, but by personal protection. Air-cooled suits, supplied with cooled air through an umbilical hose, would enable men to work away from the control base, and air-conditioned man-riding vehicles would provide mobility.

Monitoring

For the in situ extraction process itself, monitoring of the ambient conditions in the extraction zone would be an essential part of the control of the process, and each particular process would have its own special requirements to be catered for when the process was being planned and developed.

For the manned areas, environmental monitoring would be more important than for conventional mining, if only because there would be far fewer men present in the roadways to take note of any incipient dangers. It is also unlikely that there could be such detailed inspections as are provided by the present-day deputy. Today's methods of environmental monitoring - by the tube-bundle system or by fixed-point sensors sited in the airways - could provide a general surveillance, giving early alerts rather than last-minute alarms. Better sensors incorporating microprocessors and improved data transmission and computer systems would steadily improve the protection.

However, these continuous but fixed-point monitors do not replace the mobile detector in the hands of the deputy. Ideally a detector is required which scans a large area of roadway and senses the presence of a hazard, even though perhaps not its magnitude. While such devices are not yet available, it appears to be quite feasible to use, say, an infrared laser tuned to the absorption frequency for methane to detect the presence of this gas over a large area. Used in the manner of radar, the detector would indicate the presence of an accumulation of methane in a corner by the absence of a reflection from that direction. Alternatively the laser beam could be guided by reflectors around long stretches of roadway, perhaps near roof level, so that the detector at the far end would register a loss of signal if a roof layer should form at any point on the route.

The purpose of a monitoring system is to provide information for action. Currently the monitored information, processed and analysed, produces messages for various levels of management to act on. Eventually as the extent and reliability of data collection improves, and the significance of the analysed data is better appreciated, a degree of automatic control of the environment will be introduced. This is certainly the objective that should be aimed at in the monitoring of the manned areas of in situ extraction, where the absence of the complexities of the extraction process itself should simplify automatic control as compared to that required for conventional mining. It also offers the possibility of constantly adjusting the controls in order to avoid excessive ventilation during periods of low pollution. While human intervention will always be required at some time in a monitoring and control system, the aim must be to let the computer make the complex, but logical decisions, while keeping management informed so that the unforeseen can be quickly recognized and dealt with manually as an exception.

AUTOMATION AND REMOTE CONTROL

In the series of visits to research establishments, those to electronics manufacturers were among the most interesting and most impressive. A remarkable range of solid-state sensors and other devices is emerging from the laboratories, and the pace will accelerate during the next decades. These devices are very relevant to the control and automation of industrial processes.

The automating of an operating process may conveniently be described as the addition of three elements to the basic operating system: a sensing system to gather data on machine performance and process status, a data processing system to process the sensed data in such a way as to operate the control loop and finally an information system to present the process manager with any information he requires. This last element will be discussed in the section on communications and so we will concentrate here on advances in the first two elements.

Sensing Systems

Advances in devices that by their very nature are somewhat novel are difficult to predict with any degree of certainty. However, some general trends and possible applications will be presented here.

Systems for sensing data from a particular environment may do so either passively by detecting an influence originating within the environment, or actively by detecting the interaction of the environment on a radiation originating within the sensing system. Great progress is anticipated in both types of system. Aspects of the environment previously only crudely sensed, if at all, will be routinely detected with great precision by much more sensitive and sophisticated detecting systems. The production of radiations previously requiring unwieldy and expensive apparatus will in many cases be accomplished by compact, rugged and relatively cheap transmitters thus enabling the use of active systems previously considered impractical.

Electromagnetic Systems

At present the promising fields for major progress in this area are in the microwave and infrared regions.

The production of useful powers of microwave radiation from compact solid-state devices is being actively pursued (e.g. by RSRE, GEC, Philips-Mullard). It is expected that relatively cheap, rugged, compact, completely solid-state high resolution radar systems will soon be available. They need have no moving parts - the beam being electronically steered and shaped and will be capable of operating in regions of high interference - the signal being highly coded to allow its detection in the presence of very much more intense "noise".

Infrared imagers giving high resolution thermal maps of the environment with sensitivities of 0.1 °C are already under consideration by the NCB. As these become cheaper and as point and single line systems become available their use for heating detection, machine monitoring, man finding, temperature control, etc. may very well increase. The advent of tunable infrared lasers in a relatively cheap industrial form would allow the sensitive monitoring of a whole variety of atmospheric constituents either as process products or for standard atmospheric control. The use of infrared lasers and detectors as alignment and guidance tools could offer distinct advantages over visible light, i.e. greater penetration and eye safety.

Ultrasonic Systems

Considerable progress is being made in ultrasonic imaging and ranging systems. These have the advantage of providing resolutions much closer to those of visible and infrared radiations than to the relatively crude resolutions of even high resolution radar, and yet are able to propagate through environments impenetrable to light. This may be useful in certain in situ mining situations.

Nuclear Systems

In nuclear detectors a major advance that can be looked forward to is the development of a high resolution semiconductor gamma detector rugged enough to operate in severe industrial conditions. This would, among other applications, enable high resolution neutron-gamma systems to be used for automatic chemical element analysis in, say, coal preparation, open-hole exploration, mineral identification in transport and storage, etc.

"Processed" Sensing Systems

In the above discussion we have presented some of the major trends in sensing in the future. Detailed analysis of the whole gamut of sensing devices is impractical here and would, of necessity be incomplete and very soon out of date. However, one advance that probably deserves consideration across the whole field may be termed that of "processed" sensing, that is the use of sensors in which the sensed data itself can only be extracted by the use of considerable processing, involving previously stored data and information from other sensors.

With the advent of increasing amounts of data processing available in ever cheaper and smaller units, it will become increasingly unnecessary to find "clean" sensors, i.e. sensors that sense individual variables directly and are acceptably insensitive to interfering variables, e.g. a CO sensor acceptably insensitive to H_2, CH_4, etc. and to fluctuations in temperature and humidity. "Dirty" sensors, i.e. sensors susceptible to a variety of interference, can be used provided the effect of these interferences can be allowed for by sophisticated data processing of these and other sensor outputs. Even a sensor whose output deteriorates with age could be used provided the ageing characteristics are incorporated into the data processor. The implications for the criteria to be placed on a good sensor are that specivity ("cleanness") becomes less important and reliability, lifetime, cost, etc. become the main qualities.

Computer Development

Computer hardware and systems development is one of the fastest moving areas of technology. The development of first the transistor and then integrated circuit techniques have reduced a room full of equipment ten years ago to a single rack mounted unit today and this will itself be reduced to a single integrated circuit in ten years time. Price and power consumption have fallen in similar manner and it can be expected that central processor and memory costs will fall by one to two orders of magnitude by the year 2000. This will enable systems of very large size (by today's standards) to be used both on the surface and underground. The only significant limitation on the development and exploitation of computer systems will be the cost and manpower requirement for the software development (i.e. system specification and programming).

Overall Systems

The individual components of automatic systems have been considered. The overall level of automation that may be achieved by the year 2000 will now be assessed.

The current mining process requires the extensive use of man's powerful intellect and eyesight. It appears that all routine tasks of coal cutting, clearance, processing and the establishment of new drivings and roof supporting could be carried out automatically. However, the performance of the system under abnormal conditions, e.g. roof falls and maintenance, would require either the presence of men or the use of sophisticated (robot-like) machines under the direct control of men (either locally or from the surface). The reason for the manual intervention is that the development of computer-controlled machines that could cope with all the conditions that could be encountered in the mine is unlikely to occur in the foreseeable future.

The difficulty in completely automating the current mine is that the control problem is too complex for solution. A detailed system analysis of the mining process is required and from this a computer simulation developed. On this simulation various automatic models could be evaluated to establish the validity of each method. It is possible that from this technique a radical change of approach could be devised that would reduce the number of variables in the system to a level where the advances in sensor and computer development would make manless mining feasible.

COMMUNICATIONS

From the research and development that is now taking place, it is possible to extrapolate what form the mine communications system may take in 25 years time.

It is possible that the control of the mining operation will be concentrated on the surface, for overall control, and at face control stations for local control. These stations will be linked by a wide band communications system (probably optical fibre but possibly coaxial cable). They will have high quality telephone connections with each other and mobile working parties, transport, and other less important fixed locations. They will have closed circuit television monitoring of virtually all working areas of the mine. Computer-driven displays of monitored information and interactive information system facilities will supplement the TV information. Away from the control centres, telephone stations accompanied by simple intrinsically safe (IS) keyboard/ displays will enable similar facilities to be available excluding TV displays. For individuals moving around the mine the use of the leaky feeder radio system will give telephone facilities (probably helmet-mounted) and to relevant officials and maintenance engineers, data gathering and display facilities in a handheld (pocket calculator type) unit.

To enable this type of system to come into existence it is necessary to exploit to the full the general research effort being carried out by the communications industry. Particular areas that will need attention are the handling of wide band links, especially the handling and jointing of optical fibre systems and the development of intrinsically safe (IS) driver and receivers for the links, IS system control computers, IS solid-state cameras and IS and flameproof displays. The development of small, light, portable equipment for use by mobile personnel is required.

Over the period of the next 25 years it will be possible to improve communications to a level approaching the ideal with high quality telephones accompanied by television and computer controlled monitoring and information systems. This ability to have accurate information on the mining operation available to each level of management, at the physical point where it is required, will in itself lead to far more effective control of the mining operation.

CONCLUSIONS

The team that wrote the appreciations of future mining summarized in this paper submitted a number of conclusions to the NCB. These made suggestions for the areas in which future research should be carried out.

The conclusions are of two kinds, strategic and tactical. The "strategic" conclusions are broadly based and fundamental to all consequent considerations. The "tactical" conclusions are limited in scope within a strategic appreciation.

Strategic Recommendations

- The various methods of in situ energy extraction should be assessed by a team competent to cover all the relevant aspects of science, technology, and economics. It should refine the list to two or three possibilities, determine the preparatory work to be done, and phase it in relation to the overall plans of the coal industry.

- A similar degree of attention should oversee developments in drilling, since rapid and accurate access to workings will be vital to all types of mining, whether for mineral extraction or for in situ energy conversion.

Tactical Recommendations

The following set is not considered to be exhaustive, but would, among others, merit research attention:

- Coal conversion by microbiological attack;
- The mechanics of "hydrofraccing";
- Improved hard materials for cutting rock;
- Hydraulic devices for cutting rock;
- Development of telechiric devices;
- New appreciations of strata mechanics, with particular reference to roadway stability;
- New materials for bonding and stabilizing strata;
- Ventilation of workings remote from shaft, e.g. by boreholes delivering compressed air;
- Versatile refrigeration systems;
- Life-support systems for isolated men;
- Involvement of new developments in signal processing in monitoring, control, and automation;
- Data transmission systems, particularly fibre optics;
- Computer technology applied to all coal extraction and energy conversion processes;
- Selective flocculation of coal and shale;
- Reduction of sulphur in coal by chemical, biological, or other means.

The deliberations of the research team on this subject and the visits made by them to research laboratories did not uncover any completely new or unexpected technique to radically change mining. Many interesting things were seen however, and much is already being involved in the evolutionary approach to mining, e.g. the involvement of latest instrumentation in plans for automation.

ACKNOWLEDGEMENT

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PROGRESS IN COAL MINING TECHNOLOGY IN THE USSR

A.V. Dokukin

The coal mining industry of the USSR plays a major role in the national economy and determines the energy potential of the country and its metallurgical basis. The USSR leads the world in coal reserves and scope of coal mining. About 730 Mt will have been produced in 1977, while in 1980 production will exceed 800 Mt. To achieve this target, the collieries and open-pit mines are being technically re-equipped on a wide scale, using few-operations technology and complex mechanization and automation of production processes.

The Academy of Sciences of the USSR, the Skochinsky Institute of Mining, and other organizations focus their attention on research efforts generated by the scientific and industrial potential of the USSR. Thus, coal as a chemical carrier of energy will retain its value beyond the current century.

Analysis of research in the field of physical and chemical conversion of the solid substance, coupled with forecasts, indicates that the coal mining technology based on changing its aggregate state in situ by plasticization and liquefaction will have little practical application before 2000. There might be some application for underground gasification of coal when mining rather faulted and substandard deposits, for use in gas turbines of high efficiency. Research is continuing, but until the end of the century the production of coal and its use in power engineering and metallurgy will remain traditional. Meanwhile mining systems will continue to be modified through complex mechanization and automation of production processes while conserving the natural aggregate state of coal and simultaneously recovering valuable accompanying minerals.

The most important trend in USSR coal mining is the fast growth of the open-pit method, which is the most suitable for complex mining of resources and which provides higher technical and economic indices and more favorable labor conditions than underground mining. That is why in 1980 about 280 Mt coal will be produced by open-pit mining--over 35% of total production, as against 31% in 1975. Open-pit coal production will be accelerated in accordance with the directives of the Fifteenth Congress of the Communist Party of the Soviet Union.

New coal deposits with favorable working conditions will also be developed, beginning with those most suitable for open-pit mining. They include the Kuznetsk, Kansk-Achinsk, Ekibastuz, and South

Yakutsk coal basins whose thick coal seams and small stripping ratio allow the construction of opencast mines with an annual production of 10 to 50 Mt of coal. Coal from these deposits is competitive with gas and oil and is of great importance to the national economy.

With an annual production of 50 to 60 Mt of cheap coals from the Kansk-Achinsk and Ekibastuz basins, it is proposed to construct energy supply systems having no analogue anywhere, with an output of 65 to 75 × 10^6 kWh, near the opencast mines.

The greater part of open-pit coal production will be concentrated within these areas by 1990, using powerful excavation machinery and in-line and continuous-cyclic technology. The main directions of technical progress in open-pit coal mining are the following:

- Wider use of continuous technology with continuous-action machinery such as bucket wheel excavators with an output of 5000 to 12,500 m^3/h (Figure 1), which makes it possible to obtain the required coal grade, high efficiency of production, and year-round excavation of seams without resorting to explosives;
- An increase in transportless mining with powerful shovels with extended boom and a bucket capacity of 100 to 120 m^3;
- Application of the continuous-cyclic technology while stripping the hard overburden rocks with quarry excavators, mobile crushers, conveyor, and combined transport;
- Use of mining and transport equipment of great power and capacity, and hence high concentration of production;
- Increased application of recultivation technology for the soil disturbed by mining operations, using continuous hydraulic transport for building up a layer of fertile soil that corresponds to agricultural requirements and can serve for foresting;
- Complex mechanization and automation of technological processes for stripping, mining, and soil recultivation.

In order to achieve the coal production target, to change over to a more progressive technology, and to raise the technical level of open-pit mining, the research and development organizations are trying to create draglines with an annual capacity of 20 to 30 × 10^6 m^3, quarry excavators with a bucket capacity of 20 to 30 m^3, locomotives, coal carriers, crushers, and conveyers. A

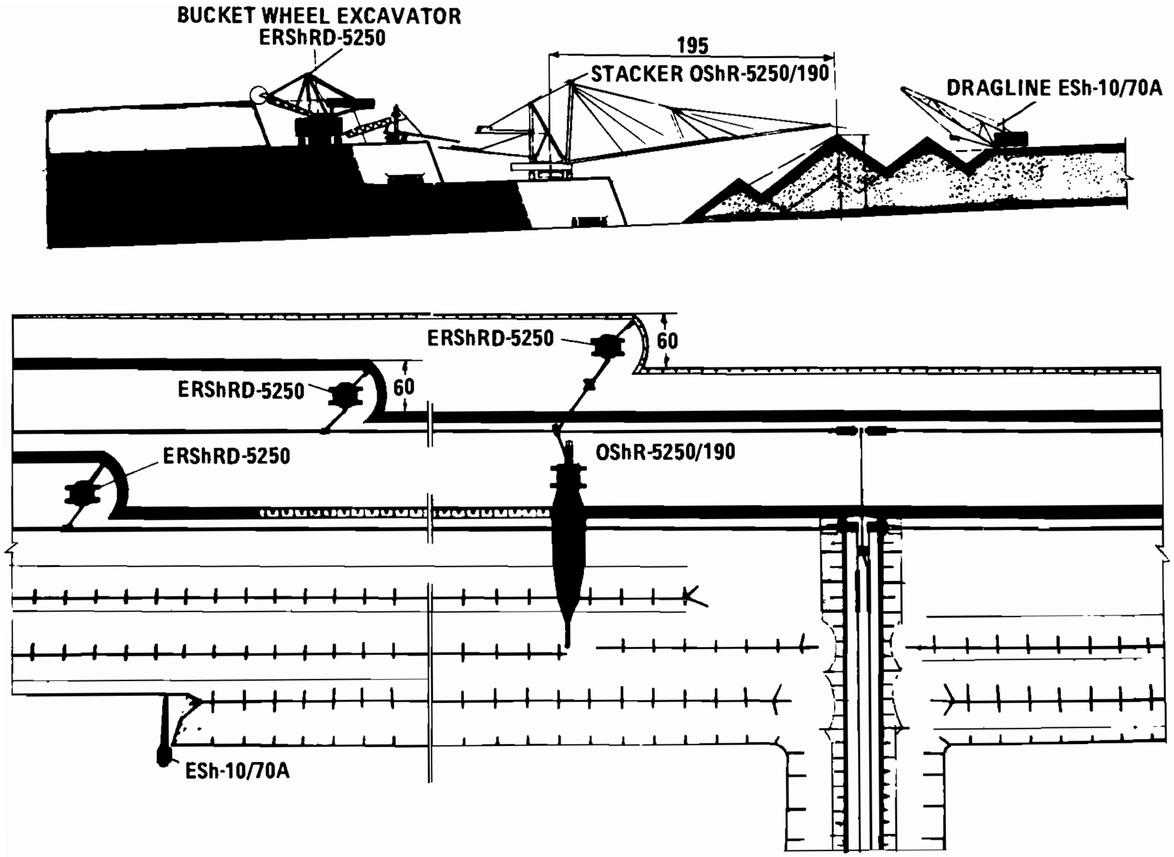


Figure 1. The continuous technology of mining thick coal seams with bucket wheel excavators and stackers.

powerful walking excavator (ESh-100/100) with an annual capacity of 16 × 10^6 m^3 is in operation at the Nazarovsky opencast mine in the Kansk-Achinsk basin. The Bogatyr opencast mine in Ekibastuz has a bucket wheel excavator (ERShRD-5000) with an annual capacity of 15 × 10^6 m^3, while at the Safronovsky opencast mine an excavator with a bucket capacity of 35 m^3, a boom length of 65 m, and an annual productivity of over 6 × 10^6 m^3, has been in operation for over 15 years.

Transportless technology will allow stripping and mining operations to be carried out in turn by the same excavator of great capacity with an extended boom. Thus, draglines with a bucket capacity of 15 m^3 and a boom 70 m long, as well as those with a bucket capacity of 100 m^3 and a boom 106 m long, placed on the open-pit bank, are capable of mining coal deposits down to 100 m. Transportless coal production is possible also using shovels with a bucket capacity of 35 m^3 and a boom 65 m long placed on a bench. These techniques are used for mining operations in the Cheremkhovo coal basin. There the productivity of an opencast miner has reached 1000 t per month. Transportless mining with walking draglines and rehandling of overburden rock into the excavated space (Figure 2) is the most common.

Introduction of an intermediate loading of overburden rock on the open-pit bank makes efficient removal of the rock possible. Such a technique reduces the volume of stripping by steepening the working bank slope of the opencast mine while considerably reducing the capital expenses.

The continuous-cyclic technology combining the operation of shovels with continuous-action transport is used for mining coal deposits with hard rock overburden where bucket wheel excavators cannot be used. For example, at the Beryozovsk opencast mine of the Kansk-Achinsk basin an EKG-20 shovel with a bucket capacity of 20 m^3 and a stacker with an output of 5000 m^3/h operate simultaneously. The overburden rock is transported to spoil banks by the shortest distance.

Extending the boom of a stacker up to 190 m considerably widens the field of application of continuous-cyclic technology, the excavated space being used as a spoil bank with selective soil recultivation.

The continuous-cyclic technology will be extensively used at the Kuzbass coal deposits, with shovels with a bucket capacity of 8 to 12 m^3, self-propelled crushers, and conveyor transport.

Where the stripping ratio is great, we resort to combined systems of mining: the lower overburden benches are developed with draglines and bucket wheel excavators with direct transport of overburden rock into the space excavated, while the upper benches are removed with a quarry excavator and the rock is carried away by self-propelled wheel vehicles.

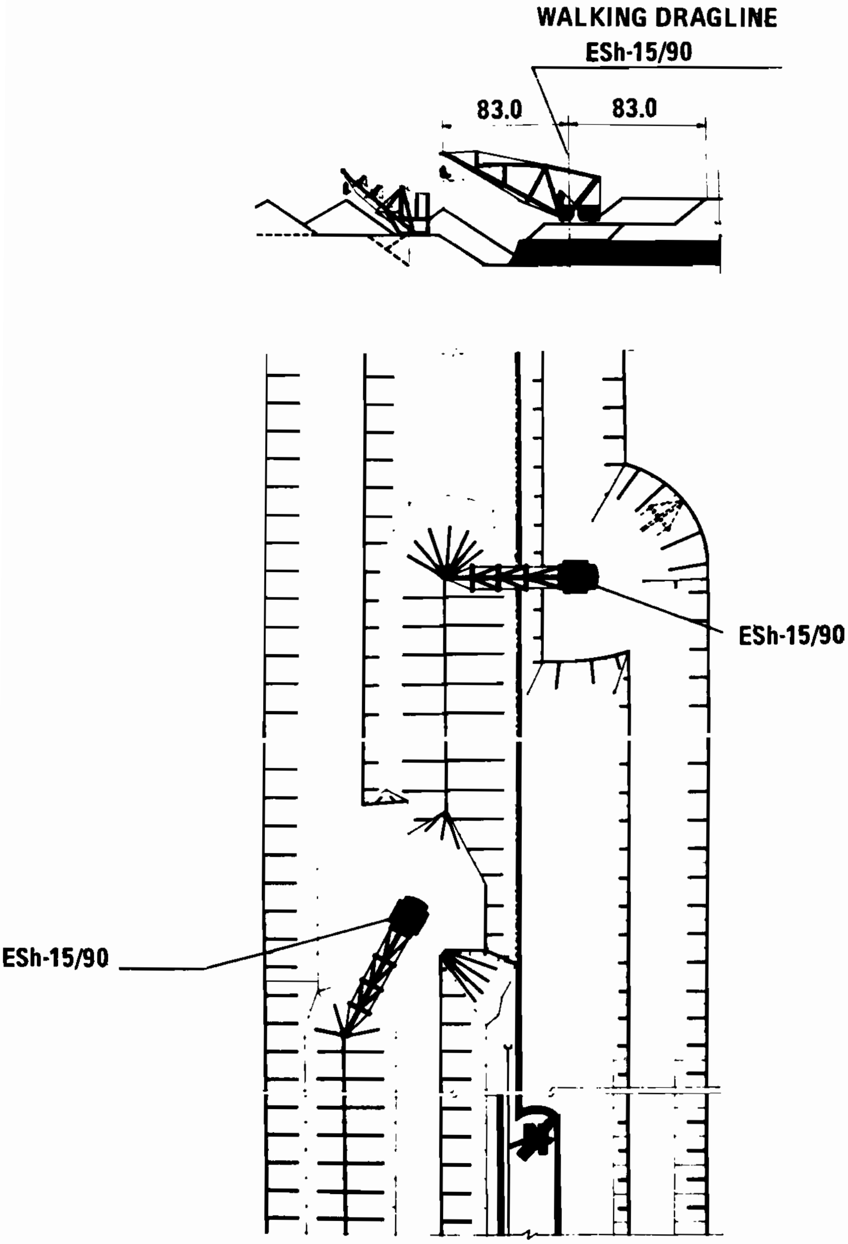


Figure 2. The transportless technology of mining with walking draglines.

The continuous technology based on bucket wheel excavators of high capacity must be used for rock of average hardness. This requires the development of machines with a higher cutting force, i.e. up to 20 to 23 kgf/cm^2. The conversion of excavators to hydroelectric drive with high-torque hydromotors built into the bucket wheel is rather promising.

When the continuous technology is used for hard enclosing rock, powerful shovels are used, combined with small mobile quarry vibro-crushers, conveyor transport, and continuous-action stackers.

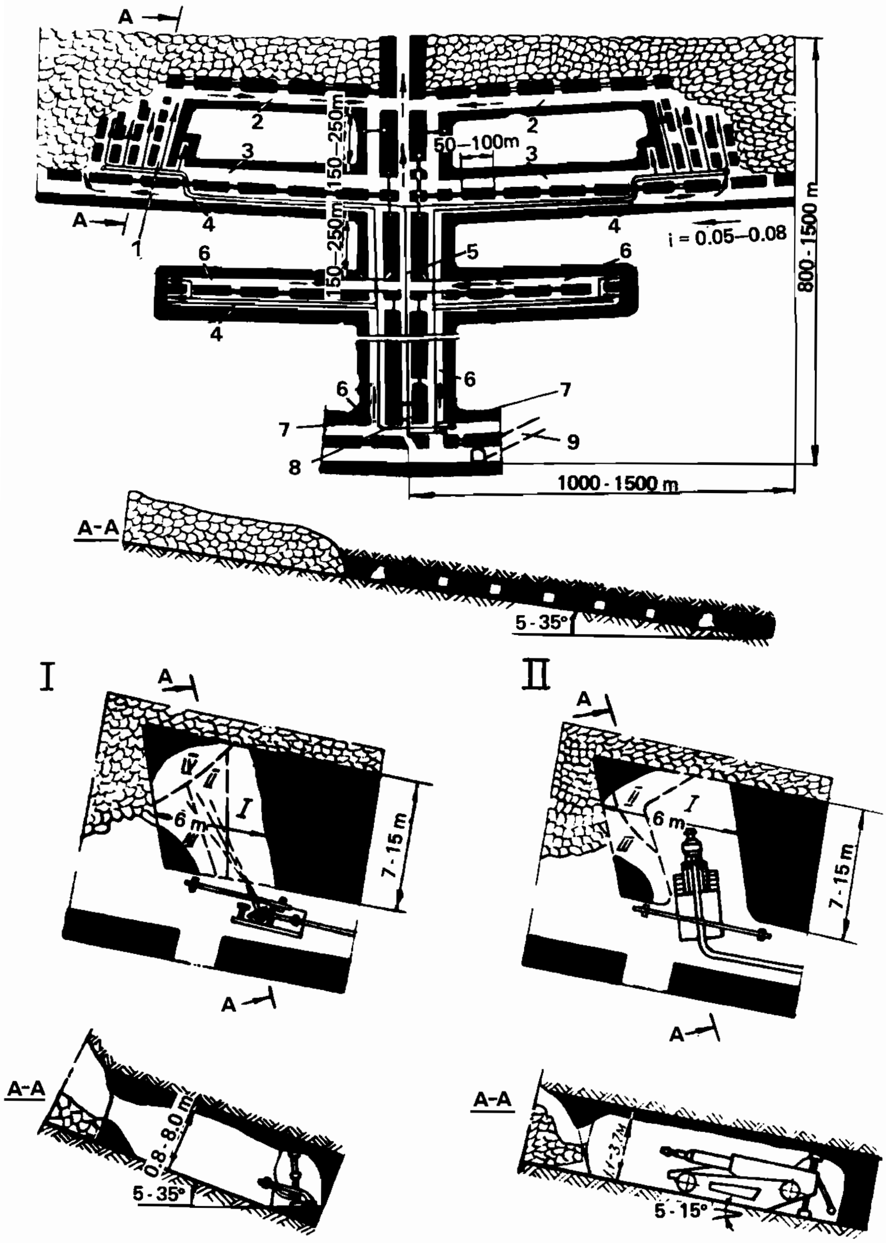
To mine a series of coal seams some of which are thin, we shall use augers or mechanized complexes which provide for a higher ratio of coal recovery, lower ash content, and selective mining.

The complex technical problems of underground coal mining are also dealt with in the coal industry. Coal production in collieries will exceed 510 Mt in 1980--an 8% growth over 1975. The techniques of coal mining will change with seam thickness, and the percentage of coal production from thin and gassy seams will increase.

Analysis of the events that take place in the rock massif during mining operations has made it possible to outline a few-operations technology of mining by mechanical and hydraulic means, as well as methods of minimizing or localizing the harmful influence of gas, high temperature, rock pressure, and stress condition of rocks, and thus reducing coal losses underground. Fields of application and optimum parameters have been established for the following: complex mechanization and automation of coal mining processes with roof caving and goaf stowing while mining steep thick seams and seams under towns, water reservoirs, railroads, etc.; hydraulic mining of coal seams in complicated geological conditions (Figure 3); preliminary mining of protected seams as a means of preventing sudden coal and gas outbursts where mining seams are liable to outbursts; the technique of mining thick seams by inclined layers while using mechanized complexes in each layer (Figure 4); augering of thin slightly inclined seams, and drilling off and coal discharge in steep seams using the potential energy of a gassy coal massif.

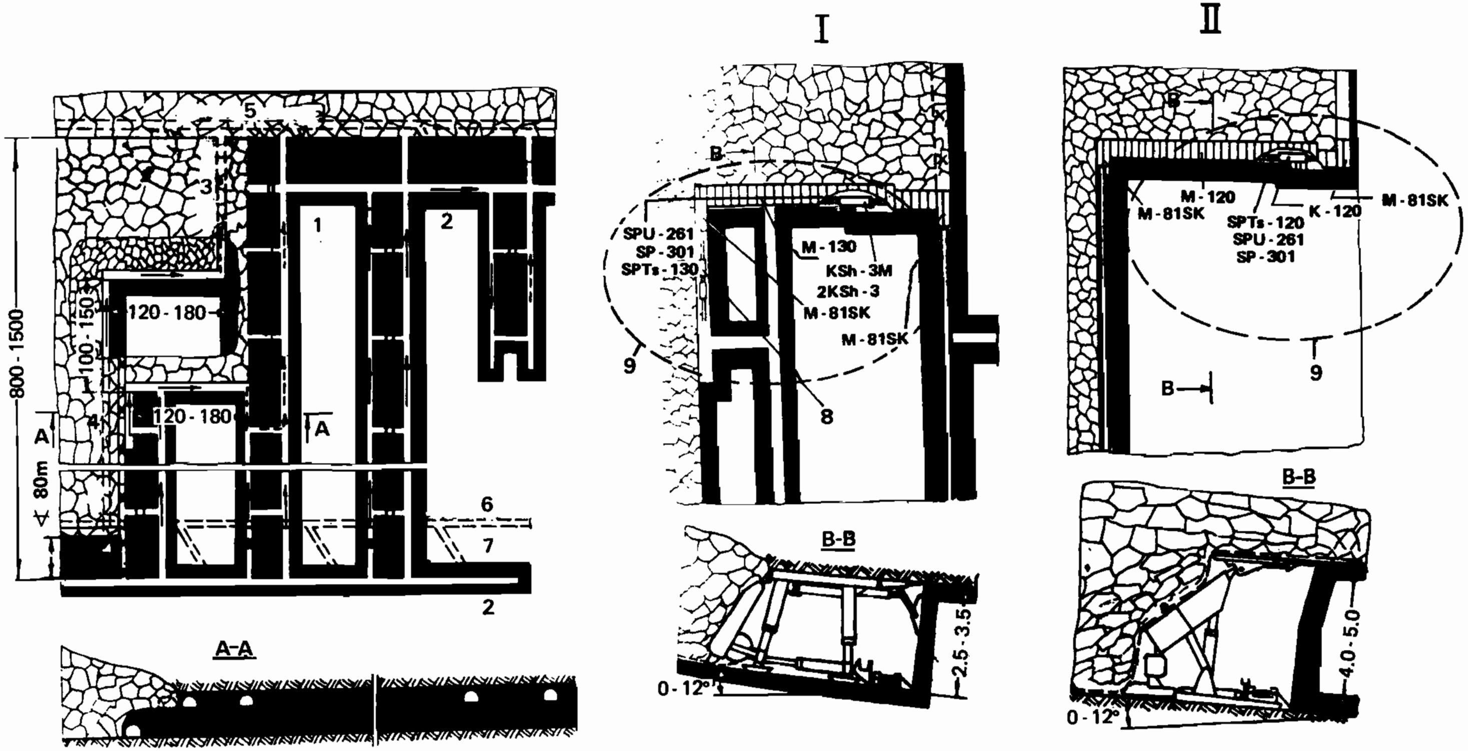
Development of underground coal mining technology between now and the year 2000 will result in a space-technological model of a colliery marked by a higher concentration of mining operations and by extensive use of block schemes for deposit opening. Labor-consuming manual operations will be replaced by automation. Promising operating collieries will be reconstructed and modernized to increase their output; and new large collieries will be created on the deposits with the best mining and geological conditions in Kuzbass and Donbass, the latter over 1000 m deep.

The new collieries will typically have an annual capacity of 3 to 6 Mt for flat seams (1.5 to 4.5 Mt for steep seams), and up



KEY: 1 - COAL WINNING RAISE, 2 - AIR ENTRY, 3 - AUXILIARY ENTRY, 4 - COAL TRANSPORT ENTRY, 5 - HIGH PRESSURE PIPELINE, 6 - PANEL INCLINE FOR COAL FLUMING, 7 - FLUMES, 8 - PANEL INCLINE, 9 - TRANSPORT CROSSCUT

Figure 3. The technology of hydraulic coal mining: I - with hydraulic monitors, II - with mechanical and hydraulic shearers.



KEY: 1 - AIR INCLINE FOR THE UPPER SLICE, 2 - MAIN AIR ENTRY, 3 - AIR INCLINE FOR THE LOWER SLICE, 4 - CONVEYOR INCLINE FOR THE LOWER SLICE, 5 - AIR GATE IN STONE, 6 - CONVEYOR GATE IN STONE, 7 - CROSSCUT, 8 - PUMP STATION, 9 - SPU-261, SP-301, SPTs-130 FACE CONVEYORS; M-120, M-130 MAIN POWERED SUPPORTS; KSh-3M, 2KSh-3 SHEARERS; M-8ISK FACE-END SUPPORT

Figure 4. The technology of mechanized mining of thick coal seams by inclined layers: I - of the upper layer by a support type of complex, II - of the lower layer by a protection and support type complex.

to 8 to 12 Mt provided the coal concentration is high. Recently the Raspadskaya colliery, with an annual output of 8 Mt, has been put into operation in Kuzbass.

For the past 15 years, the main processes in underground coal mining have been converted from a multioperational to a few-operations technology. Complex mechanization of mining seams with a dip angle of up to 35° has been widely introduced, its level reaching 60% by 1976. For steep seams that level is now about 5%, but it will increase over the next 15 years as aggregates such as AK-3 (Figure 5) for mining on strike, and shield aggregates such as ASch (Figure 6) for mining on dip, are created.

Scientific achievements now make it possible to build collieries of a new type with a high concentration of mining operations and five to six times the present labor productivity collieries such as Yubileynaya in Kuzbass, Dolzhanskaya-Kapitalnaya in Donbass, Progress in Mosbass, Vogashorskaya in the Pechora basin, and Kazakhstanskaya in Karaganda, among others).

Technical progress in underground mining is provided for by introducing constant parameters and means of mechanization which correspond to certain mining and geological conditions. Apart from standardization of technological schemes and equipment, the equipment is modernized, its power and reliability are increased, and complexes are constructed for mining thin seams with miniaturized equipment, impulse machinery and pneumo-ballon supports, and for mining the entire thickness of seams up to 5 m and drawing off the underroof layer of horizontal seams up to 8 to 9 m thick. There is wide application of automated complexes with continuous conveyor transport that provide for coal winning at manless coal faces.

Hydraulic coal mining is being developed and improved so as to permit a single-operation technology with continuous hydraulic transport from coal face to consumer, increasing hydromine production by 3 to 4 times.

Of the developments and workings that require loading operations, 32.6% were driven in 1976 with the help of road headers. By 1990, use of mechanized complexes in the main mining processes will have reached a rather high level. The problem of using the complexes where a roof is difficult to control will have been solved, and the carrying capacity of the mechanized supports will reach 80 to 140 t/m^2, depending on seam thickness. We already have supports with a carrying capacity of .70 t/m^2 (in the equipment sets KM87P) and up to 100 t/m^2 (in KMT and KM120); we produce cutter loaders and shearers with a thyristor drive of 450 kW and more for coal seams with a resistance to cutting of up to 400 kgf/cm (cutter loader K-128P), impulse plows with separate drives, and other equipment, all of which allows a considerable increase in the efficiency of technical processes and an expansion in the field of application of the technology created. We shall begin introducing coal-winning and road-heading machines

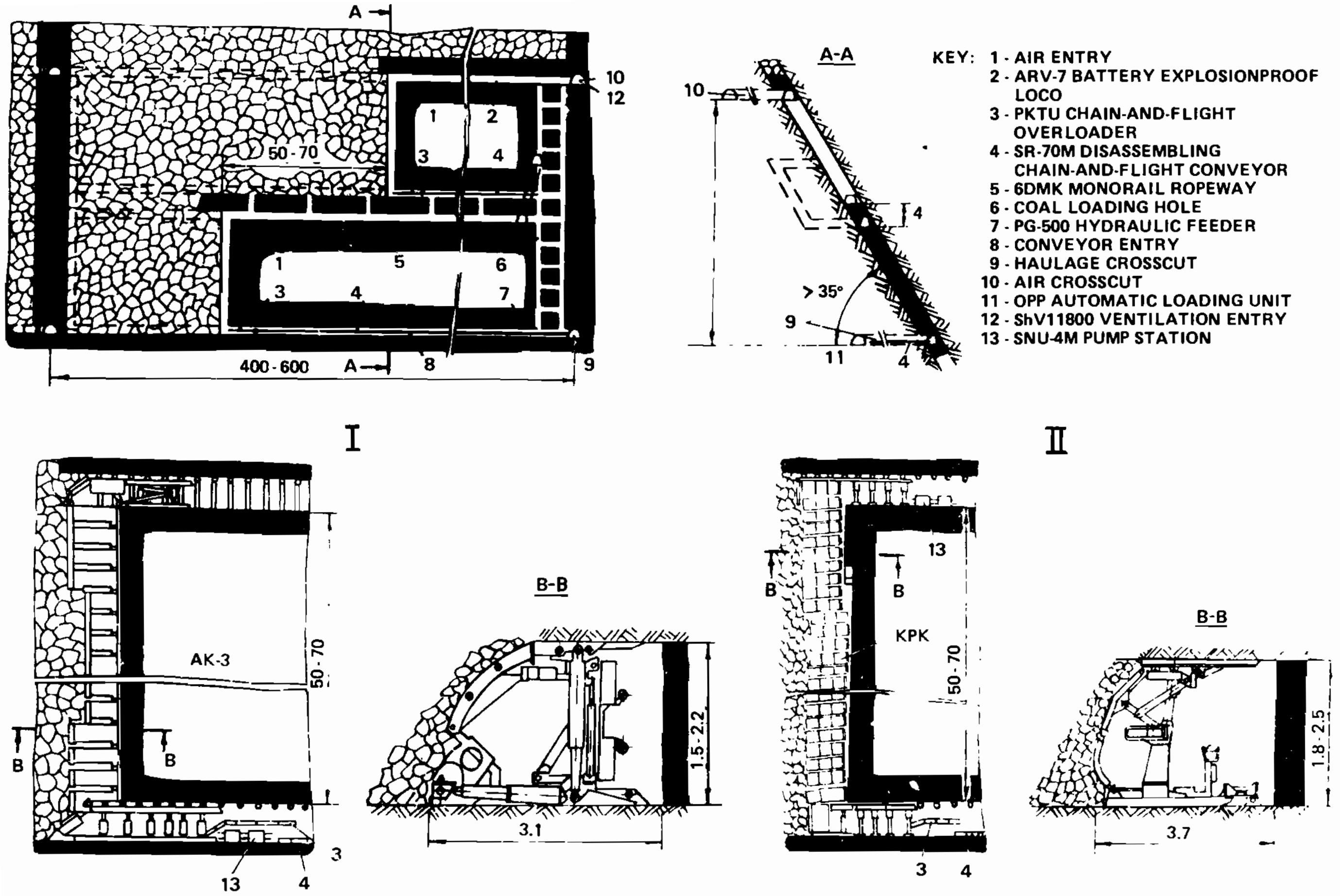
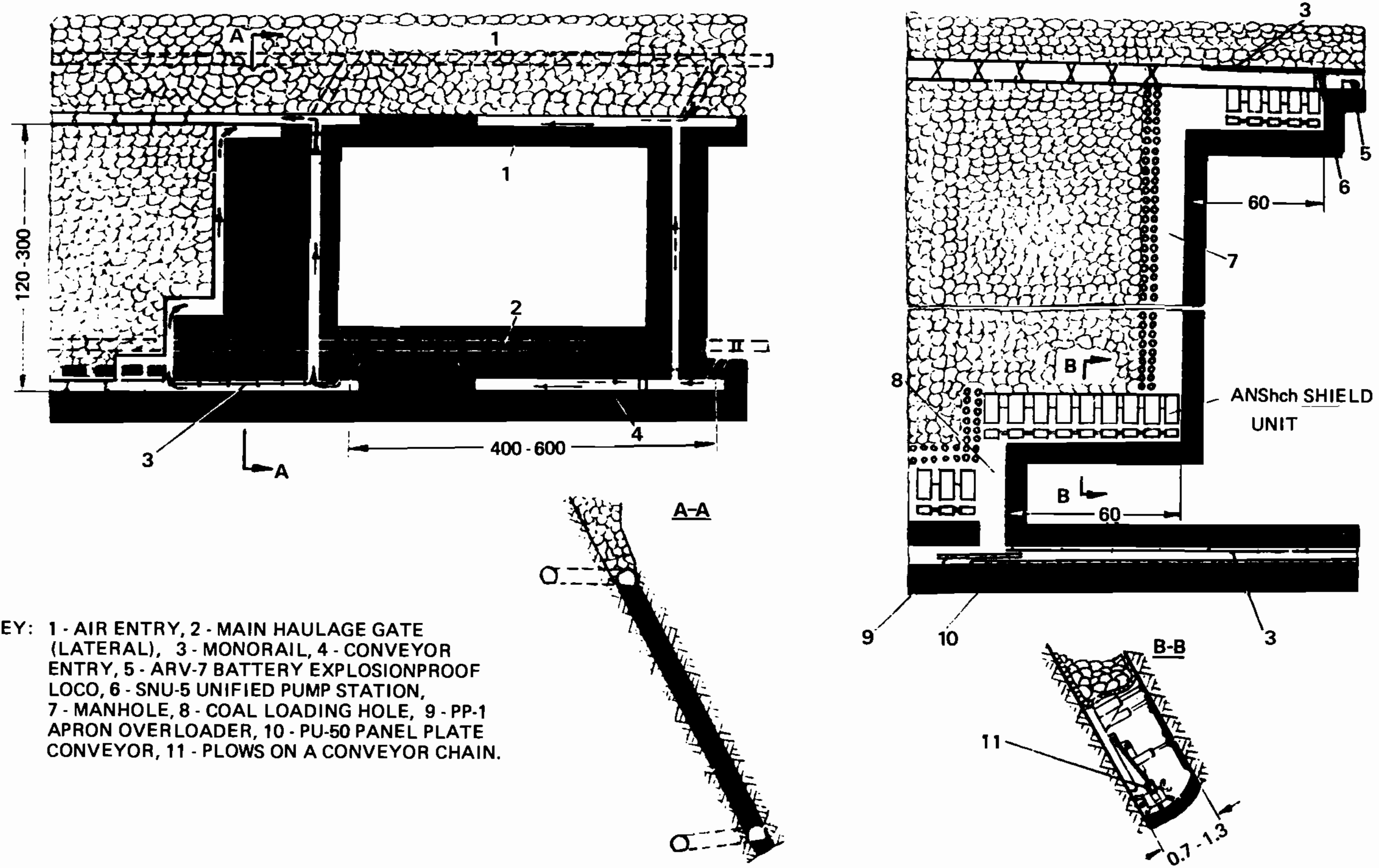


Figure 5. The technology of mining steep seams on strike: I - by aggregates (AK-3 unit), II - by mechanized complexes (KPK).



KEY: 1 - AIR ENTRY, 2 - MAIN HAULAGE GATE (LATERAL), 3 - MONORAIL, 4 - CONVEYOR ENTRY, 5 - ARV-7 BATTERY EXPLOSIONPROOF LOCO, 6 - SNU-5 UNIFIED PUMP STATION, 7 - MANHOLE, 8 - COAL LOADING HOLE, 9 - PP-1 APRON OVERLOADER, 10 - PU-50 PANEL PLATE CONVEYOR, 11 - PLOWS ON A CONVEYOR CHAIN.

Figure 6. The technology of mining steep seams on dip by shield aggregates (ANShch unit).

based on hydromechanical means of cutting, and impulse plows with autonomous power supply. This will lead to considerably increased productivity, introduce automation, and assure favorable labor conditions.

The efficient application of mechanized complexes is accompanied by reconstruction and modernization of mining operations, by combination of mines, by bigger mining panels, and by wider use of progressive means of opening and developing main roadways. The longwall retreating system with the coal face advancing along raise and on strike has priority.

Progress in open-pit and underground coal mining based on achievements in the fundamental and applied sciences paves new ways for a radical improvement in the means of efficient exploitation of natural mineral resources and provides for a reliable basis for development of the national power engineering and coke industry with coal as a raw material.

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OPTIMUM COAL WINNING METHODS IN DEEP MINES AS A FUNCTION OF GEOLOGICAL AND TECHNOLOGICAL FACTORS

W. Ostermann

A PROCESS OF CONCENTRATION IN THE FRG

Since the end of the sixties, the bituminous coal mining industry of the FRG has been operated by five big mining companies. The interconnected Ruhr deposit is worked by Ruhrkohle AG. Since the end of the fifties annual production has been adjusted to declining sales (Figure 1). (In this paper, all tonnages have been given in terms of the "saleable product".)

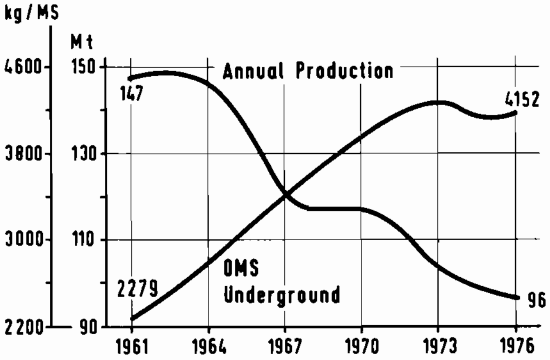

Figure 1. Production and output per manshift (OMS) underground.

A process of concentration towards the most efficient and economic mines was initiated, being intensified within the last decade (Figure 2), thereby increasing the average size of a mine to a daily output figure of about 9100 t. At the same time the number of mines was reduced from 140 in 1961 to 43 in 1976. This concentration was possible because the formation of the centralized company Ruhrkohle AG provided the opportunity to combine the formerly independent mines into units of optimum size irrespective of traditional concession boundaries. Thus, a greater number of combined mines could be established. Since 1973, mining capacities for which exhaustion could be foreseen by the need for greater working depths have been replaced. Overall mining capacity has been maintained by developing new takes (Figure 3) and connecting them to existing mines. The considerable financial expenditure involved in this measure is a typical feature of the coal mining industry in the FRG. The development of productivity during recent years has been marked by the high shift outlay necessary to secure the future of the FRG's coal mining industry.

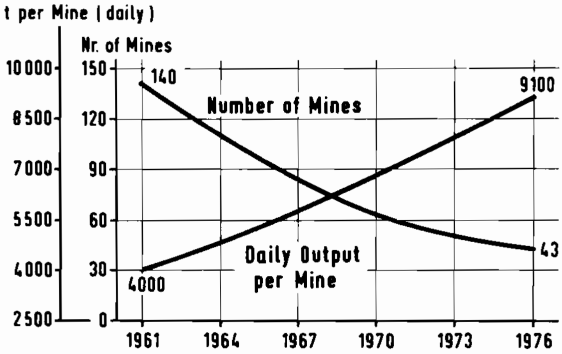

Figure 2. Concentration of coal production.

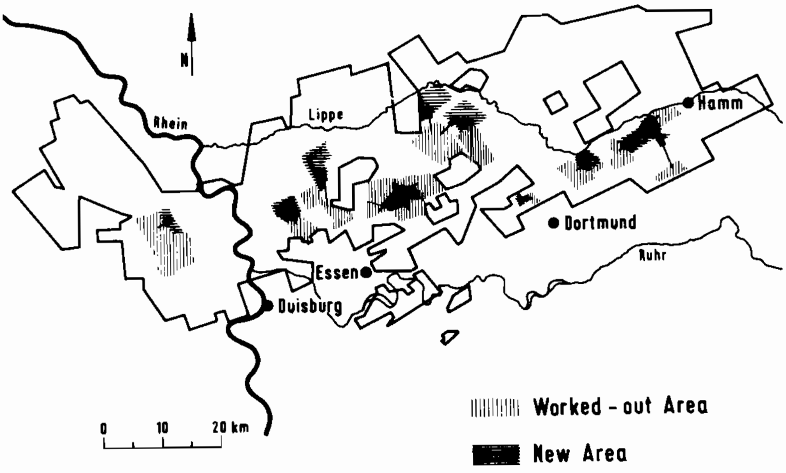

Figure 3. Access to new mining areas.

LONGWALL MINING - THE OPTIMUM COAL WINNING METHOD

The coal mining industry is faced with the important task of safeguarding the energy supply during the coming decades. In view of the supply risks entailed by a heavy dependence on oil imports and the fact that the nuclear power process has not yet reached full commercial maturity, coal has great prospects for long-term supply commitments. The coal industry has reserves that far outweigh those of other fossil fuels. Considered in proportion to the reserves of oil and natural gas, the proportional consumption of coal can and must be increased considerably (Figure 4). The FRG can rely on these large technologically feasible resources for planning purposes. Coal can provide an essential contribution to the primary energy supply, mainly in the form of high coking coal. The reserves are exclusively underground from deposits characterized by their close sequence of seams of varying thickness between 0.70 and 4.50 m, the major part being between 1 and 2.5 m thick. This high concentration of the reserves in a few large regions of the FRG requires the use of mining methods that give the highest possible yield and profitability.

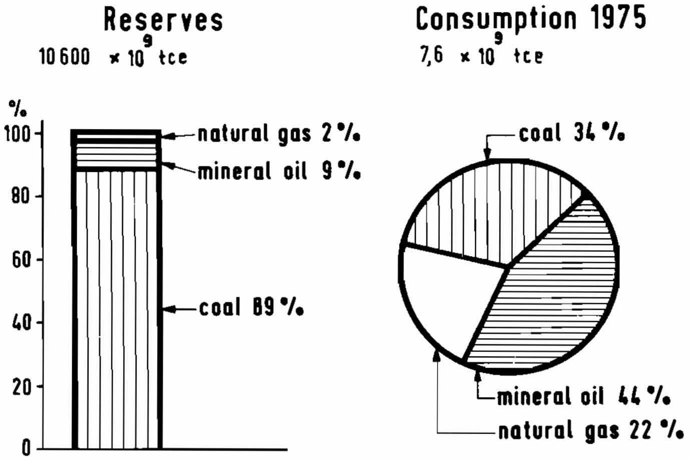

Figure 4. World reserves and consumption of fossil fuels.

Owing to the great average mining depth of 800 m--and in some places already well over 1000 m--methods that do not allow extraction over a wide area are not feasible in conjunction with multihorizon mining. This means that room-and-pillar mining, currently predominating the world scene, can be eliminated from further consideration not only because of the poor reserve yield but also for the engineering reason of the harmful punch effects by the pillars on underlying workings. The conditions of extraction are further aggravated by high tectonic stresses that split the deposit into many individual blocks and thus effect some reduction of workable reserves. These reasons promoted the development of an extraction method that now allows extremely high production from one face and thus permits a high concentration of operations. This concentration is necessary--in contrast to shallow mines--to compensate for the extensive infrastructure underground, with its heavy fixed-costs, and for the disproportionately higher development costs. For the following requirements:

- optimum recovery of reserves,
- reducing to a minimum the harmful punch effects by pillars on underlying seams, and
- highest possible DOF (daily output per face), i.e. high concentration of coal mining operations,

longwall working has proved the economically most favorable mining method for all bituminous coal deposits comparable with ours in terms of seam thickness, adjacent strata characteristics, and inclination.

Our development efforts were first focused on the mechanization of coal winning, which consequently led to the development of powered supports. The number of faces was thereby reduced to less than one fifth and the DOF correspondingly increased to about 1300 (Figure 5).

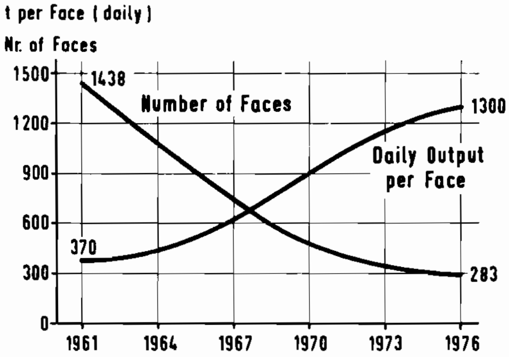

Figure 5. Concentration of underground coal mining operations.

Of course, the formation of the deposit has to meet some minimum geological requirements, apart from the mining technology and job qualification needed. At present, longwall faces can be worked efficiently in thickness between 0.70 and 5 m, bearing in mind that the extraction of marginal thicknesses soon becomes a problem if additional geological difficulties occur. The most favorable working range is in flat measures or those with a dip of up to 20°. Allowing for a reduced capacity of the equipment the means of mechanization used in flat measures can also be applied in inclined measures up to 60°, subject to special provisions: faults should not exceed one-and-a-half to two times the seam thickness of up or down throws in areas to be extracted by longwall faces so that the face equipment can be moved through the fault zone without serious decline in production or damage to the machinery employed. Limits are imposed to mine climate, rock pressure, and gas levels by the depth and the degree of carbonization. These handicaps will always have to be combatted by technical innovations and by adjusting the methods to changing conditions. Thus, it has been possible to improve the applicability of the longwall method steadily by adapting it to the conditions of the deposits.

Development tasks relating to the deposit are aimed at increased productivity in the marginal thickness ranges, in particular in the more inclined seams, and at overcoming geological faults more rapidly and cheaply. They are also directed towards the improvement of climatic conditions, adjustment (particularly of face-end techniques) to increasing rock pressure, and towards an improved method of methane drainage.

THE SCOPE OF LONGWALL MINING

The equipment and machinery for coal winning, face supports, and face haulage used in longwall mining has attained a high technical standard. The plow was invented and further developed in our country as the seams, in terms of thickness and hardness of the coal, have always favored its application. Today different types of plows are used with the chain guide on the face or gob side.

The gleithobel (Figure 6) can work seams with a greater hardness of coal and a soft floor safely and efficiently. For the lower and medium thickness ranges there are two efficient plowing methods, the characteristic feature of which is the variable speed ratio of plow to face conveyor. Plowing speeds of up to 2.5 m/s are possible.

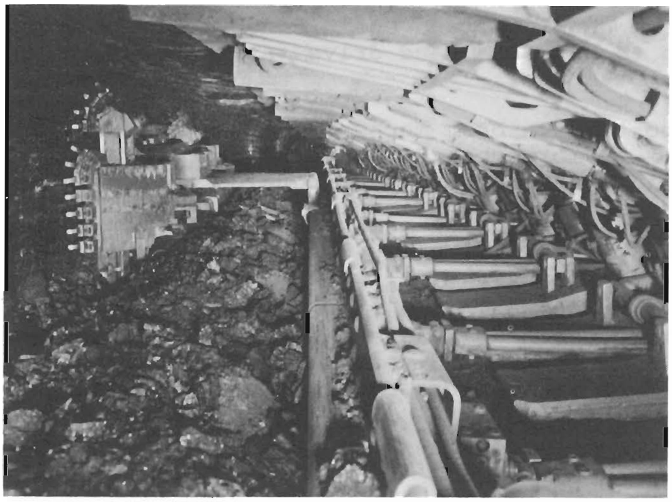

Figure 6. The gleithobel.

A powerful impetus from the UK has made shearers the major cutting machine in the FRG. Modern machines are equipped with two ranging drums fitted at the ends of the machine body (Figure 7) cutting the total seam thickness from roof to floor in one pass. Nearly 40% of the machines are equipped with motors of 300 kW or more. Except in steep seams, coal winning has thus become fully mechanized by the two winning methods of plowing and shearer cutting.

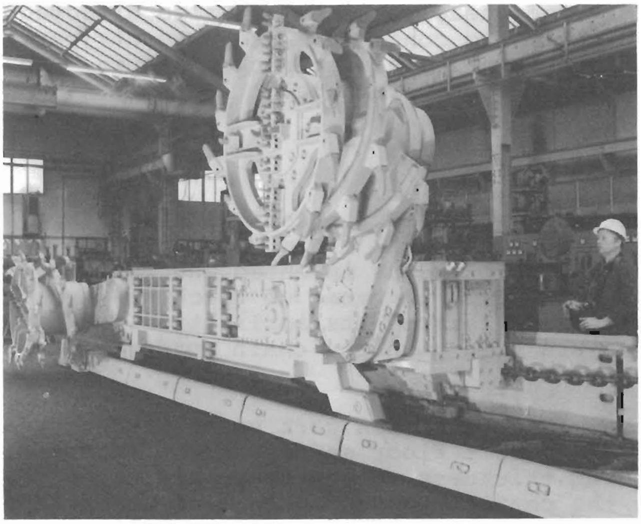

Figure 7. The shearer.

Single- and double-strand chain conveyors with a chain link diameter of up to 2 × 30 mm and drive ratings up to 4 × 160 kW are employed at the face.

Face supports have been mechanized even faster than coal winning--ratios of more than 85% have been achieved. Shields and chock shield supports have made considerable headway (Figure 8). With these efficient winning installations, even very thick and dirty seams, difficult to extract because of the unfavorable adjacent strata conditions, can be worked safely and efficiently. The same seams in many cases had to be eliminated from extraction plans ten years ago as unworkable. This has favored shield supports which, in consequence, have made spectacular headway during the seventies. In the last 3 years alone, the number of faces with shield supports has increased fivefold (Table 1).

Figure 8. Shield supports.

Table 1. Shield support in connection with fully mechanized winning.

Faces	1970	1973	1976
Shearer + Shield	1	13	54
Plow + Shield	0	7	46
Total	1	20	100

In the lower thickness range of up to about 1.6 m plowing is used almost exclusively, but there has been a considerable increase in shearing (over the last few years in particular) in the upper thickness range (Figure 9). The reason for this development is the particular effectiveness of the combined use of double drum shearers and shield supports. Figure 10 shows the DOF attainable under different geological conditions with the alternative technical equipment. From this the superiority of the shearer in comparison to the plow is evident with shield supports beyond approx. 1.6 m thickness and shearers of a lower height are being designed. The attainable output from a coal face is less if the operation is hampered by faults, if it is situated at a greater depth, or if a dirt band is interlaminated with the seam. The possible output is reduced by the sum of these three adverse influences to some 40% of the optimum value (the lowest curve in Figure 11). The same tendency is shown by the results from plow faces under difficult geological conditions, but, as already mentioned, with a lower DOF from the beginning.

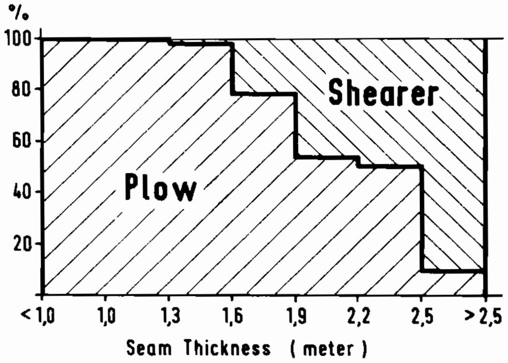

Figure 9. Production winning methods.

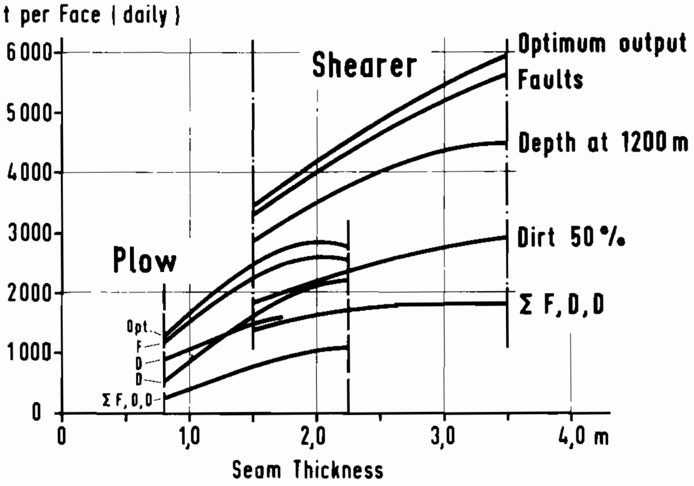

Figure 10. Output from shield faces under different geological conditions.

FUTURE DEVELOPMENTS IN LONGWALL MINING

The best operational results in the FRG's longwall faces are obtained in places where the integration of the winning, support, and haulage equipment has proved especially successful under the given geological conditions. Therefore decisive tasks for the future are to achieve a trouble-free interplay of all the equipment in the face system. The combination of the equipment into jointly controlled units is the logical step towards automation in the face area. In contrast to developments during the early sixties, the main objective of automation in the face area today is not a reduction of manpower. At that time it was clearly proved that the elimination of the last man from the face is disproportionately expensive, that it generally requires additional qualified craftsmen, and that in case of a breakdown the operation cannot dispense with human action. The results were increased downtime and consequently a drop in the ratio of machine-running to machine-available time.

In contrast, today's efforts towards automation and process control are to transferring human decisions to the automated mode. By thus releasing the man, not only can decisions be made more quickly, since changes can be registered sensitively by meters, but perceived trends can be used as a basis for decisions. Thus, the course of operations can be adjusted sooner than would be possible with manual control. Compared to former methods this will save time and increase the ratio of machine-running to machine-available time. Increased productivity through automation will not be achieved by reducing manpower at individual working points but by increasing the DOF, which also means increasing the effect of concentration. Microcomputers are a decisive prerequisite for this task; they have already contributed to remarkable successes in rationalizing other branches of industry.

Independently and in parallel to such tasks, work is being pursued on new equipment and machinery that may possibly be able to replace today's plant at a later date. For instance, in the coal winning sector there is the dustfree extraction and loading of coal by water at very high pressure, and an example as regards face haulage is represented by new drive systems enabling the required increase in power rating to be fitted in a smaller space and consequently the reduction of difficulties at the critical T-junctions at the face ends.

THE OUTLOOK

Longwall working is a particularly efficient mining method and is the basis for the success of the major coal mines in the coalfields of the FRG. Its further development by raising all coal faces to the values of today's peak operations and beyond will also permit further concentration, and therefore rationalization, elsewhere below ground - particularly in the haulage, material transport, and manriding sectors. Furthermore, the optimum size of a mine will continue to increase, since concentration has restored a clear overall picture of operations in a mine and has made it easier to manage major mines of up to about 15000 t per day.

Further concentration in the face area will increase productivity and thereby permit the FRG's hard coal industry to continue its big investments in the opening of new takes without adverse effects on underground productivity. This development may make longwall mining more advantageous for other coal deposits throughout the world for the same reasons as have applied in the FRG, namely, a much better reserve recovery combined with more profitable winning operations, but demanding a more complex technology and therefore higher requirements on the mine personnel. The extremely high efficiency of longwall mining is provable, however, under optimal geological conditions, both in our pacemaker faces as well as by results in the USA and in South Africa. From the point of view of raw material and energy conservation, the lower recovery of the room-and-pillar mining system seems to be more and more problematic for the excellent deposits on which this method is being used today.

HYDRAULIC COAL MINING IN THE USSR

A.E. Gontov

The first experimental and prototype hydraulic sections and underground coal mines of the USSR were put into operation about 30 years ago. In the Kuznetsk basin, the first hydrosection was put into operation in 1952 at the Tyrganskiye Uklony mine. In 1953 the Polysayevskaya-Severnaya (now Zarechnaya) mine, with a complete technological cycle of hydromechanization, was commissioned. The first experience gained in hydromines contributed to completion of big research projects, in situ testing of machines and machinery complexes, setting of operational and technological requirements for hydromining techniques, planning of large hydromines with higher technical and economic indices, and training of operators, engineers, and technicians.

Setting up of the All-Union Research and Development Institute for Hydraulic Coal Mining in 1955 was an important event for hydromining technique development. The Institute not only helped to consolidate scientific efforts and experiments in this field, but was provided with an experimental shop to manufacture test pieces of equipment and with a start-up and adjustment service. These facilities considerably shortened the time for manufacturing, testing, and perfecting technological processes, machines, and equipment. In the Donetsk and Kuznetsk coal basins there are 11 mines using the hydraulic technological process for coal mining, operating under various geological conditions. During the past years experience was gained in carrying out operations under the following geological conditions:

- Seam thickness from 0.9 to 20 m;
- Seam dip from 5° to 80°;
- Coal hardness from soft to extremely hard;
- Gas content from nongassy to highly gassy;
- Tectonic nature from uniform to highly disturbed.

Before 1965, coal in hydromines was extracted by a blasting-and-hydraulic system of mining of low efficiency (80%). A hydraulic monitor mining system was used only in the deposits of very soft fissured coal (9%); a mechanical hydraulic system was used only in 11% of the cases. During the last ten years, use of the blasting-and-hydraulic system was reduced sevenfold. At the same time, the share of the hydraulic system and mechanical hydraulic techniques sharply increased. This change was encouraged by new highly efficient machines and equipment, technological processes of extraction, hydraulic transport, and coal dewatering. At present practically all the operations of the production process from coal cutting to coal dewatering at the coal preparation plant are mechanized, making use of machinery and equipment specially designed for hydraulic mining by the Institute VNIIGidrougol in close cooperation with the personnel engaged in production.

Design work in the field of mechanization of hydraulic coal-winning operations may be conventionally divided into the following aspects:

- Coal face machines,
- Gravity and pressure hydraulic transport and pulp preparation facilities,
- Pipe fittings for water suspension and slurry,
- Hydromechanization of ancillary operations,
- Monitoring equipment.

Development of new coal face machines is taking two parallel directions: first, the design of new types of machines for conventional mechanical mining; and second, the modernization of conventional machines. Various types of hydraulic monitors have been developed and are being successfully used in our hydromines. There are remote control hydraulic monitors GMDZ-3 and GMDZ-4 rated for pressures 12 and 16 MPa, respectively, and water consumption up to 100 m^3/h; and a self-propelled program control hydraulic monitor 12GP-2 rated for pressure 12 MPa and water discharge up to 450 m^3/h. There is also a self-propelled hydraulic monitor with pressure booster SGU-2M: power is supplied to it from the low-pressure water pipeline, and the pressure is boosted to the required level directly at the face. Then there is a lightweight mechanical-hydraulic machine LMGP-5 to drive entries in steep seams, and a mechanical-hydraulic heading machine MGPP-3A designed to work in stone. Both machines have hydraulic turbine drives which make them usable at gassy faces.

For use in pressure hydraulic horizontal transport systems we have a small-size one-stage coal slurry pump 12U-10 designed for 900 m^3/h throughput and 90 mm water head pressure. A two-stage high-pressure coal slurry pump 14UV-6 is designed for 900 to 1000 m^3/h throughput and 320 to 330 mm water head pressure. The latter is successfully used in hydraulic lift systems and main hydraulic transport systems. Section pumps 12MSG-7 supply water for hydraulic monitors with capacity 800 m^3/h and pressure up to 10 MPa. They are reliable in operation with supply water containing up to 70 g of solid particles per liter.

Scientists, designers, and production personnel pay great attention to the development of reliable pipe fittings for water suspension and slurry, and as means for fast assembling and dismantling of pipelines, and of instruments to control solid concentration in water. The 3PP-300 valves, designed for the 6.4 MPa slurry pipelines, have been tested and planned for mass production. Couplings for fast assembly of 100 to 350 mm pipelines for 12 MPa, and 125 mm pipelines for 16 MPa, are now manufactured on a commercial basis. Instrumentation to control solid concentration both in an open flow and in a pipeline has been developed. We have also a set of control instruments (KPU) which makes it possible to keep records of output from individual coal faces, sections, and a mine as a whole. Besides keeping the records of output, this KPU helps to watch ash content of coal in flow and of flotation tailings. The KPU, combined with the suction devices which can control density of slurry, can automatically sample a flow and maintain desired properties of the mixture in the pipeline.

Technological plans for development, coal winning, and transport utilized at present can be discussed if we examine two hydromines--Yubileynaya and Krasnogorskaya--which operate in different geological conditions characteristic of many coal basins in the country.

The Yubileynaya mine exploits 14 flat seams of 0.8 to 3.6 m thickness, each with relatively regular occurrence. The coal is of "G" and "Zh" grades. Blocks N1 and N2, although part of the mine, are autonomous units and do not have common roadways. Each block is connected by individual slurry and water pipelines to the central preparation plant. The mine uses two mining methods. The first method is longwall retreating: coal is extracted by the KSh-1KG and 2K-52 shearers operating in combination with the OMKT, OKP and KM-87D powered roof supports. The second method is room and pillar mining. In this case the pillars may be oriented up the dip and on the strike, and coal extraction is made by the K-56MGM and K-56MG power loaders and hydraulic monitors. The rooms in seams of less than 1.8 m thickness are cut by hydraulic monitors, while those in seams of 1.8 m or more are cut by the K-56MG power loaders. The panels in seams 29a, 30, and 32 are mined by a multiface method that makes it possible to distribute development and winning operations over the whole panel area and combine these operations in time and space. This arrangement made it possible to increase the output from a panel up to 1 to 1.5 Mt of coal per year. At present two teams of workers operating in this arrangement produce up to 70% of the total output of the mine.

The extracted coal is carried from the faces to the main hydraulic lift chamber by water flow in open flumes. The mine takes in and puts out a fixed volume of water, while the volume of coal carried by the system varies with the number of coal faces in operation and the production rate. The main hydraulic lift chamber is located in the pit bottom. It is equipped with

DKU-11 slurry machines which screen and crush oversize material down to +70 mm grade. The 12UV-6 coal pumps with the ZGM-2 booster slurry pumps or the 14UK6 coal pumps without boosters are used for lifting. Slurry pipelines are connected with suction ends of the coal slurry pumps on the surface that carry slurry to the preparation plant. Water for high-pressure hydraulic monitors is delivered from a surface tank by 12MSZ-7×8 pumps. Water pressure before entering the hydraulic monitor is maintained at 10 MPa. Water for mechanical-hydraulic machines is also delivered from the surface by the 12UV-6 or 12MSG-7×8 pumps.

The Yubileynaya mine is a part of the fuel-metallurgical complex (mine preparation plant - coke-chemical production) of West Siberia. Coal from the mine is carried to the preparation plant over a distance of 10 km by the slurry pipelines. This kind of transport has a number of advantages over rail transport: the decreased load on the mine, preparation plant, and metallurgical plant rail tracks; no load-unload operations; no pollution of the environment which might be the result of coal loading and transportation. At the same time our studies showed that hydraulic transport did not decrease metallurgical coke quality.

The field of the Krasnogorskaya mine is confined by an anticline. The lock of the anticline has been mined at the upper working levels. The coal measures consist of seven contiguous seams steeply pitched under 50° to 80° and thicknesses ranging from 1.5 to 9 m. The coal measures are of complicated tectonic character. There are many plicative and disjunctive faults in the formation. The coal is of coking grade. Relative gas yield is 9 to 30 m^3/t of output. One of the seams is prone to sudden outbursts of coal and gas. Development and winning work is done by means of high-pressure hydraulic cutting with the help of the GMDZ-4M and 12GD monitors. The main method of mining consists of sublevel hydraulic cutting under flexible steel mesh lagging. The lagging is mounted in one plane confined by the hanging and lying walls of the seam at each fourth sublevel. The lagging is not used in seams of medium thickness.

The seams are opened in blocks. For a number of reasons (contiguousness of the seams, liability of coal to spontaneous combustion) the block length along the strike does not exceed 150 m. The blocks are opened by intermediate crosscuts from the lateral drift which is driven parallel to the centerline of the anticline. Several blocks are in operation at a time. Within the limits of one block, coal is transported by water in open flumes down to a coal slurry pump station located at a junction point of the lateral drift and crosscut. The 12U-19 coal slurry pumps push water mixture down the 250 to 350 mm diameter pipeline to the main hydraulic lift chamber.

The hydraulic system of mining in the very complicated geological conditions (geological faults, contiguousness of the seams, high gas emission, liability to spontaneous combustion) positively affected efficiency of mine operation. The mine increases output every year. Labor productivity at the Krasnogorskaya mine is 75.2 t/month--1.5 to 2 times higher than at other mines of the Prokopyevsk-Kiselevsk area where conventional technology is used under similar conditions. Production costs are considerably lower.

Work is continuing on further improvement of the equipment and technology for hydraulic coal mining. At the Krasnogorskaya and Tyrganskaya mines the mastering of new technological patterns for opening up, developing, and working thick steep seams has begun; the experience gained in the multimachine method of coal winning, which is widely used when working flat seams, has served as a basis here. It will help to increase the rate of development working drivage from 90-100 to 500-600 m/month and the annual output per block from 100,000-150,000 to 500,000-1,000,000 t. The increase in the size of blocks and the intensification of their development will permit the reduction of coal losses in pillar from 6.0 to 2.5%. With the help of new technological schemes and high-pressure hydraulic cutting of coal at the Tyrganskaya mine, where steep seams are being worked, the daily output per face has reached 1100 to 1200 t.

The hydraulic system of mining shows other advantages over the old technology in the course of many years of its application, perfection of equipment, and labor organization. Hydromines are able to mine deposits in faulty conditions. Systems for hydraulic mining, machines for hydraulic cutting of coal, and hydraulic transport systems allow for working seams characterized by various geological faulting with sections of any configuration and parameters, with comparatively high technical and economic indices. Methods for working flat thin seams with hard mineralized intrusions, with the help of hydraulic cutting providing for a small number of operations without presence of men at the face, have been developed and are being successfully used. A high level of productivity under the given conditions--15 to 19 t per manshift--has been achieved. As a result, the amount of reserves opened up and then rejected as being unsuitable for working by hydromining has been reduced to a minimum. For example, during the Ninth Five-Year Plan period, at hydromines in the Kuznetsk basin 2.8% of rejected coal reserves were added to the total output; in the Kuzbassugol Production Unit 7.7%, in the Yuzhkuzbassugol Production Unit 12.0%, and in the Prokopyevskugol Production Unit 12.2%. That is why recovery rate (taking into account operational and total losses and commercial reserves rejected as unsuitable for mining) at hydromines is higher than at conventional mines. During the Ninth Five-Year Plan period it amounts to 73.6%: in the Kuzbassugol Production Unit 73.2%, in the Yuzhkuzbassugol Production Unit 69.1%, and in the Prokopyevskugol Production Unit 59.0%.

The modern equipment used in hydraulic and mechanical-hydraulic mining does not require permanent presence of men at the coal face. Hydraulic monitors are mounted in a supported development heading and are controlled remotely. In the process of mechanical-hydraulic extraction, an operator of the K-56MG power loader also works in the supported area. The workers of the development and winning faces thus are less likely to get injured. The injury rate in hydromines is 2.5 times lower than in other mines. The Zarechnaya mine had no case of serious injury during 15 years.

Our studies showed that water in hydromines penetrates coal seams and partially dissolves free methane, reducing its amount in the air, while in conventional mines the gas is released continuously and in full measure. Dust concentration in hydromine air does not exceed 0.25 to 0.5 mg/m^3. The history of hydraulic coal mining has not one case of methane and coal dust explosion or ignition. One of the contributing factors is that the hydromines have minimum blasting work; in the near future, explosives will be eliminated completely.

For a long time technological progress in hydraulic coal mining was hampered by the management structure of hydraulic mines. Hydromines were a part of the production units of predominantly conventional methods of coal winning. And naturally, the main material and financial resources were allocated primarily for the improvement of conventional technology and the improvement and introduction of the corresponding mining machinery. At the majority of conventional mines (the Lenin Commemorative mine, the Kocksovaya mine, and others) the hydraulic sections were closed.

A production unit of hydraulic coal mining, Gidrougol (Hydrocoal), was set up in the Kuzbass in 1975. The unit incorporated five mines, three preparation plants, the research institute VNIIGidrougol, a new plant, Gidromash, for manufacture and repair of the equipment for hydromines, a mine construction administration, and other enterprises and services. This unit concentrates the efforts of scientists, designers, and people of industry to promote the further perfection of technology and production processes and to consolidate material and financial resources to solve the most urgent and promising problems. The main problems relate to the further concentration of mining operations, to the development of new technological schemes and machines for complete mechanization of coal winning and development operations in steep seams, and the like.

With higher rates of mastering the technology and the increase in technical and economic indices, underground hydraulic mining has attained the highest labor productivity and the lowest costs in the coal industry. Labor productivity at hydromines in the Kuznetsk basin is 1.8 times higher than at conventional mines and 2.1 times higher than the average productivity in the basin. At the Zarechnaya and Yubileynaya hydromines, which are working flat seams, the highest labor productivity in the industry has been achieved: 185.4 and 203.8 t/month (at the Yubileynaya N2 mine, 284 t/month, which is higher than the average productivity for opencast mining in the Kuznetsk basin:

260/t month. Annual average rates of labor productivity increase at hydromines amount to 6%.

Production cost per ton of coal at hydromines in the Kuznetsk basin is 2.4 roubles lower than at conventional mines with similar conditions, and 3.7 roubles lower than at all the underground mines of the basin. The lowest cost has been achieved at the Yubileynana N2 mine--3.4 roubles per ton--and at the Zarechnaya mine--4.9 roubles per ton. The level of costs achieved at these mines is lower than that at opencast mines in the Kuznetsk basin (6.3 roubles per ton). During the period 1975-1976 the cost per ton of coal produced at the Kuznetsk basin hydromines has decreased by 0.9 roubles. Owing to the higher level of specific power installed and specific capital per worker, the share of manual labor in cost of production at hydromines was 35.7%, whereas at conventional mines it was 46.9%. This indicates that the structure of production costs at hydromines is influenced by the change of the social character of labor: machines work for man, and the share of manual labor in the creation of products of equal value at hydromines is substantially less than at conventional mines.

A high level of profitability has been achieved at hydromines: 22.7%.

Using the experience of hydraulic mining in the USSR, a number of highly developed capitalist countries (the USA, Canada, Japan, the FRG, and others) began to implement programs on hydromine development. In 1974 an agreement was made between the Licensintorg* of the USSR, the Kaiser Resources Company in Canada, and the Mitsui Mining Company in Japan for mutual work on creating the machinery and technology for hydromines of high productivity in working thick steep, thick flat, and medium seams. There is considerable worldwide experience in hydraulic transport of coal for long distances.

The labor intensity of hydromines and conventional mines with similar conditions has been compared, and commercial field trials have been carried out, at hydromines in the Kuznetsk basin. They confirm the feasibility of achieving, at the new large hydromines with completed technological cycle, a monthly output per worker of 400 to 500 t while working flat seams, and 150 to 300 t while working steep seams under adverse mining and geological conditions. A study of the present situation with respect to the equipment and technology for hydraulic mining in the USSR and elsewhere, and of the technical and economic indices attained at hydromines, indicates the expediency of intensive development of this progressive method of underground coal mining.

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*The organization responsible for issuing licenses to foreign industries.

A comprehensive program of hydraulic mining development in the USSR has been developed at the Ministry of the Coal Industry of the USSR. The increase in output will be ensured mainly thanks to raising the production capacity of operating hydromines: e.g., at the Yubileynaya mine, from 3.5 to 9.0-12.0 Mt, and at the Inskaya mine, from 2.1 to 6.0 Mt. Besides, development of the Kalinin Commemorative mine is planned, with a total annual output of 8 Mt from the Tyrganskaya, Prokopyevskaya, Kalinin Commemorative, and Ziminka mines. Development of the Krasny Uglekop hydromine, with an annual output of 4.5 Mt, will also take place, on the basis of the mines Severny Maganak, Maganak and Krasny Uglekop in the town of Prokopyevsk, Ilyinskaya in the Yerunakovskoye deposit (7 Mt) of the Krasnoyarskaya mine in the Lenin district, and Tomusinskaya in the South Kuzbass district with a capacity of 12 Mt. Thus, by the end of 1990 coal output by the hydraulic method in the Kuznetsk basin is expected to grow, which--along with further development of opencast mining--will lead to a sharp increase in the efficiency of the industry.

OPEN-CUT COAL MINING IN THE USSR: TECHNIQUES AND ECONOMICS

N.V. Mel'nikov

Unflagging increases in world industrial output are of necessity paralleled by a growth in the consumption of various energy-yielding minerals. World fuel consumption in the past 20 years has more than doubled and in terms of conventional fuel has reached approximately 8×10^9 t. Combustible minerals account for more than 90% of all natural energy sources in conventional use. The average annual rate of increase in consumption since World War II is 4.5%.

The distribution of mineral fuel resources among the countries of the world is most uneven. A characteristic feature of the present world energy budget is a slight increase in coal consumption, its share in the generation of power currently comprising about one third of the total.

Expectations in the mid-1960s of a considerable decline in coal mining, which were based on the prospect that other energy sources would replace coal, proved to be faulty due to a swift increase in energy consumption, insufficient oil and gas resources in the Western countries, the technical and economic difficulties involved in the development of promising oil and gas deposits, the rapid increase in the prices of these fuels, and an overestimation of the available fuel deposits. Meanwhile, there are reassuring prospects of developing cost-saving techniques of producing liquid fuel and gas from coal, and of magnetohydrodynamic generation of electricity.

According to forecasts, the rate of world energy consumption growth up to the end of this century will continue at approximately 5% annually, and by 2000 will increase, in terms of conventional fuel, to 30×10^9 t. A considerable part of this demand will be covered by coal, which will continue to be the major energy-yielding mineral.

Progress in the USSR coal mining industry is backed by extensive coal deposits. The aggregate geological deposits of fossil coals that are available to open-cut mining comprise approximately 200×10^9 t. Most of them are confined to the Kansk-Achinsk basin. As a rule the deposits have a high coal layer (from 10 to 90 m), horizontal or gently dipping and non-displaced, and a stripping capacity of 5 to 100 m, mainly of none too hard rock, with a ratio of overburden ranging from 1 to 3 m^3/t.

Two deposits of this basin--Irsha-Borodinskoye and Nazarovskoye --are currently being exploited. As for latent deposits, the most favorable mining conditions are found at the Itatskoye, with a coal seam of 90 m; the Beryozovsk, where the coal seam is from 40 to 60 m; and the Abanskoye, where it ranges from 2 to 28 m. The ratio of overburden at these deposits is 1.0 to 1.5 m^3/t.

There are several deposits in the Kazakh Soviet Republic: first, the very large Ekibastuz hard coal deposit, then the Maikyuben and the Turgai brown coal deposits. The Ekibastuz deposit is a closed synclinal trough with a gently dipping coal seam at a depth of up to 530 m. The three seams currently mined are close to one another, have an aggregate capacity of 156 m, and are of very complex structure. The Maikyuben basin has one or two beds of compact or divided brown coal, their thickness reaching 25 or 30 m, and inclinations ranging from 5° to 30°; the closest they come to the surface is 5 to 10 m. The Turgai basin incorporates a number of closed-type deposits that have up to three main seams of simple structure from 10 to 70 m thick, dipping gently and being somewhat deeper (from 35 to 100 m). The ratio of overburden ranges from 3.5 to 4.8 m^3/t. The basin is distinguished by difficult hydrogeological conditions.

The Kuznetsk hard coal basin has considerable resources for open-cut mining; more than 90% of its coal is of valuable energy-yielding grade. All local deposits have many seams that range from 1 to 30 m and have a high ratio of overburden (up to 9 m^3/t) and considerable rock hardness.

The advantages of open-cut mining were considered by the USSR government even in the formative years of our State. Special measures were provided for on a nationwide scale in all our Five-Year Plans, and the necessary funds were allocated to ensure priority development of open-cut (versus underground) mining. Accordingly, the volume of coal mined by the open-cut method has been growing steadily; the same can be said of its relative share in total coal mining and of the application of modern techniques (Table 1). The average annual rate of open-cut mining increment in the Ninth Five-Year Plan (1971-1975) reached 6.3%.

A characteristic feature of modern open-cut operations in the coal industry is the increase in the rock mass (Table 1). This reflects the intensification of open-cut coal mining and its application to new deposits where seams are rather deep and the ratio of overburden is higher. The latter circumstance has led to the use of stripping techniques that involve rail or motor rock transport. Considerable work is done by walking draglines or surface shovels.

Approximately 50% of surface rock and coal are loosened by the drill-blast technique. Modern drills with roller and rotary boring and bits of 190, 214, and 150 to 160 mm are used in drilling.

For rock crushing, blasting techniques have been greatly improved through large-scale application of multiple-row delayed-action blasting and the new cost-saving explosives igdanite and ifsanite.

Table 1. Characteristics of USSR open-cut coal mining.

	1950	1955	1960	1965	1970	1975
Open-cut coal mining [Mt]	27.1	62.2	101.3	139.3	164.5	223.9
Share of open-cut mining in overall coal mining [%]	10.7	16.7	20.1	24.4	26.7	32.2
Volume of overburden removal [10^6 m^3]	79	196	326	312	627	848
Number of open-cut mines in operation	27	44	52	62	68	68
Average load per mine [Mt]	1.0	1.5	1.9	2.2	2.4	3.3

Modern single-bucket excavators are provided to open-cut mines to deal with more difficult geological or technical conditions of mining, as are mechanical shovels with a bucket capacity of 8 and 12.5 m^3 and walking draglines with a bucket capacity ranging from 10 to 100 m^3 and beam lengths of 70 to 100 m. Walking draglines are used in wasting: the ESh-10/70 and the new model of the ESh-13/50. This creates the conditions for safe and economic operation of excavators and transport equipment.

Continuous-operation machinery has been widely introduced and is used for excavating more than 30% of the coal mined by the open-cut technique. Thus, the removal of overburden at the Morozovsky open pit is carried out by a powerful rotary combine with an hourly productivity of 5000 m^3. The annual capacity of this combine is 10×10^6 m^3.

Coal mining at the Ekibastuzugol Production Unit is conducted by rotary mechanical shovels with an hourly capacity of 1000 and 3000 m^3. Still larger rotary mechanical shovels with a productivity of 5000 m^3/h and a rated cutting force of 14 kg/cm^2 have been developed for the Krasnoyarskugol Production Unit.

The pool of open-cut transport facilities is being intensively renovated with diesel-electric cars and dump trucks of great unit capacity and adhesion weight. The use of coal carriers of 120 t lifting capacity, developed specifically for this industry, proved to be highly effective.

One of the most important features of open-cut operation is the rate of labor productivity growth, which is higher than the rate of increase in coal output. As a result, the absolute increment in coal mining has been achieved without increasing the number of workers. Given the natural and technical conditions of coal mining in the USSR, an increment of 1% in the share of open-cut mining in overall coal mining ensures a reduction of up to 12,000 workers engaged in coal mining.

The Guidelines of Soviet Economic Development for the Tenth Five-Year Plan (1976-1980) stipulate that by 1980 coal mining will reach 790 to 810 Mt; that the technical reequipment of enterprises on the basis of integrated mechanization and automation of production processes will be completed; that open-cut coal mining will be developed at an accelerated rate; and that labor productivity in the coal industry will increase by 24 to 25%.

Open-cut coal mining is to be developed by reconstructing operating open pits so as to increase their production capacity considerably, and by building large new ones in the eastern USSR where we have extensive deposits suitable for open-cut mining. The planned growth of technical and economic indicators of open-cut coal mining for that period is illustrated in Table 2.

Table 2. Projected growth of open-cut coal mining.

	1975	1980 (projected)
Share of open-cut mining in overall coal mining [%]	32.2	35.6
Ratio of overburden [m^3/t]	3.8	3.9
Share of mining with mechanical rotary shovels [%]	31.7	46.5
Share of single bucket excavators [%]	36.0	45.0
Labor productivity per worker [%]	100	126

The guiding consideration in the development and siting of the coal mining industry is the desire to establish very large fuel/energy complexes. This is motivated by the advantages of focusing efforts on a small number of projects, using large mining machines, and considerably cutting investment and production costs per unit of output. Two such complexes, with a high concentration of production, a well-developed network and rational mode of transport, the shortest possible coal transport distances, and a low cost of mining and power generation, are being developed in the USSR: Ekibastuz in Kazakhstan and Kansk-Achinsk in the Krasnoyarsk region.

The Ekibastuz fuel/energy complex incorporates some of the largest open coal pits, with an aggregate annual capacity of 170 Mt; the actively exploited Ekibastuz and Maikyubensk deposits and five thermal power stations with a total capacity of

20 × 10^6 kW. This complex will be the heart of many industrial districts, feeding them through the 2500 km Ekibastuz Center d.c. electric transmission line of 1500 kW. Huge funds have been set aside for the development of the complex, and tremendous material and manpower resources have been allocated.

The Kansk-Achinsk fuel/energy complex (KAFEC) is to be of even greater magnitude. It is being built on the basis of the brown coal resources of the area and will be one of the largest national centers of power generation and power-intensive industries. In the first stage of KAFEC development, in addition to the existing two large-scale open pits, four new ones will be built, with an aggregate annual capacity of approximately 200 Mt of coal. This coal will go to feed the world's largest thermal power stations of 6.4 × 10^6 kW each. The electricity they generate is to be conveyed through a 4000 km a.c. transmission line of 1150 kW to the industrial areas of Siberia, Northern Kazakhstan, and the Urals, and through a 2250 kW d.c. super ETL to the European part of the USSR. The coal supplied by the KAFEC will also feed a number of other thermal power stations in West and East Siberia.

The share of Kansk-Achinsk coal in the fuel balance will grow rapidly, to reach approximately 7% of the national total and 40% of the total for Siberia. Investment in the construction of the KAFEC will be compensated by savings in five years. Its power potential will provide the backbone of a fresh industrial spur for many industries and regions. In scope of operations, resources involved, and economic importance, the KAFEC project is comparable with construction of the Baikal-Amur Railway.

Continuing concentration of production is one of the main characteristics of current projections on the development of open-cut coal mining. There are projects for the construction of super-powerful pits at the Ekibastuz deposit (up to 50 Mt annually), at the Kansk-Achinsk basin (55 to 65 Mt annually), and at the Kuznetsk basin (up to 30 Mt annually). Labor productivity at Ekibastuz and Kansk-Achinsk will reach 2500 to 3000 t per month; the mining cost will be 0.50 to 0.86 roubles/t and the specific investment rate 4 to 5.5 roubles. Because of the favorable mining conditions, the average ratio of overburden will drop to approximately 3.5 m^3/t for the entire industry.

The bulk of stripping operations at coal faces will follow definite technological patterns with respect to conveying equipment and course stacking (with the use of walking draglines and surface shovels). Stripping operations using transport will grow 4.5 times, and course stacking 2.5 times.

The conveyance of overburden by rail will continue to prevail and, taking combined modes of transport into account, will comprise approximately half of all transport operations. The share of motor and conveyor transport will increase to approximately one third of the total. The productivity of continuous conveying machines in stripping operations will reach 20,000 m^3/h, and in coal conveying up to 15,000 t/h.

The range of serial production of mining and transport machines for open-cut mining, their further refinement, and the designing of new models will be based on the closest possible balance between the operational dimensions of the equipment and the natural-technical mining conditions; on the utmost compatibility of the machines when used in an equipment set; on a high degree of standardization; on increased unit capacity, durability, and operational reliability; and on integrated mechanization of all major and auxiliary operations in open-cut pits.

The large deposits of the Kansk-Achinsk basin will be developed using surface shovels with a bucket capacity of up to 100 m^3. The worm-drilling mode of mining will be further developed at open-cut coal pits. It will be used mainly at the Kuznetsk and the Minusinsk basins where the seams are of low capacity.

Powerful drills for blast holes of large diameter (up to 400 mm) and a depth of 70 m will be used at Kansk-Achinsk. At the Ekibastuz deposits, which are distinguished by easily drilled rock, it will be more expedient to use blast holes of 200 mm and apply cutting type bits. Owing to the diversity of natural conditions in the Kuznetsk basin, where the technological patterns of operation and the sizes of the machinery used also differ, holes of 118 to 400 mm will be made to a depth of 50 m with the use of different bits.

The pool of excavating machinery will be supplemented with new effective equipment of traditional modes of operation. Soviet-made excavators for open-cut operation cover five basic models and seven modifications (Table 3).

Table 3: Characteristics of bucket excavators.

Model		Bucket Capacity [m^3]		Maximum Operational Depth [m]
Basic	Modification	standard	mounted	
EKG-3.2		3.2	2.5-4.0	13.5
	EKG-2u	2.0	2.5	19.0
EKG-4.6		4.6	4.0-6.3	14.4
	EKG-3u	3.0	4.0	20.2
EKG-8I		8.0	6.3-10.0	17.8
	EKG-4u	4.0	5.0	23.7
EKG-12.5		12.5	10-16	22.5
	EKG-10u	10.0	8.0-12.5	25.6
	EKG-6.3u	6.3	8.0	32.0
EKG-20		20.0	16-25	24.0
	EKG-16u	16.0	12.5-20.0	30.1
	EKG-10u	10.0	12.5	41.5

Since surface shovels have a relatively limited range of application in the coal industry, it is planned to manufacture four basic models and four modifications (Table 4).

Table 4. Surface shovel models*.

Basic	Modification
EBG-15/40	EBG-10/50
EBG-35/65	EBG-40/60
EBG-80/80	EBG-100/70
EBG-100/100	EBG-125/90

*The numerator stands for bucket capacity (m^3), the denominator for beam length (m).

The walking dragline models that are most suitable for use at existing and planned coal mines are listed in Table 5.

Table 5. Walking dragline models*.

Basic	Modification
ESh-5/45	-
ESh-10/70	ESH-13/50
ESh-16/67	ESh-20/55
ESh-25/85	ESh-30/75
	ESh-16/100
ESh-40-50/85	ESh-60/77
	ESh-45/90
ESH-65/90	ESh-75/85
	ESh-55/100
ESh-80-90/100	ESh-100/100
	ESh-110/85
ESh-120/100	ESh-160/85

*The numerator stands for bucket capacity (m^3), the denominator for beam length (m).

The development of continuous-action machines is associated with large-scale use of mechanical rotary shovels for coal excavation proper and others for hard roof stripping. At present, there is a trend toward reducing the linear dimensions of rotary machines and developing more compact and mobile models. The standard set of continuous-operation machines (mechanical rotary shovels, rehandling machines, spoil bank formers) includes machines with a rated capacity of 630, 1250, 2500, 5000, and 12,500 m^3/h. It is also planned to use mechanical bucket wheel excavators of a theoretical capacity of 630, 1250, 2500, 5000 m^3/h (Table 6). Use is to be made of technological patterns of mining operations involving mobile and semistationary crushing installations.

Table 6. Characteristics of bucket wheel excavators.

Model	Theoretical Productivity in Loosened Rock [m^3/h]	Cutting Force [kg/cm^2]	Cutting Height [m]
ERGV-630	1100-690	11-21	9.0
ERP-1250	2500-1250	14-20	21.4
ERP-2500	2500-1750	7-15	16.0
ERShRD-5000	5000	14	30.0

In addition to conventional augers, a twin-head auger with a standard rod string is to be produced that uses bits with diameters of 2.0 m to 2.8 m and has a productivity of up to 8000 t per shift. With this machine, effective working of coal deposits difficult of access will be possible.

The development of electric-powered rail transport is based on an increase in the adhesion weight and power of locomotives and in dump-car and coal-car lifting capacity. Open coal pits will use electric locomotives with an adhesion weight of 180 t and diesel-electric cars of 240 and 360 t adhesion weight; dump-cars of lifting capacities of 105, 145, 165, and 200 to 240 t, and coal-cars with a lifting capacity of up to 140 and 200 t. Progress in motor transport is ensured by the application of powerful coal carriers that can lift up to 120 and 300 t, and dump trucks with a lifting capacity of up to 180 t to carry overburden.

The application of open-cut techniques in vast and rich coal deposits, coupled with optimal siting and intensive development and the use of rational operational patterns and highly effective equipment sets, ensures the most advantageous cost-benefit relation for open-cut coal mining (Table 7). Labor productivity is 6.3 times higher on the average than in underground mines, and production costs are about 75% less. The relation is even more striking in some of the other basins. Another great economic advantage of the open-cut method is that the rated investment in the construction of open-cut pits is about one fifth of that required for the same capacity in the construction of underground mines.

Table 7. Technical-economic indices of USSR open-cut coal mining.

	Labor Productivity	Full Production Cost
	[% of underground coal mining]	
The industry as a whole	631	24
Kuznetsk	310	55
Moscow	400	49
Chelyabinsk	270	46
Sverdlovsk	924	14
Krasnoyarsk	557	25
Karaganda	323	35

We have discussed earlier the favorable effect of an increase in the capacity of open-pit mines on the cost-benefit ratio of their operation. This is illustrated in Table 8.

Table 8. Coal mining cost in relation to open-cut capacity.

Open-Cut Capacity [Mt/year]	Production Cost [% of the average for the industry]
Up to 0.6	233
0.6 - 0.7	185
0.7 - 1.5	153
1.5 - 2.5	126
2.5 - 5.0	105
Over 5.0	59

The influence of the natural and technical conditions of exploitation of coal deposits, and that of mechanization of mining on mining costs, is illustrated in Table 9.

The master policy of coal industry development in the USSR will continue to be the ever-increasing and predominating application of progressive modes of open-cut coal mining.

Table 9. Coal mining cost in relation to mode of overburden removal.

Mode of overburden removal	Production cost [% of the average for the industry]
Walking draglines and surface shovels	45
Mechanical bucket wheel excavators	55
Transport facilities	138
Combined systems	115

TECHNOLOGY OF BUCKET WHEEL EXCAVATORS FOR VERY HIGH PRODUCTION RATES IN OPENCAST LIGNITE MINES IN THE FRG

K.J. Benecke

The development of the bucket wheel excavator (BWE) technology started in Germany about 40 years ago. The German lignite deposits offer ideal geological conditions for the use of these excavators. The first units were of the order of up to 10,000 bank m^3 daily design capacity, in line with the size of the open pits existing at that time.

With growing energy demand in the FRG since the early 1950s, pit sizes increased steadily in production rate, depth, and extent. In the lignite mining industry of the German Rhineland this development was particularly favored by merging fifteen formerly individual companies into one concern, the Rheinische Braunkohlewerke AG (RBW), and reducing the number of mines to a few large-scale open pits.

In parallel to this development was the development in size of the BWE. Until the early 1950s daily capacities ranged up to 20,000 bank m^3. Then, however, the development of high-capacity wheel excavators started with a BWE for 40,000 bank m^3 daily design capacity in 1952. Further progress was rapid and logical. Today we recognize four distinct size classes or generations of the BWE, with design capacities around 40,000, 60,000, up to 120,000, and recently even up to 240,000 bank m^3 per day. A first unit of that fourth generation, designed for 200,000 bank m^3 per day, has been in scheduled service at the Fortuna Mine of RBW in the FRG since January 1976.

With this fourth size class (Table 1) however, the size progress has temporarily come to an end; that is to say, at the moment no plans exist for future open pits requiring still larger excavator units. This fact had already become apparent when progressing from the third to the fourth excavator generation: no further increase in digging height was incorporated in the design because the working geometry had already reached its maximum limit in size class 3. Onward development must thus be restricted to the output capacity (Figure 1).

Starting from a BWE of 20,000 bank m^3 daily capacity, the design of such units had to proceed on entirely new lines (Figure 1). Thus, wheel diameters were tripled from 7.5 to 21.6 m;

Table 1. Technical data of BWE sizes.

BWE Size	0	1	2	3	4
Design capacity [bank m^3/day]	20,000	40,000	60,000	120,000	240,000
Theoretical capacity [loose m^3/h]	2,230	3,860	6,070	9,350	19,120
Nominal bucket volume [m^3]	0.6	1.4	2.3	4.6	6.4
Wheel diameter [m]	7.50	11.50	12.25	17.50	21.60
Wheel drive power [kW]	340	630	920	1590	3360
Wheel boom length [m]	28.0	36.2	42.4	70.5	70.5
Digging height [m]	21.0	30.0	32.0	50.0	51.0
Operation weight [t]	920	2,100	3,100	7,500	13,000
Number of crawlers	6	6 + 2	6 + 3	12 + 3	12 + 3
Crawler area [m^2]	98	190	260	540	780
Ground pressure [kg/cm^2]	0.95	1.10	1.20	1.40	1.65
Face conveyor width [mm]	1200	1600	1800	2200	3000

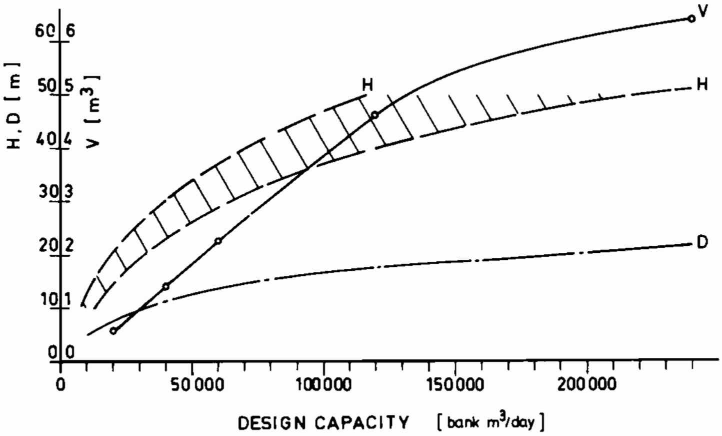

Figure 1. Bucket volume, V, digging height, H, and wheel diameter, D, for various design capacities.

digging heights were increased 2.5-fold from 20 to 50 m, and buckets increased tenfold from 0.6 to 6.4 m^3. The development of size class 3, however, with a daily capacity of 110,000 bank m^3 was required for the Fortuna mine, still the largest pit with an annual output in the order of 120 × 10^6 bank m^3, and a final pit depth of nearly 320 m. The latest size class 4 BWE and connected open-pit mining equipment, capable of handling 240,000 bank m^3/day, was required for the intended production increase at Fortuna mine as well as for the handling of about 320 × 10^6 bank m^3 per year from a depth of nearly 500 m in the future Hambach open-pit mine of RBW. These volumes correspond to a handling rate of 5.3 m^3 (bulk) per second. The conveying path for the flow of material must not be narrowed at any point, but widened on its way from the excavators to the stackers or customer loading points. This principle is reflected in Table 2. Such high handling rates necessitate the use of new system concepts.

Table 2. Design data for conveyor of the 240,000 bank m^3/day system.

	Bucket wheel excavator	Conveyor system	Stacker
Belt width [mm]	3200	3000	3200
Speed [m/s]	4.5	6.0	5.2
Troughing	42°	43°	42°
	5-part	3-part	5-part
		deep trough	
Capacity with 5°			
heaping angle [m^3/h]	21,100	23,600	24,400
Handling rate [t/h]	35,000	37,000	37,000

The following will deal with the complete handling system of the 240,000 bank m^3/day concept.

The Bucket Wheel Excavator

The first link of the handling system is the BWE. The former basic design concepts and the geometric dimensions have been kept the same as in the size class 3. Decisive modifications, however, have been introduced in the bucket wheel, in the conveyors, and in the crawler track assembly. The principal dimensions of the excavator and the arrangement of the belt conveyors can be seen in Figure 2.

The bucket wheel is of the semi-cell type. The diameter is 21.6 m and the number of buckets is 18. No additional intermediate cutters are fitted, because this would have resulted in

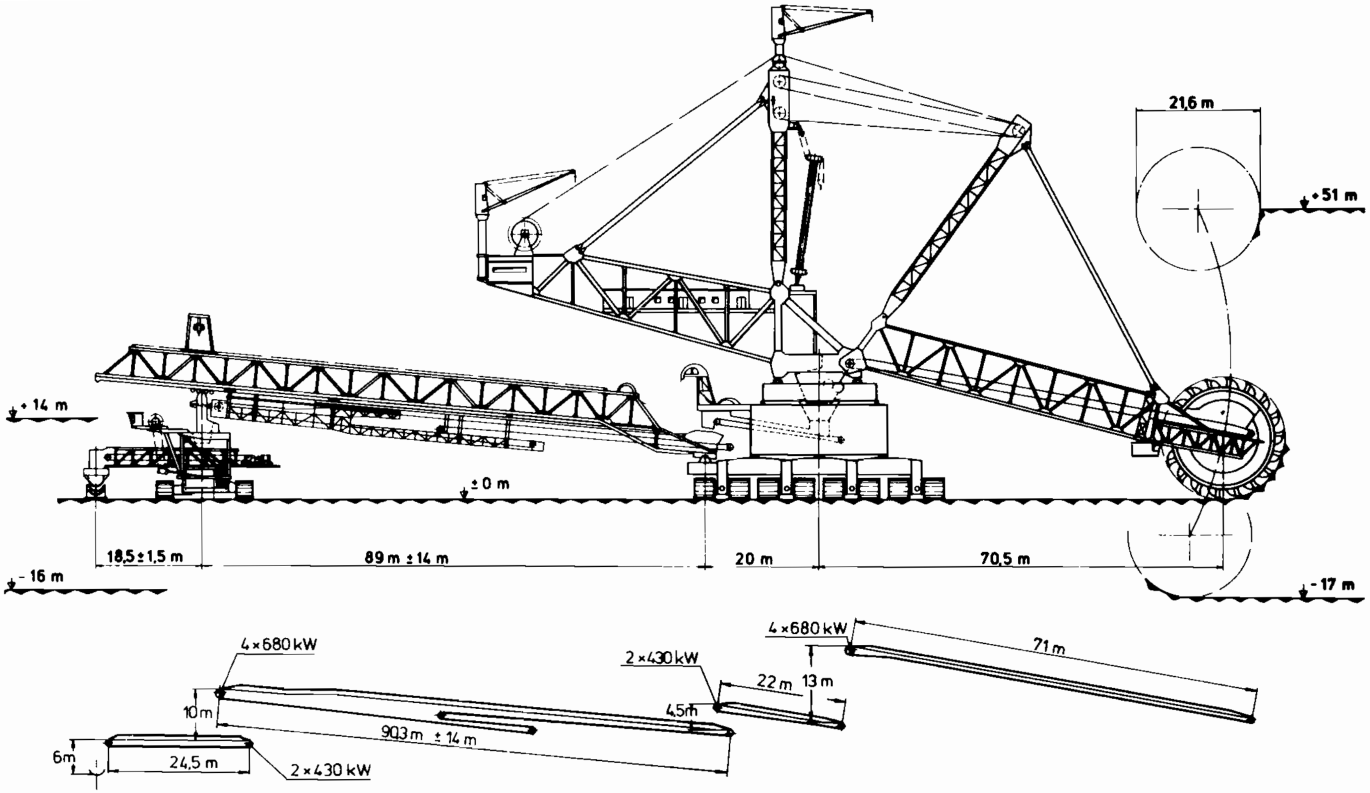

Figure 2. The bucket wheel excavator and its belt conveyors.

further increase of the bucket wheel size. The bucket wheel when lowered to the ground forms a 6° angle to the boom. Four motors with a combined capacity of 3360 kW drive the wheel. The two-step bucket wheel main gear unit is preceded by four 840 kW bevel spur gear units connected with the main gear unit via curved tooth couplings. Magnetic powder couplings are provided as safety links between each motor and its gearing.

The conveyor belts in the bucket wheel excavator are 3200 mm wide. Their carrying runs are supported by 5-part catenary idlers and their return runs by 3-part catenary idlers. The carrying run troughing is 60° in the feed zone and 42° over the remaining length. The return run is troughed by 15°. All conveyors, with the exception of the conveyor in the connecting bridge, run at a speed of 4.5 m/s. The belt in the connecting bridge runs at 5.2 m/s. The belts in the wheel boom and in the connecting bridge are each driven by four 680 kW motors via two-way gear units of the bevel spur gear design. The connections between the gearing and the driving pulleys are flanged. The drive pulleys for these belts have a weight of 29 t each.

The excavator superstructure is supported by a 20 m mean diameter two-track ball race, which rests on the undercarriage. The 320 mm diameter balls run in cages. Slewing movements of the superstructure are actuated by eight pinions that mesh with a gear rim on the undercarriage. Four 80 kW slewing gear units drive these eight pinions via planetary stages.

Two hoist winches of 4300 mm diameter raise and lower the wheel boom by two independent 16-fold rope reeving systems consisting of 75 mm diameter ropes and individually supported 2200 mm diameter rope sheaves. The rope safety factor of the two rope systems is higher than 6, which means that threefold rope safety is maintained in the load carrying system, should one hoist winch or one rope system fail. Each rope system incorporates in its ballast box fixing end an adjusting device with a rope tension measuring unit to enable checks on the rope forces. The raising and lowering speed measured at bucket wheel is 5 m/min. Each hoist winch is driven by two 450 kW motors. The speed reducer pinion shafts are mechanically coupled for synchronism of the two hoist winches.

The excavator is supported at three points, each on a crawler group consisting of four individual crawlers. The 64 track wheels of each crawler group are mounted in bogies such that the vertical load is distributed uniformly over all wheels. The two-wheel, four-wheel, and eight-wheel bogies, and the track frames (15 m long) of the crawlers are of ample size to ensure that both the vertical loads and the horizontal forces that may occur in any load case are fully transmitted through the bogie axles to crawler level. The track frames and the cross beams of the crawlers are special welded constructions made of heavy plates up to 120 mm thick. Each individual crawler is driven via planetary gearing flanged to the drive sprocket shaft. The bucket wheel excavator can travel 1:18 gradients during operation and when moving to another place. For repairs, jacking pads are fitted to the crawler track assemblies and each assembly is engineered to allow all track frames to be drawn off over a center pin.

24 cranes, hoists, and trolleys with carrying capacities up to 350 kN are provided on the excavator system for servicing, maintenance, and repair work. Special devices capable of traveling along the conveying routes are provided for mounting and dismantling the catenary idlers.

Erection of the excavator started at Hambach in July 1976. In September 1978, the BWE will start working to open up the new Hambach pit.

Conveyor System

The conveyors downstream of the bucket wheel excavator must be able to fully remove all excavated material. Therefore, the conveyors have belts 3000 mm wide, are equipped with three-part deep troughed catenary idlers in 1200 mm spacing, and run at a speed of 6.0 m/s.

Six drives, each with 1500 kW output, four of these in the head drive terminal of the belt and two in the tail terminal, drive the belt. The belt tension of 2276 kN maximum which results from the drive power when the belt starts, entails a drive terminal (Figure 3) with an overall length of 76 m, a height of 14 m measured to the top of the electrical equipment house, a maximum width of 11 m, and a design weight of 700 t. The belt runs in the drive terminal over two 1500 mm diameter drive pulleys, then over a take-up pulley, likewise 1500 mm diameter, and then back as return run to the connecting conveyor bridge. The take-up path is 8 m long and motor-operated rope winches are used for tensioning. Whilst the first drive pulley is cantilevered 12 m beyond the front pylon of the drive terminal and 7 m high above grade, the second drive pulley rests on an instrument bogie behind the rear pylon. Load cells measure and control the belt tension.

The two supporting pylons are spaced 19 m between centers and stand on pontoons 4 m × 11 m and 4.4 m × 11 m, respectively, that rest on the ground. The clear space between the pontoons is 15 m wide and 2.8 m high. The shifting crawler described in the next section travels into this clear space when the drive terminal has to be shifted or taken to another place.

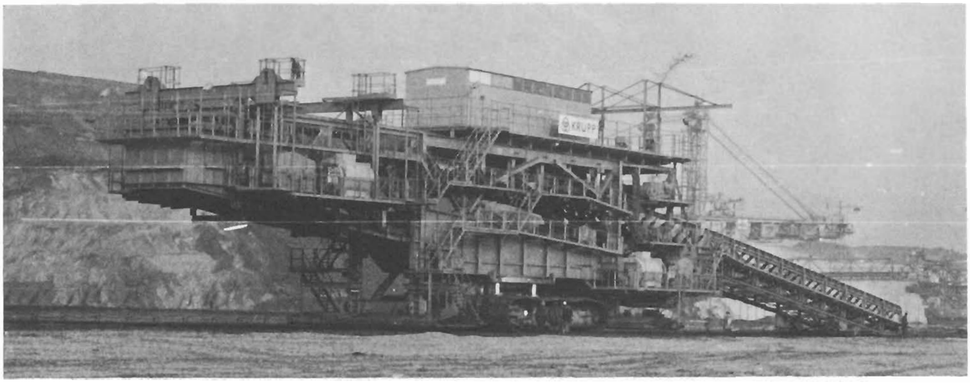

Figure 3. Drive terminal for conveyor system.

Shifting Crawler

The large dimensions and heavy weights of the belt systems of this new high-capacity class necessitate special technical means as shifting and relocating aids. Therefore, the conventional walking feet or walking mechanism principle has been abandoned and a special shifting crawler has been developed for the purpose. The objectives and criteria governing this development were:

- Universal application for the various drive terminals without the need for any additional appliances or additional personnel.
- High maneuverability when shifting and relocating the drive terminal even over major distances.
- Additional application as traction vehicle and heavy-load carrying vehicle in the open-pit operation.
- Independency of power sources by means of diesel-hydraulic drive.
- High traveling speed.
- Low operating and investment costs.

These demands led to the development of the shifting crawler which is shown in Figure 4 and which works in the Fortuna open pit to full satisfaction.

The shifting crawler has an equalized two-crawler assembly. This distributes the load uniformly over the ground. It travels

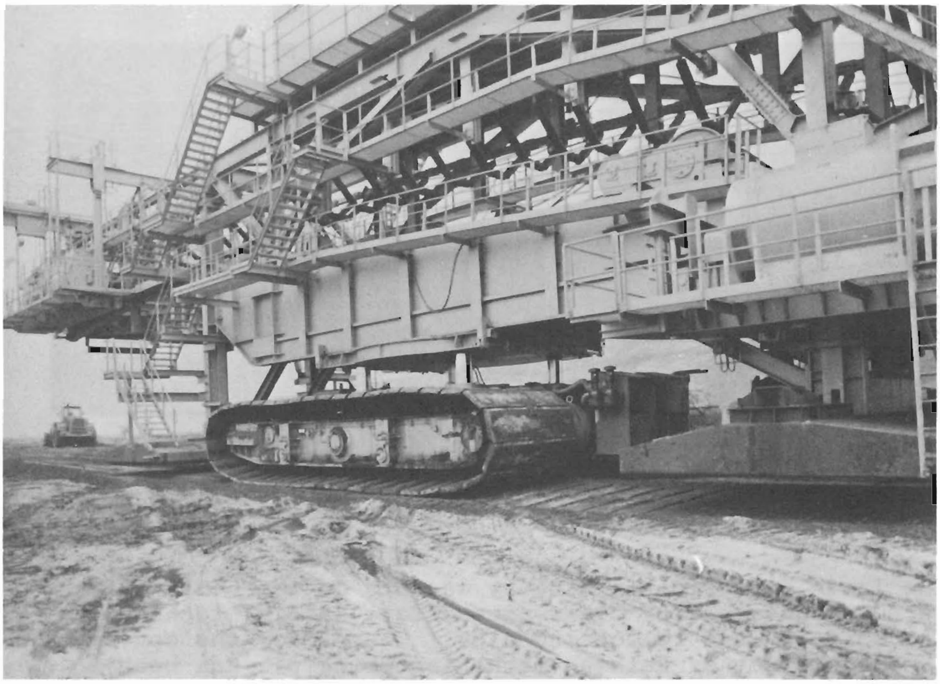

Figure 4. The shifting crawler.

without load 25 m/min, and when loaded with a 700 t drive terminal still at 12 m/min. A diesel engine drives the shifting crawler. Separate hydraulic circuits are provided for the crawler assembly, the lifting mechanism and all auxiliary functions. The shifting crawler is able to travel curves of any desired radius under full load by switching the crawler chains in opposite traveling directions.

Intermediate Drives for Belt Conveyors

Practice and experience have shown that 4 × 1500 kW drive terminals obviously mark the limits of development both from the technical and the economic point of view. A further increase in driving capacity would not only entail larger drive terminal sizes with ensuing increased design weights, but also higher belt tensions and would thereby pose new problems in the manufacture of increased-strength steelrope-reinforced conveyor belting.

In the new Hambach open pit, not only the volume of materials to be handled as a result of the application of 240,000 m^3 BWE, but also the depth to be overcome, will be definitely higher. An installed power of 1120 kW alone would be required to overcome a rise of 10 m in view of the expected handling rate of 37,000 t/h. However, since long conveyors with a minimum of transfer points between the conveyor flights are desirable to avoid malfunctions, especially in open-pit mines where distances to the spoil dumps are long, this problem can only be solved by using a special design concept, namely the belt-to-belt intermediate drives, briefly referred to as the "T-T system".

As can be seen in Figure 5, the carrier, or main belt is supported in such high handling capacity systems by one or several short booster drive belts. The tractive power of the booster belts is transmitted by friction contact to the carrier belt. Each booster belt may be provided with two drives for the head and tail pulley. The use of an adequate number of booster belts and the strength of steel rope belting nowadays available allow any system length and rise to be overcome. The minimum length of an intermediate drive belt required for safe transmission of the tractive power to the main belt depends on the installed capacity of the intermediate drive motors and the intensity of friction under the most favorable operating conditions anticipated.

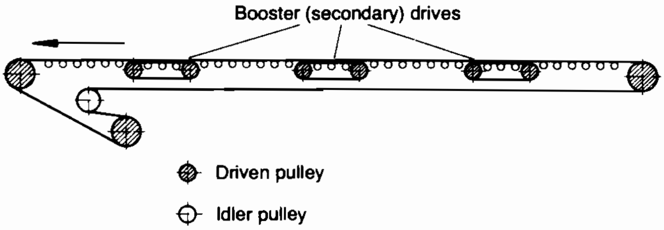

Figure 5. Cross section of the intermediate drives for belt conveyors.

An intermediate belt drive of the T-T system was tried out for the first time in a conveyor system in the Fortuna open-pit mine in mid-1973. This first application of the T-T drive under full-scale operating conditions, in a 16,000 t/h overburden conveyor system lasted 18 months and did not pose any problems under any weather conditions. In particular, belt abrasion was insignificant. Comprehensive investigations and measurements were conducted by the supplier during the entire trial period with a view to ascertaining the friction prevailing under all operating and weather conditions and collecting all the data needed for an optimum design for later T-T drives. These encouraging results led to the installation of two more intermediate T-T drives in the same open-pit mine in the second half of 1975.

Figure 6 shows one of these intermediate drives in a belt conveyor system 2200 mm wide, 16,000 t/h nominal capacity and 1100 m center distance. The total driving capacity was 3440 kW for the conveyor, 4 × 430 kW for the main belt head drive, 2 × 430 kW for the intermediate T-T drive, and 2 × 430 kW for the main belt tail drive. The installation of the intermediate booster drive belt with its 80 m length between pulley centers enabled the existing main belt to overcome an additional 16 m step in terrain.

Figure 6. An intermediate drive.

This installation also demonstrated the advantages offered by the T-T drive principle since, despite 30% higher power requirement to overcome the additional rise in terrain, the existing belting could be retained in use, the belting did not have to be subdivided or shortened, and no additional transfer point was needed. The encouraging results achieved in the application of intermediate T-T drives for long belt conveyors are likewise attainable in the new 240,000 m^3 capacity class with single conveyor flights up to and even beyond 10 km in length.

Boom Stacker

The last link in an overburden handling line is the stacker. Stacker types featuring rope suspended slewing feeding booms have been developed during the past decades as the most favorable stacker form capable of handling 110,000 bank m^3/day. Whilst the first stacker of this size, commissioned in 1957, had a conveyor system composed of five belts, only two belts are employed in recent designs.

In the course of further development aimed at a stacker suitable for the new 240,000 bank m^3/day capacity class, it soon became obvious that the design and operating weights would become excessive and uneconomic for the two-belt stacker type. Therefore, a three-belt stacker provided with a feeding bridge supported by crawler track assemblies was conceived and built. The third belt constitutes the conveying link between the feeding bridge belt and the discharge belt. The operating weight of this three-belt stacker is about 1000 t lower than that of a two-belt stacker with equal handling capacity and rope-suspended feeding boom. Nevertheless, the operating weight of 5246 t is nearly twice that of the conventional 110,000 bank m^3/day stackers.

The dimensions of the new stacker (Figure 7) permit stacking of a dump 35 m high. For better dump stability, it is possible to subdivide the deep dump into a deep base and a 20 m intermediate deep step. In this case, the stacker travels on a level 20 m below, and the bridge supporting carriage on the level of the conveyor system. For a maximum handling capacity of 24,400 m^3/h (about 6.8 m^3/s) with 5° heaping angle of material on the belts, a trouble-free flow of material and therefore very thorough engineering of the handling route, and in particular of the transfer points, is of vital importance. For this reason, the mean height of passage for the material between the catenary idler center roll and the conveyor framework is not smaller than 1700 mm at any point. Belts 1 and 2 ascend by 12° in the most unfavorable operating position. The belt slope has to be moderate in the feeding zone of the discharge conveyor (belt no. 3) and hence the discharge conveyor forms a curve after the feeding zone with a radius of about 675 m. The result is that the belt ascends only by 12° in its feeding zone when the discharge pulley is at its normal height of 36.5 m above grade, and 16° when the discharge pulley is in its highest position of 41.5 m above grade. This ensures that in normal operation the overburden can be handled without any difficulties even in unfavorable weather.

The conveying route, which is composed of a feeding belt (belt no. 1), transfer belt (belt no. 2), and a discharge belt (belt no. 3), has a design width of 3200 mm. Belts no. 1 and no. 2 run at a speed of 5.2 m/s, whilst no. 3 belt reduces the live load on the suspended boom and a rubber belt only 3000 mm wide is needed for this conveyor. The drive and return pulleys of the conveyors, and the catenary idlers, are interchangeable with those of the excavator.

The power of the conveyor drives is based on a handling rate of 37,000 t/h. Figure 6 shows the drive ratings of the belts. This stacker, like the BWE, employs two-way gearing for the belt drives.

The discharge boom is raised and lowered at a speed of 2 m/min as measured at the discharge pulley, by means of two hoist winches and two independent 12-fold reeving systems. The rope diameter

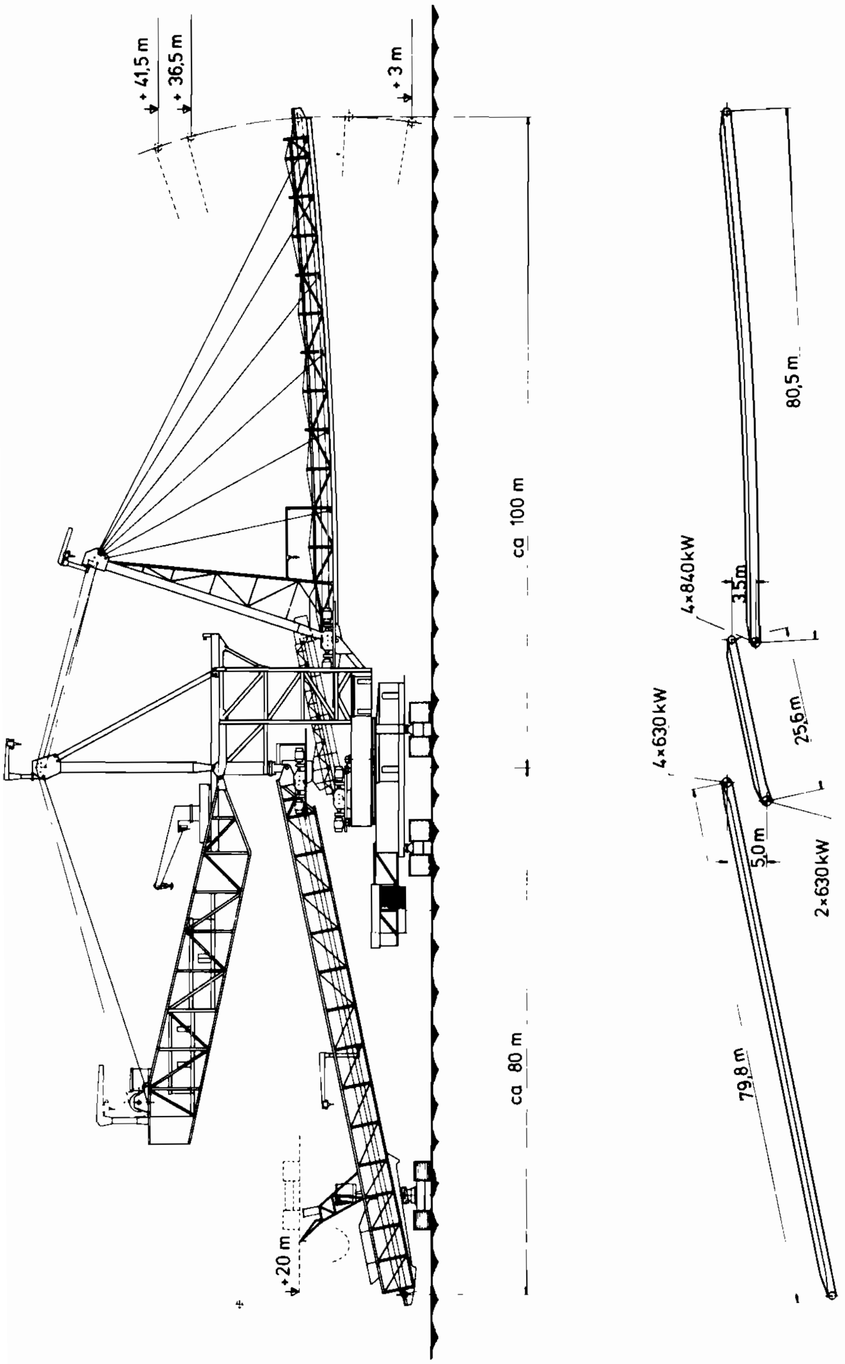

Figure 7. The new boom stacker.

is 44 mm. Each rope sheave is independently supported to ease exchange. For slewing, the stacker superstructure rotates on a 15 m diameter ball race. Three slewing gear units powered with 40 kW and adequately spaced impart the rotary movement to the superstructure. The slewing speed is about 23 m/min at the discharge pulley and is variable.

The stacker is supported at three points, each on a group of two crawlers. Each crawler is driven by one 130 kW motor via planetary gearing to which the drive sprocket shaft is flanged. An equalized two-crawler assembly supports the feeding bridge. The stacker is capable of traveling 1:18 gradients in operation and 1:14 gradients when moving to another place. Seven cranes and hoists with up to 350 kN carrying capacity are mounted on the stacker for maintenance, servicing, and repair work.

This stacker will be commissioned together with the BWE at the Hambach mine in September 1978.

Final Remarks

The development of the BWEs and stackers of the 240,000 bank m^3/day capacity class posed many new problems which could be solved thanks to the experience gained in the building and operation of the former 110,000 bank m^3/day capacity class.

New approaches were also adopted in evolving the conveyor drive terminals. The new shifting principle of transfer crawlers reduces relocation work as well as investment costs.

The new high-capacity class open-pit mining equipment means a further encouragement to the mining company in their endeavors to achieve an annual lignite output of 110 to 120 Mt from only three large open-pit complexes. The coal will be available at moderate cost, thus helping to stabilize the FRG's energy and raw material supply.

Acknowledgments

Table 2 and Figures 2 through 9 have been published in the *Coal Miner*, September 1976, in an essay titled "Open pit mining equipment for very high rates of production" by A. Krumrey, Chief engineer of Fried. Krupp GmbH, Krupp Industrie- und Stahlbau, D-4100 Duisburg 14, FRG.

UNDERGROUND GASIFICATION

UNDERGROUND GASIFICATION OF COAL IN THE USSR

K.N. Zvyaghintsev

Underground gasification of coal (UCG) provides a method for converting in situ coal into a combustible gas.

The concept of UCG was first put forward by the great Russian scientist D.I. Mendeleyev in 1888. It was supported in 1913 in England when Sir William Ramsay suggested an engineering solution to coal bed gasification via single holes, and later, in 1925, in the USSR when B.I. Bokii suggested UCG with the help of mine workings.

The advent of the idea of UCG, and its development, are due to the evident advantages of this technology. Among these are the elimination of hard and often unhealthy jobs of men underground and the production of fuel in the most convenient form for transport and use--as a combustible gas.

UCG efforts were initiated in the USSR in 1933 simultaneously in the three main coal basins--Donbass, Kuzbass, and Mosbass--and continued until, in 1941, they were interrupted by World War II. This work corroborated the possibility of gasifying in situ coal beds without first rubblizing them and resulted in development, for the first time in history, of the so-called stream method for gasifying coal in a channel.

The same chemical reactions as in a conventional surface gasifier are basic to the UCG process: carbon combustion, carbon dioxide reduction, steam decomposition, and carbon monoxide conversion. The composition and the heating value of the product gas depend upon the composition of the gasification agent, coal quality, and the geological conditions at sites. Theoretically, the heating value of a gas produced by air gasification cannot exceed 44×10^5 J/m^3. However, it can become 46×10^5 to 50×10^5 J/m^3 due to the water vapor involved in the process and decomposition of the organic mass of coal. With increasing oxygen concentration in the blast (oxygen content 65%), the heating value of the product gas may amount to 63×10^5 J/m^3.

The UCG effort was resumed after the War and has continued up to the present. The USSR is the leading country in UCG development. All stages of UCG are performed from the surface without having to employ men underground. The process involves the following basic stages.

- Drilling of vertical, inclined, and inclined-horizontal access holes through a coal bed, which serve for blast injection and gas removal;

- Formation of reaction channels in the coal bed between the injection and the production holes, in which the coal interacts with the flowing blast and gas streams, i.e. for coal gasification;

- Gasification of coal by supplying blast through the injection holes and drawing gas through the production holes.

The air injection and the gas production holes are arranged in a certain pattern to form an underground gasifier. On the surface above the underground gasifier, there are air and product gas pipelines. Some distance away are air compressor equipment and a gas processing plant.

Figure 1 is a schematic diagram of a UCG station. Holes are drilled by the conventional rotary method. Reaction channels in the coal bed are made by linking holes by filtration or by fire, depending on the natural permeability of the coal; by hydraulic fracturing with water or high-pressure air; and by directed drilling.

As has been mentioned, a combustible gas from in situ coal is formed by the same chemical reactions as in a conventional surface layer gasifier; but coal gasification in a channel exhibits several specific features. The two most important are the following.

First, the coal does not move; instead, the combustion zone itself moves, followed by other gasification zones. As the coal bed is consumed, the roof subsides under the rock pressure and fills the space formerly occupied by the coal. As a result, the size and the structure of gasification channels are preserved for rather a long time. Hence, the gas composition remains relatively constant.

Second, there are no gastight gasifier walls. Therefore, the process involves not only the moisture of the coal proper but also that of the surrounding rocks and gravitational groundwater, if any. The design of an underground gasifier or hole pattern, the method of channel formation, the air injection conditions, and the technical indicators of the UCG process are not determined solely by the class of coal. They also depend upon coal bed structure and thickness, its gas permeability and depth, the lithological composition and the physicochemical properties of formations lying in the top and in the bottom of the coal bed, and the hydrogeological conditions of a site.

In the USSR much experience has been accumulated in UCG of various coals, from brown to hard ash ones. Their thickness

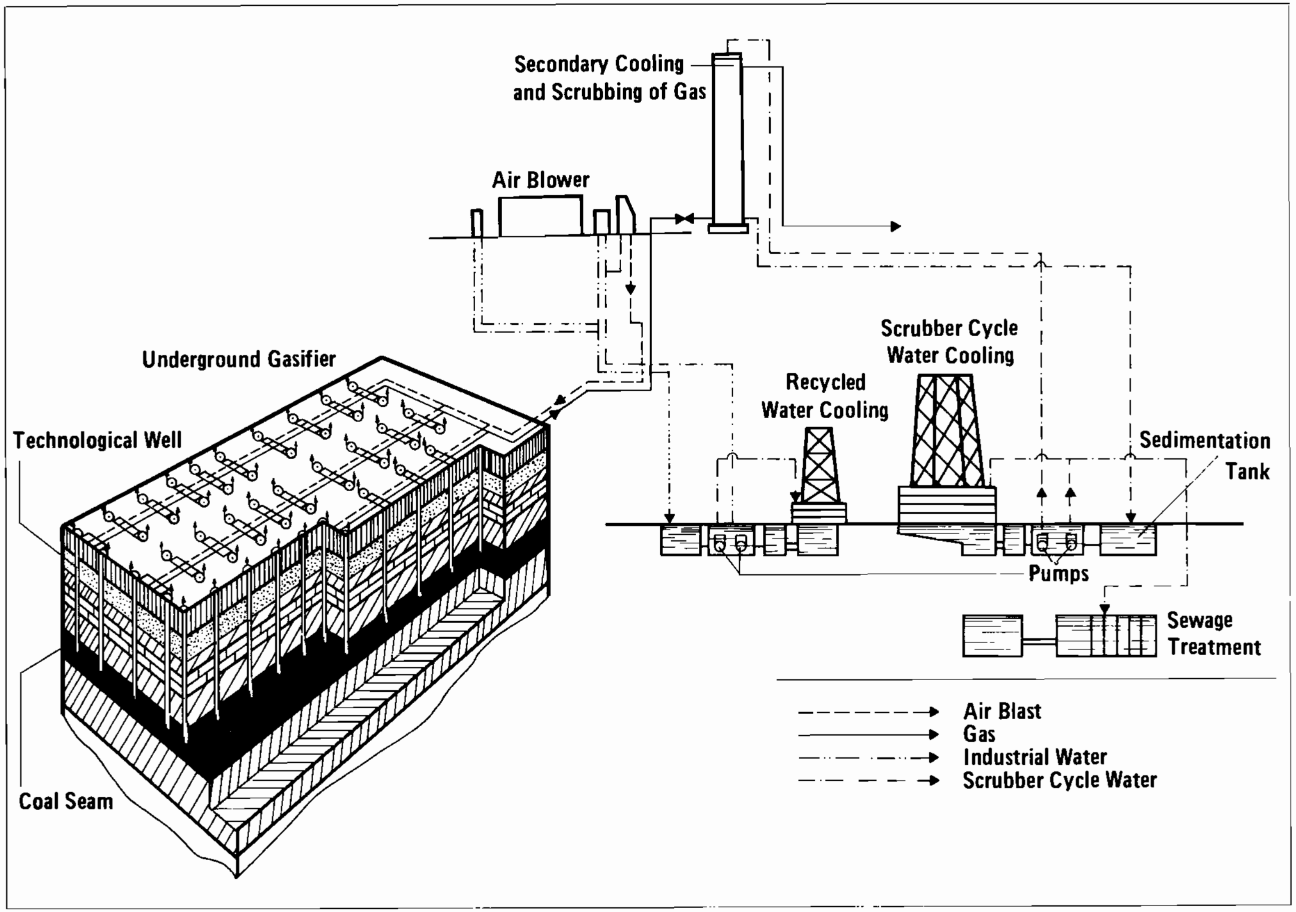

Figure 1. The Podsemgas UCG station.

varied from 0.75 to 20 m, their depth from 40 to 300 m. Gas permeability of coal beds ranged from 1 to 2000 millidarcy. Depending on the class of coal, moisture content was between 2.5 and 55%; volatiles per combustible mass were between 3.7 and 64.5%. The heating value of the product gas ranged from 80×10^5 to 306×10^5 J/kg.

The geological and hydrogeological conditions at the sites were also different. Use was made of both horizontal and steeply dipping coal beds. At some sites the hydrogeological conditions were termed as complex, i.e. prior to UCG the site had to be drained by pumping off groundwater.

Based on this experience, we have succeeded in developing underground gasifier designs for both horizontal and steeply dipping coal beds. Several dependencies characterizing the course of channel formation and gas production processes have been established: for example, that of the rate of fire filtration linkage on air injection rate, coal bed thickness, and hole spacing. Methods for hydraulic fracturing of a coal bed by water and high-pressure air have been developed. The technology of drilling inclined-horizontal holes (which are inclined in the formations and horizontal in the coal bed) has been worked out.

The effect of coal bed thickness and watering conditions on the quality of the product gas has been elucidated. The dependency of the heating value of the product gas upon the air injection rate has been established, and the role of the nature and thickness of overlying and underlying formations in channel preparation and coal gasification processes has been clarified.

The principal conclusion of the Soviet investigations is that fairly good results on UCG are obtained under appropriate geological and hydrogeological conditions of the coal bed and with certain quality of coals.

Two Soviet UCG plants are operational in different mining-geological conditions. One, in Yuzhno-Abinsk, has been in operation since 1955. It is in the Kemerovo region (Kuzbass). Steeply dipping beds of hard coal are being gasified. Coal bed thickness is 3 to 10 m. The inclination is 55 to 57°. The heating value of the coal is 290×10^5 J/kg, and the volatile content 32 to 36%. The coal is processed down to depths of 300 m. Gas production of the station is 0.5×10^9 m^3 per year. The product gas is used as an energy-producing fuel at 14 enterprises located within 25 km of the station.

The second plant, Angren station, has been in service since 1961. It is situated in Central Asia, in the Tashkent region, near the town of Angren. A horizontal bed of brown coal, varying in thickness from 3 to 20 m and in depth from 150 to 220 m, is being gasified. The heating value of the coal is about 190×10^5 J/kg, and the moisture content 30%.

The design production capacity of the plant is 2.3×10^9 m^3 of gas per year. The product gas is transported and used at the Angren electric power station 5 km from the gasifier. The practical indicators of the UCG process are listed below.

Table 1. Indicators of the UCG process.

	Station	
	Yuzhno-Abinsk	Angren
Gas heating value [10^5 J/m^3]	37 - 44	32 - 36
Gas production per ton of coal [m^3]	4100	2600
Gasification efficiency [%]	55 - 60	55 - 60
Gas production per m^3 of injected air [m^3]	1.1 - 1.3	1.1 - 1.3
Gas leakage [%]	10 - 23	10 - 23
Coal losses [%]	20	20

It follows from this table that the gas from UCG recovers 55 to 60% of the heating value of the consumed coal, leakages being taken into account. The rest of the coal heating value is consumed in heating the gas and the formations, and in groundwater heating and evaporation. Coal losses are equal, on the average, to 20%.

Running UCG plants on a commercial scale in the USSR has revealed the following advantages of this process over mining and strip mining.

- The impact on the environment is far less. The fertile soil layer is preserved; there are no dumps or waste heaps. The land is returned to agriculture after surface communications have been dismantled;

- Use of gas rather than solid fuels in energetics with all ensuing advantages;

- Improved conditions of work: underground jobs of men are completely eliminated, all the operations are performed from the surface;

- Possibility of recovering coals with high ash and sulfur content;
- Much shorter construction time for UCG stations than for mines and coal quarries.

Economic calculations show that the efficiency of UCG processes directly depends upon plant capacity. At equal capacities, UCG fuel production is cheaper than in mines or stripping.

Among the weaknesses of the available UCG technology are the moderate heating values of the product gas and, hence, uneconomic costs of transporting it over distances greater than 25 to 30 km.

In conclusion, note that the successful UCG tests conducted in the USSR with various coals under various mining-geological conditions are a reliable basis for employing this method for fuel production also from coals lying at depths of more than 500 m.

UNDERGROUND COAL GASIFICATION: ECONOMICS AND TECHNICAL OUTLOOK

M.K. Buder, O.N. Terichow, and D.J. Goerz, Jr.

The purpose of this presentation is to stimulate the further development of underground coal gasification (UCG) and to examine the prospects for its commercialization in the USA. We recognize that the developmental effort in the USA has been limited compared to Soviet work which has been underway for almost half a century. We also acknowledge that the US Department of Energy (DOE) representatives in the audience have more direct UCG experience than members of the private sector. However, we have prepared this theoretical paper based on internal paper studies to measure our understanding of the technology against practical existing operations.

INTRODUCTION

The economics of the in situ gasification of two types of coal deposits, horizontal and steeply dipping coal beds, is considered here. Horizontal seams can be gasified by the linked vertical well (LVW) method, while steeply dipping beds (SDBs) by a different technique. As illustrated in Figure 1, the LVW process takes place in two stages: linking followed by gasification. Reverse combustion linking as used by DOE in its Hanna, Wyoming, field tests is the basis for the economic evaluation. These tests have demonstrated that sustained gas production at a consistent heating value can be obtained with resource recovery efficiencies on the order of 70% [1].

Preliminary economic studies [2,3] speculate that in situ gasification by the LVW method could compete favorably with coal mining followed by aboveground gasification to produce fuel gas, synthetic natural gas (SNG), and electrical power. In a commercial-scale LVW operation, the considerable drilling, linking, and piping requirements can account for well over 20% of the product gas cost [2-5]. The actual percentage of gas cost determined by these LVW field operations depends on site and process parameters such as coal bed thickness and depth, coal permeability, overburden properties, operating pressure, well spacing, and the linking method used.

Our studies indicate that the cost of gas generated from SDB gasification (shown in Figure 2) is less sensitive to UCG field costs, since the amount of required drilling, linking, and piping per unit of product gas energy value would be less

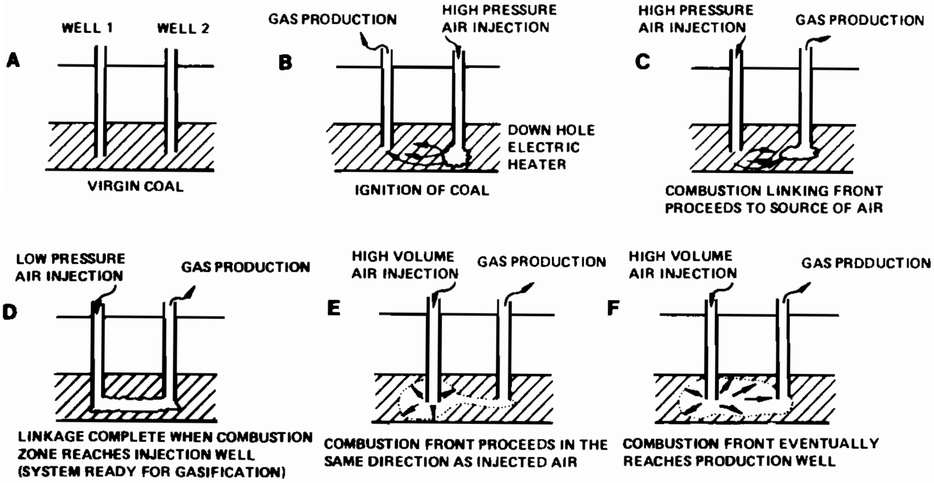

Figure 1. Steps leading to gasification in LVW process.

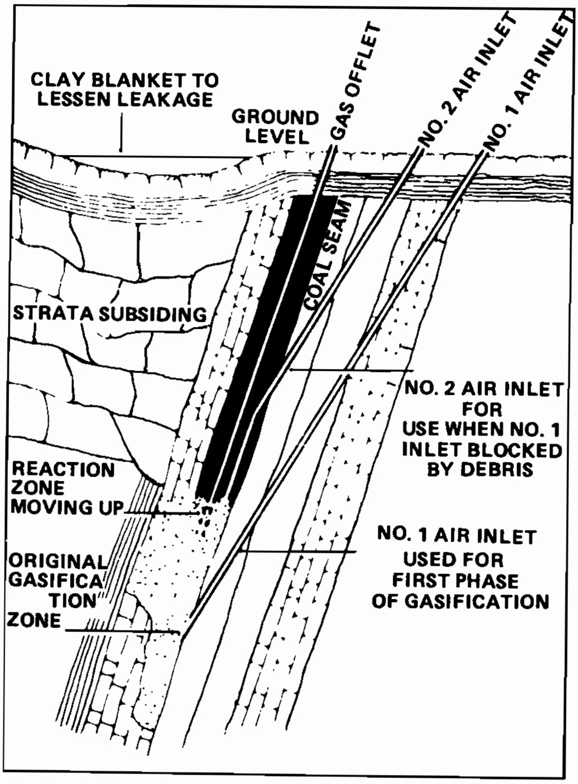

Figure 2. Use of two air inlet boreholes in a steeply sloping seam.

Source: [5]

than in the LVW gasification of a comparably thick coal bed. SDB gasification involves oblique drilling alongside and through the coal bed, thus eliminating much of the need to drill a field of spaced holes through often hard overburden to reach the coal as in the LVW case. Also, the need for the substantial linking operations characteristic of LVW fields is appreciably reduced in SDB gasification. Unlike the LVW method, in situ gasification of SDBs has never been attempted in the USA, although DOE has just initiated an experimental SDB program [1]. However, the USSR has gasified thin SDB deposits at Lisichansk [6,7].

COAL RESOURCES

UCG should not be envisioned as an alternative to mining, but rather as a method of coal recovery to complement mining.

There is a proven reserve of about 400×10^9 t of economically mineable coal in the 48 contiguous States of the USA, which corresponds to about 9% of the total estimated reserve of 4.3×10^{12} t. Assuming a 50% recovery factor, 200×10^{12} t (or 4500 quads*) of coal can be extracted from the proven reserve. By comparison, as Figure 3 shows, there are only 225 quads of proven natural gas reserves in the lower 48 States out of a potential total gas reserve of 870 quads.

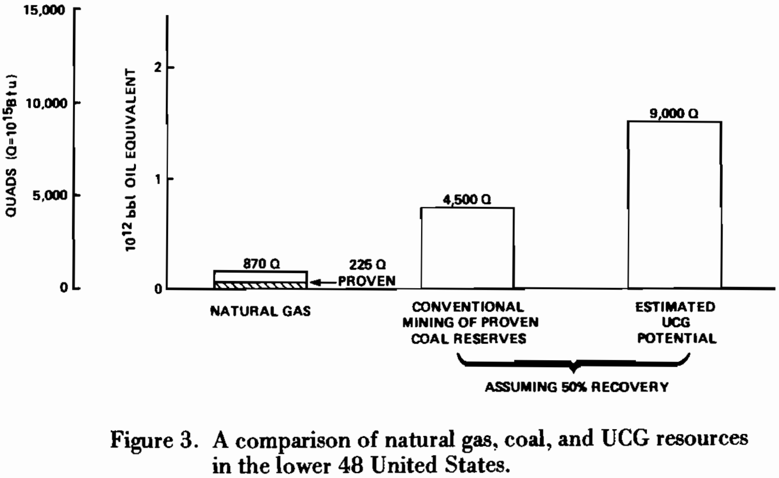

Figure 3. A comparison of natural gas, coal, and UCG resources in the lower 48 United States.

Sources: API/AGA, USBM/USGS, and DOE.

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*I quad = 10^{15} Btu, or about 10^{18} J.

Preliminary DOE estimates predict that UCG could potentially triple the economically recoverable coal reserve of the 48 contiguous States [1]. Figure 3 shows an estimated 9000 quads of coal potentially extractable by UCG with 50% recovery. This is 40 times the size of the proven natural gas reserve. About 97% of the potential UCG energy contribution resides in horizontal coal beds, with the remaining 3%, some 25×10^9 t, occurring as SDBs. At 50% recovery, this SDB resource alone could produce 2.6×10^6 MW-years of equivalent power generation, assuming a heat rate of 10,000 Btu/kWh and a coal energy value of 9000 Btu/lb. This corresponds to about 4000 plant-years of power generation, based on 1000 MW power stations operating at an average 65% load factor.

GENERAL DESIGN BASIS AND COST ESTIMATES

Costs for producing raw, low energy fuel gas by UCG have been estimated from designs with the LVW and SDB concepts. Cost estimates included only gas production--all processing facilities were omitted.

Table 1 summarizes the general design basis used. Both systems were sized to produce a constant gas rate equivalent to 500 MW of electric power generation. To meet this requirement, 29.4×10^6 standard (st.) ft^3/h of 170 Btu/st. ft^3 gas must be produced at a constant rate. Although the assumption of a lower gas energy value would have been more conservative, the 170 Btu/st. ft^3 figure was chosen because it conforms with average

Table 1. Design basis for LVW and SDB cases.

Item	Design basis used
Gas production rate	29.4×10^6 st. ft^3/h of 170 Btu/st. ft^3 dry gas
Coal heating value	9000 Btu/lb (in place)
Other coal properties	Permeable for linking, shrinks/spalls when heated, 85 lb/ft^3 density (in place)
Coal bed thickness	20 ft
Overall efficiency	60%
Product gas conditions	300 °F, 50 lbf/in^2, free of tars
Air requirements	0.57 st. ft^3 air/st. ft^3 gas
Life of facility	20 years

experimental results obtained by DOE at Hanna, Wyoming over a 20 day period.

The coal chosen for gasification is a western subbituminous coal with an energy value of 9000 Btu/lb and a density of 85 lb/ft^3 in place. Use of subbituminous coal is important for two reasons: its greater permeability relative to higher-rank coals facilitates reverse combustion linking, and its tendency to shrink and spall when heated aids in providing the "packed bed" underground reactor desirable for efficient gasification. The coal is assumed to lie in a continuous seam with an average thickness of 20 ft.

The designs assume a 60% overall efficiency, which we define as the energy content of the product gas divided by the energy content of all the in-place coal, except that intentionally left behind as roof support pillars or barriers between modules. By design, about 20% of the total coal was left in place for these purposes. A 60% overall efficiency is conservative compared to the 70% figure mentioned earlier in reference to DOE experience at Hanna, Wyoming. The product gas is detarred near the production wells and delivered to a central processing area at assumed conditions of 300 °F (150 °C) and 50 lbf/in^2 above atmospheric pressure. The 0.57 air/gas ratio used was determined by DOE experience.

Further assumptions or specifications for the conceptual design were made in addition to those shown in Table 1. First of all, no credit is taken for the energy value of the tars and other condensibles produced, nor for the sensible heat in the gas emerging from the wells, although these combined effects can account for about 10% of the product gas energy content. Secondly, zero gas leakage is assumed, although USSR experience has often indicated the loss of a small percentage of product gas. DOE has not yet detected any gas leakage in its tests, but gas losses from stress-related cracks in overlying strata are expected to become a problem with increased well spacing and larger systems. Thirdly, it is assumed that sufficient water is available underground to sustain the gasification reaction; the moisture in the coal itself can supply a significant fraction of the water needed. It is also specified that all process instrumentation is located aboveground. Presumably, uniform gas quality can be attained by controlling water influx to the reaction zone through adjustment of the air injection rate or the gas back pressure. Finally, power, water and other resources are assumed readily available nearby.

The LVW Facility

The site for the LVW gas production field is assumed as a relatively flat area having dimensions of roughly 2.8 miles by 1.3 miles (2300 acres). The coal bed lies an average of 500 ft below the surface and is accessed by vertical cased wells spaced 100 ft apart. Linking is achieved by reverse combustion.

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Figure 4 shows the stepped gas production pattern assumed for the LVW field design. It resembles the production pattern experienced in DOE's recent Hanna II tests [8]. As gasification proceeds, more reaction surface area becomes available and the rate of water influx increases. Therefore, to maintain gas quality, the air injection rate must be varied periodically during the life of each pair of injection and production wells. Increasing the air injection rate accelerates water consumption through gasification. Some other production pattern could have been chosen, but the one shown in Figure 4 combines simplicity and actual experimental results.

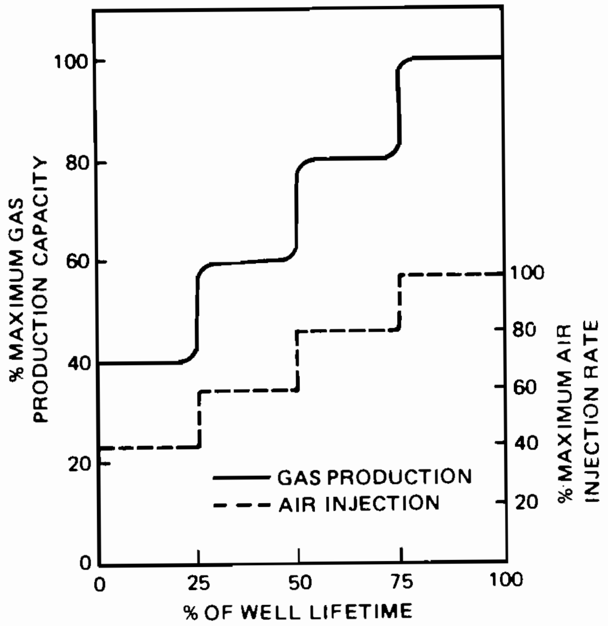

Figure 4. Gas production and air injection patterns assumed for LVW case (the same units are implied for air and gas rates).

Calculations predict that it will take about 31 days for each production well to pass through all four levels of gas capacity from 40% of maximum production to full production, projected at 25 × 10^6 st. ft^3/day. Operation at each capacity level lasts 7.7 days. To obtain constant gas output equivalent to a 500 MW power generation rate, 40 production wells are required to operate concurrently in four groups of ten. Each group of ten wells operates at a different capacity level, corresponding to one of the four steps in Figure 4. By this design, every 7.7 days one of the four groups reaches exhaustion and a fresh group of production wells comes on stream at 40% of full capacity. Per year, 474 new production wells must be drilled and linked. Including the 120 wells arbitrarily provided as a capital expenditure, the total number of wells required over the 20 year life of the entire UCG field is 9500.

Consistent with the above description, the UCG field is divided into four equal sections as shown in Figure 5. At any time, a group of ten production wells is operating in each section at one of the capacity levels shown in Figure 4. In each section there is space for parallel rows of 30 wells.

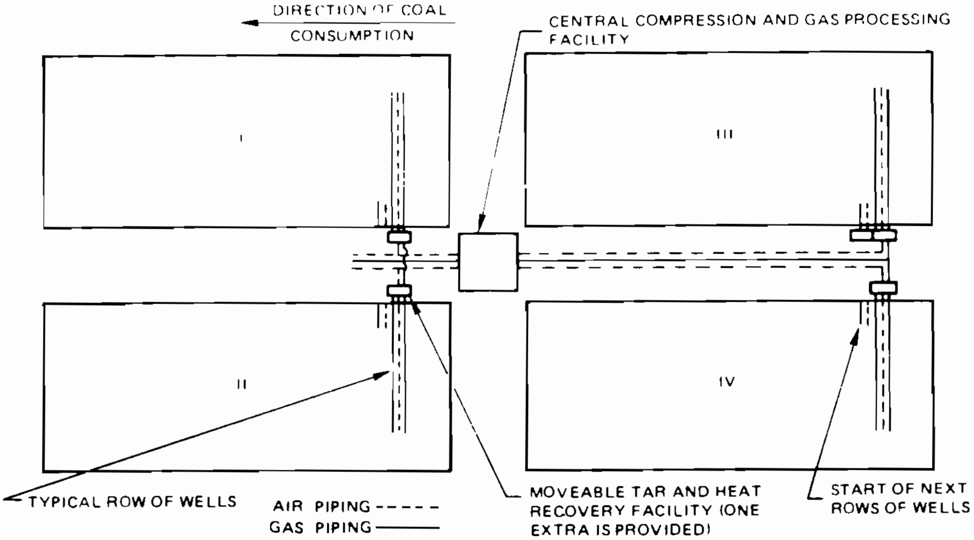

Figure 5. Layout of LVW gas production field.

When a row is in active operation, five of its wells at a time are either producing gas or receiving compressed air. As Figure 5 illustrates, three rows in every section are simultaneously active. Air is injected in the middle row and gas is produced from the straddling rows. Drilling, casing, linking, and relocation of piping are continuous, concurrent operations. Because of its unpredictability, the reverse combustion linking phase limits the logistics of the entire operation.

The hot gas produced is cooled from about 600 to 300 °F (300 to 150 °C) and detarred at the edge of each section in movable field processing stations composed of skid-mounted heat exchangers, process vessels, and pumps. From these stations, low-pressure steam, tar, and return cooling water are transferred to the central processing facility. The latter is the site for air compression, gas collection, a cooling tower, a flare system, tar storage facilities, and, potentially, a gas treating plant. The main control house is also located at the central facility, but some instrument panels are provided at the field stations, which are relocated as gasification proceeds downfield. The central processing facility and all piping from it to the field stations are situated away from areas of potential ground subsidence directly above the gasification zones.

The SDB Facility

As opposed to the large field of wells and piping making up the LVW field, the SDB site takes the form of a long strip along the outcrop or upper extremity of the steeply dipping coal bed. The site selected for this design is a narrow 11.4 mile strip along a mountainside having a 20° average slope. The 20 ft thick coal bed dips at 45° into the mountain, and is accessed by modules of wells spaced 100 ft apart.

Figure 6 illustrates the configuration of air injection and gas production wells for one SDB process module. Five gas

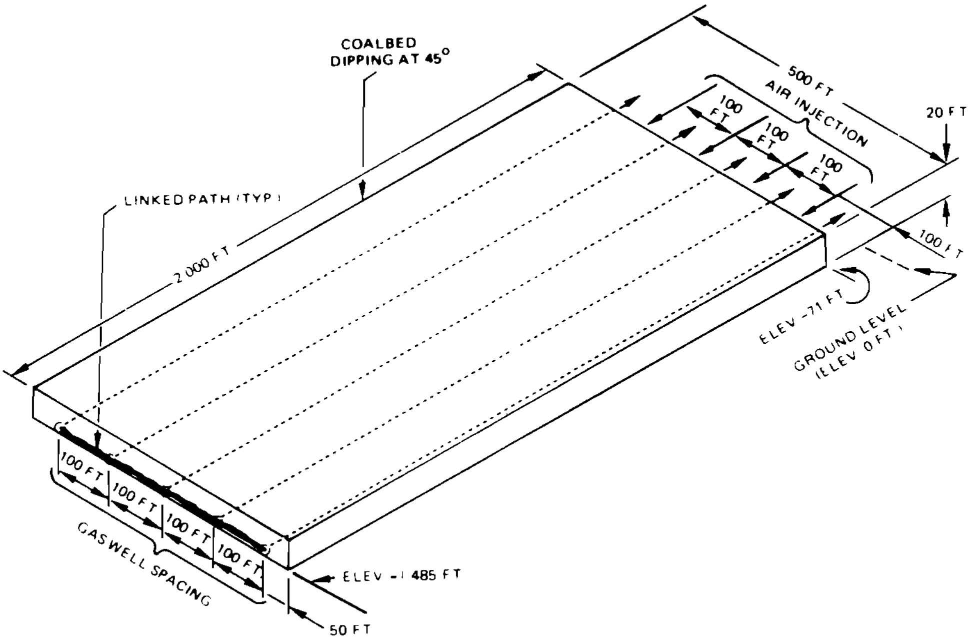

Figure 6. One SDB gasification module showing major dimensions (not to scale).

production wells spaced at 100 ft intervals are drilled an average distance of 2100 ft down through the coal bed at the 45° dip angle. Casing is provided for the top 100 ft of each gas well. Midway between each pair of gas wells in the module, provision for air injection is made by drilling through the underburden to enter the footwall of the coal bed.

Ten modules such as that shown in Figure 6 must operate concurrently to produce the required amount of gas. The SDB site is designed so that each module operates independently. Gasification proceeds upward from the linked paths joining the air injection bore holes with the gas production wells at the bottom of the module. Except for a short period after ignition, the rate of gasification is expected to proceed at a fairly constant pace, unlike the stepwise increase in gasification rate encountered with the LVW system. A constant gas production rate of about 14×10^6 st. ft^3/day per well is assumed in the SDB design.

In the 20 year life of the site, 120 modules will be gasified, covering a distance of 60,000 ft (11.4 miles) along the outcrop of the coal bed. Every 20 months, a complete transition must be made to a new set of 10 operating modules.

Figure 7 is a plan of the SDB site showing the layout and movement of piping and equipment. All raw gas produced is piped to the central processing facility from the point of gasification, which starts directly opposite the central processing facility and proceeds outward in both directions along the coal bed. Process piping is purchased and added as needed during the course of the facility's lifetime. In this design, the air compressors, as well as the gas cooling, detarring, and emergency relief equipment, are mounted on movable skids that travel along a graded strip.

Cost Estimates

Capital and annual cost estimates were prepared from the conceptual LVW and SDB field designs described above. From these estimates the cost of producing raw, low-energy gas was derived. All costs assume early 1977 dollars and wage levels.

The total capital costs estimated for the installed LVW and SDB facilities are $\$56 \times 10^6$ and $\$44 \times 10^6$, respectively. Table 2 gives a breakdown of these figures into the major capital cost elements. For both the LVW and SDB designs, about 20 to 25% equipment and piping redundancy was incorporated to facilitate full production during well or module transition operations. Costs for instrumentation and electrical were largely factored. In each case, 10% was added to the total capital investment to account for owner's costs such as site investigation, land purchase, plant start-up, operator training, etc. Interest during construction was assumed at 9.5% over a two-year construction period with a 0.5% commitment fee.

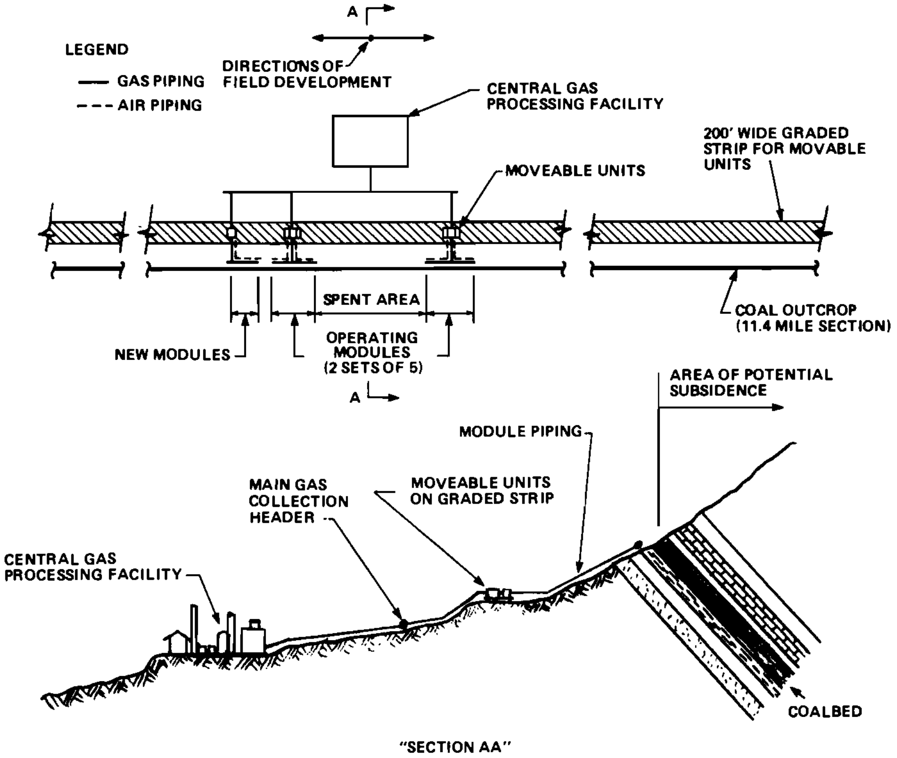

Figure 7. The conceptual SDB gasification site (not to scale).

Estimated annual costs are listed in Table 3. These are based on continuous, year-round operation. From the sum of the annual costs and the cumulative yearly gas production, raw gas production costs of \$0.94 and \$0.79/10^6 Btu for the LVW and SDB cases, respectively, were determined. About twice these figures would approximate the cost of upgraded low-energy gas which has been treated to remove particulates and sulfur compounds at a facility near the gas production field.

Operating labor costs were based on round-the-clock 8-hour shifts of six and five men for the LVW and SDB cases, respectively. Operating supplies were factored as 20% of operating labor. Annual maintenance labor and material for this type of facility was assumed to be 2% of the capital cost in each case.

Table 2. Capital cost summary [10^6 \$ 1977].

Cost item	LVW	SDB
Site preparation, buildings	2.6	6.0
Air compressors	10.6	10.3
Process and miscellaneous equipment	3.7	3.3
Piping	17.0	7.2
Instrumentation	1.7	2.0
Electrical	1.9	2.8
Wells and casing material	1.5	0.1
Total direct costs	39.0	31.7
Indirect costs	3.4	1.6
Total field costs	42.4	33.3
Engineering and home office costs	4.2	3.3
Contingency	9.4	7.4
Total capital costs	56.0	44.0

Table 3 shows a significant cost contribution accountable to air compression power and fuel requirements for gasification and linking, respectively. Electrical power was assumed to cost $0.025/kWh, and the relatively minor amount of diesel fuel for the linking operation was priced at $0.50 per US gallon. Alternative means of driving the gasification air compressors might have been chosen. For example, it may have been cheaper to purchase steam for turbine drivers from an assumed nearby power plant. However, such an assumption would limit the relevance of the cost estimate. Alternatively, gas turbines fueled by the product gas might have been used, but the feasibility of using UCG-derived gas to drive gas turbines has not yet been proven.

The coal royalty arbitrarily applied in these estimates corresponds to $1.00/t of coal gasified, or about $0.07/$10^6$ Btu of gas produced. Figure 8 shows the moderate variation in LVW and SDB gas cost as the charges for coal royalty depart from the base cases. Quantitatively, the effect is about six cents change in gas cost per dollar of variation in coal royalty. The capital-related costs shown in Table 3 are based on a 37% annual charge over a 20-year plant life to give a 15% discounted cash flow (DCF) return. Capital is raised at a 60/40 debt/equity ratio. Debt is repaid over a five-year period at 9.5% interest rate. However, interest during construction, commitment fees, and prestart-up expense were amortized over the 20 years of project life. A 48% income tax rate was assumed, and the

Table 3. Summary of annual expenses and cost of raw gas.

Cost item	Annual cost [10^6 $ 1977]	
	LVW	SDB
Drilling subcontract	4.6	2.8
Field modification labor and material	0.4	2.1
Linking labor and supplies	1.2	0.3
Operating labor and supplies	1.1	0.9
Maintenance labor and material	1.1	0.9
Power and fuel	9.1	8.4
Coal royalty	3.0	3.0
Capital-related (@ 37% to give 15% DCF)	20.6	16.3
Total annual cost	41.1	34.7
Annual gas production (10^{12} Btu/yr)	43.8	43.8
Raw gas cost ($/$10^6$/Btu)	0.94	0.79

plant was depreciated on a double declining balance basis. Escalation, depletion allowance, severance tax, and investment tax credit were assumed to be zero, with the resultant effect of a more conservative cost estimate.

In retrospect, the dominating cost factors in this conceptual design are related to air compression, piping, and, especially in the LVW case, pregasification operations (drilling and linking). These cost factors are sensitive to coal bed thickness and depth, well spacing, gas heating value, and pressure. Elements such as coal properties, overburden characteristics, and terrain will also influence costs. Figure 9 shows a cost extrapolation from the LVW base case to various coal bed depths between 200 and 1000 ft for both the 20 ft thick seam considered here and another extrapolation to a 30 ft thick seam. Raw gas production, according to Figure 9, is projected to cost an additional 2 cents/10^6 Btu for every 100 ft increase in coal bed depth. Gas cost varies by about the same amount per foot change in coal bed thickness. The dashed line which represents the SDB base case shows that SDBs may be gasified in situ at lower cost than thicker horizontal coal beds exceeding some cutoff depth (about 600 ft for the cases shown). Cost sensitivity to the parameters just discussed illustrates how site selection can be critical to UCG economics.

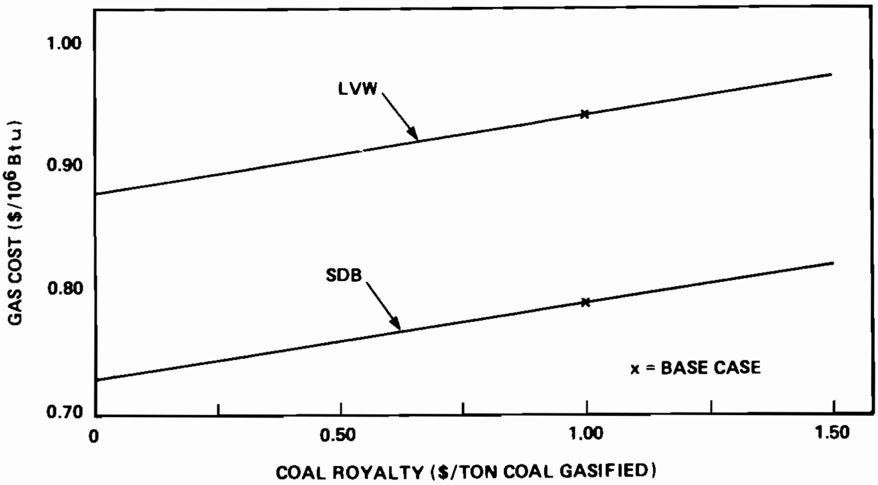

Figure 8. Variation of gas cost with coal royalty.

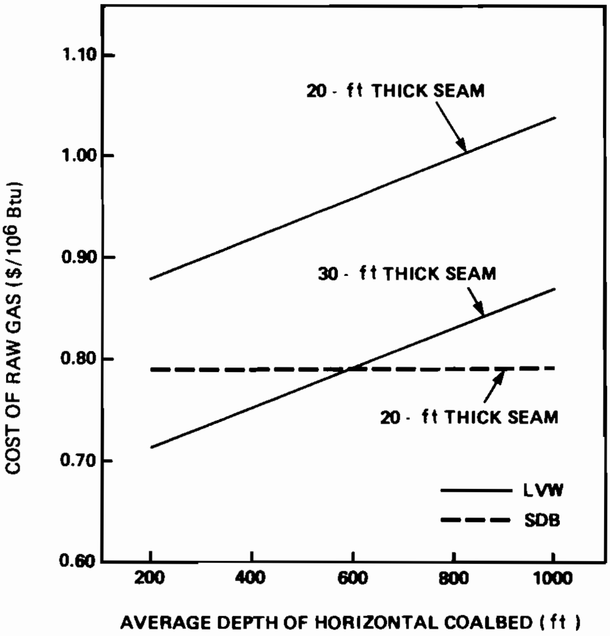

Figure 9. Estimated raw gas costs for LVW gasification related to coal bed geometry and compared to the SDB case shown.

A reasonable comparison can be made between the cost of producing raw low-energy gas by UCG and the cost of mining coal of the same energy value, in this case 9000 Btu/lb. Figure 10 shows how coal mining costs in dollars per ton relate to the equivalent cost of UCG-derived raw gas on an equal energy content basis. The dashed lines indicate that the 94 and 79 cent/10^6 Btu raw gas costs based on the conceptual LVW and SDB designs described here correspond to raw coal costs of about $17.50 and $14.50/t, respectively. If the coal cannot be mined at lower costs, UCG might be considered an economic alternative. Coal, of course, has the advantage of being less expensive to transport than low-energy gas. For on-site utilization, however, the UCG-derived fuel gas can become economically competitive with mined coal, especially when thick seams are gasified (as shown in Figure 9). Other factors, such as end use of the fuel and environmental considerations, must also be weighed when debating the economic viability of UCG.

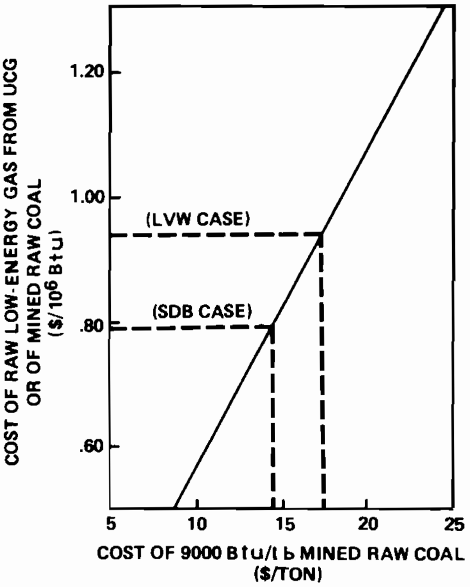

Figure 10. Comparison of mined raw coal costs with the cost of raw low-energy gas from UCG on an equal energy basis (assuming 9000 Btu/lb coal heating value).

AREAS FOR FURTHER TECHNICAL DEVELOPMENT

At this early stage in its development, UCG appears technologically feasible and, based on the assumptions made here, economically promising. Potential developments, including directional drilling, remote process monitoring and control, means of by-product tar and sensible heat utilization, and general process optimization, will further improve UCG economics. However, to avoid the reverse trend, several outstanding uncertainties must be dealt with, including the following:

- Effect of local geology, coal bed depth and thickness, well spacing, operating pressure, etc. on gas leakage in a multiwell UCG system;
- Effect of various linking methods (e.g. directional drilling versus reverse combustion) on UCG system operation;
- Quantitative relationship for gas production rate versus time over the life of a UCG module ocntrolled to produce uniform-quality gas;
- Quantitative prediction of particulate (e.g. coal fines) and condensibles (e.g. tar) content in the raw product gas;
- Usability of UCG-derived gas in gas turbine applications, notably with respect to gas cleanup requirements;
- Better understanding of environmental and safety hazards, such as pollution of aquifers, ground subsidence, and gas leakage;
- Feasibility of oxygen-blown UCG to produce nitrogen-free gas that can be upgraded to SNG or used as syngas for chemicals production;
- Establishment of realistic site-specific values for coal recovery and gas heating value for commercial-scale, multiwell UCG systems;
- Workable systems for process monitoring and control in large-scale UCG operations;
- Development of optimal field layout patterns and operational logistics for large-scale UCG systems;
- Economic segregation of coal reserves suitable for mining from those adaptable to UCG.

Before the commercialization of UCG in the USA can be realized, answers to these and possibly other questions must be found. Worldwide experience, particularly USSR, coupled with

DOE's experimental program, have, and hopefully will continue to bridge the outstanding technical gaps.

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THE UNDERGROUND COAL GASIFICATION PROGRAM IN THE USA

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INTRODUCTION

US involvement in research on underground or in situ coal gasification (UCG) started with the first field tests conducted at Gorgas, Alabama, from 1947 through 1956 [1-4]. These tests were conducted in a thin (~3 ft), shallow (<160 ft) high swelling index bituminous coal. The choice of this site was not conducive to the achievement of high quality results since the seam thickness and type of coal were not favorable for the production of a high heating value gas. In addition, the availability of large quantities of cheap oil and natural gas did not warrant further development of the technology at that time.

In 1968 Gulf Research and Development Corporation conducted a small test in Kentucky [5]. This test was conducted in bituminous coal in the high wall of an operating strip mine. The test achieved very high heating value in the product gas for an air-blown system but this apparently resulted because devolatilization rather than gasification was the predominant reaction. The test was noteworthy in that air injection pressures 30% greater than lithostatic pressure were used during the total test duration to enhance seam permeability.

No further serious development of UCG technology occurred in the USA until 1972 when the Laramie Energy Research Center's (LERC) testing program at a site near Hanna, Wyoming, began. In addition to that project additional projects were initiated at the Morgantown (West Virginia) Energy Research Center (MERC) [6] and at the Lawrence Livermore (California) Laboratory (LLL) [7,8]. With the formation of the Energy Research and Development Administration (ERDA) in January 1975, all three projects were consolidated under the direction of one governmental agency. This paper briefly describes the proposed work at both MERC and LLL, outlines the results of three tests conducted by LERC to date at Hanna, and describes future testing planned at Hanna.

EASTERN UCG TECHNOLOGY

The MERC project is directed at energy recovery from thin bituminous seams located in the eastern USA [9]. Because of the low permeability and high swelling index of this target resource, the applicability of reverse combustion linkage is unknown.

Therefore a major effort of the MERC project has involved development of directional drilling techniques in order to turn through 90° allowing long distances to be drilled horizontally within the coal seam. To date one directionally drilled well has been drilled to the Pittsburg seam with 500 ft of horizontal drilling completed within the seam at MERC's Pricetown, West Virginia, site. The high cost of achieving this has delayed further development of directional drilling technology.

Other major efforts at MERC have been directed at laboratory simulation experiments [10] and mathematical modeling [11] of the process for bituminous coal. Several simulation experiments have been completed and evaluation of the results is currently underway.

The current project schedule [12] for the MERC project is shown in Figure 1. Their first field test, Pricetown I, is scheduled for early 1978. It consists of a three-well pattern with 40 and 60 ft spacings. Air acceptance tests at various injection pressures up to and exceeding lithostatic pressure will be used to determine the feasibility of reverse combustion linking. If these tests show lack of feasibility, hydraulic fracturing will be used to enhance seam permeability prior to initiation of reverse combustion linking. Future tests will depend on the success of Pricetown I.

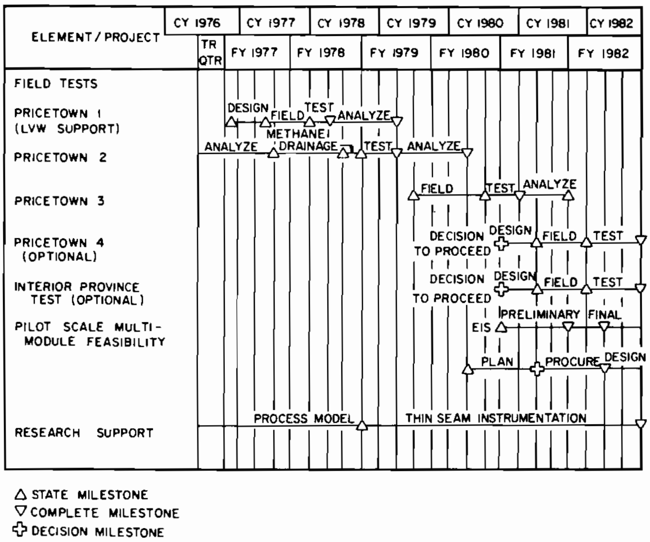

Figure 1. Eastern (MERC) UCG project schedule.

WESTERN UCG TECHNOLOGY

The LLL Project

The LLL project began in 1972 with funding from the US Atomic Energy Commission. The original concept involved use of chemical explosives to form a rubblized chimney in thick deep coal seams. This rubblized zone was then to be gasified from the top down using steam-oxygen to produce an intermediate energy gas which could be upgraded at the surface to synthetic natural gas.

The first test, Hoe Creek 1 [13], was conducted during October 1976 at LLL's site near Gillette, Wyoming, in the Felix no. 2 coal seam, a 25 ft thick subbituminous coal seam at a depth of 125 ft. Chemical explosives were placed in two well bores and the resultant fracturing after explosion did significantly increase the seam permeability, but the permeability enhancement occurred near the top of the seam with fines formed from the explosion apparently plugging the bottom portion of the coal seam.

Gasification between the two process wells at a spacing of 33.5 ft was conducted but the gasification zone overrode to the top of the coal seam resulting in a sharp drop in product gas heating value within 6 days. The experiment resulted in gasification of approximately 130 short (s.) tons of coal during a total duration of approximately 10 days.

Because of this result the next test at Hoe Creek [14] will be a repeat of work done by LERC at Hanna. Reverse combustion linking will be used for permeability enhancement between two wells spaced at 60 ft. This test will offer comparative data between two different sites with significantly different hydrologic conditions. The Hoe Creek 2 test is scheduled for October 1977.

Other major efforts at LLL have been laboratory simulation experiments, environmental monitoring of the process, development of mathematical models, instrumentation development and subsidence modeling. A number of reports have been published on this work [15-19]. The schedule of future work by LLL is shown in Figure 2.

The LERC Project

Three field tests have been completed by LERC at the Hanna field site. Hanna I was conducted from March 1973 through March 1974 [20-24]. Approximately 4000 s. tons of coal were gasified. During a 6 month period 1.6×10^6 standard (st.) ft^3/day of 126 Btu/st. ft^3 gas were produced.

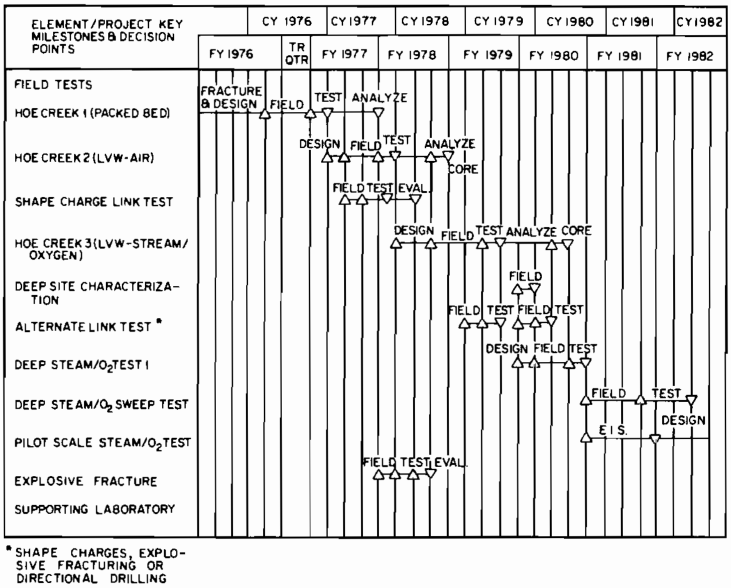

Figure 2. LLL project schedule.

Hanna II

Based upon the encouraging results of Hanna I, a second experiment, designated Hanna II, was initiated in 1975. This experiment was divided into three parts, called Phases I, II, and III. Phase I [25] was conducted from June through August 1975. It yielded an average production of 2.7 × 10^6 st. ft^3/day of 152 Btu/st. ft^3 gas during 38 days of gasification between two wells on a 52.5 ft spacing. Approximately 1260 s. tons were utilized during the experiment.

Phases II and III were conducted with the well pattern shown in Figure 3. The instrumentation wells were drilled and instrumented by Sandia Laboratories of Albuquerque, New Mexico, under ERDA funding [26].

The seam being utilized is the Hanna no. 1, a 30 ft thick subbituminous coal seam at a depth of approximately 275 ft at the Hanna II site. Wells 5, 6, 7, and 8 were completed 10 ft through the coal seam and perforated over the bottom 6 ft of the coal seam.

Reverse combustion linkage of Wells 7 and 8 was conducted during December 1975. Linkage of Wells 5 and 6 was completed in April and May 1976. No instrumentation was available along the 7-8 line to determine the location of the link, but as seen in Figure 3, the eight wells between Wells 5 and 6 gave an accurate

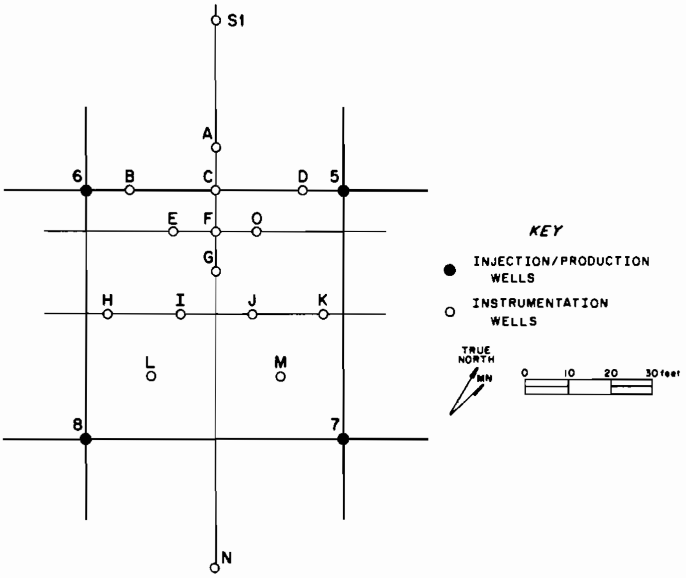

Figure 3. Hanna II, phases II and III, well pattern.

picture of the linkage path. Figure 4 shows the path of the link from Well 5 to Well 6 based on thermal data gathered during the linkage process.

Much more important is the location of the link within the coal seam relative to the bottom of the seam. The most advantageous position is within the bottom third of the seam. As the link proceeded from Well 5 to 6, the initial temperature rise observed at thermocouples in Wells D, O, G, E, and B always occurred at levels 0 to 5 ft above the bottom of the seam. Thus, placement of the link low in the seam was extremely successful. Positioning the link low in the seam allowed the gasification front to undercut the coal as it moved from Well 6 back to Well 5 after completion of the link. This resulted in fresh coal falling into the reaction zone yielding high resource utilization efficiency and producing a packed bed system.

The link was completed on May 4, 1976. Gasification from Well 6 to Well 5 was conducted from May 5 through May 20. Injection rates used were 1700, 2500, and 3500 st. ft^3/min, respectively, in a programmed fashion as shown in Figure 5. Production rates, product gas gross energy value, and gas composition for the five major components are shown in Figures 5-7. As can be seen the step function increases in air injection rate had no effect on gas composition or gross heating value. Until the last eight days when the gasification zone approached Well 5, the heating value was extremely constant.

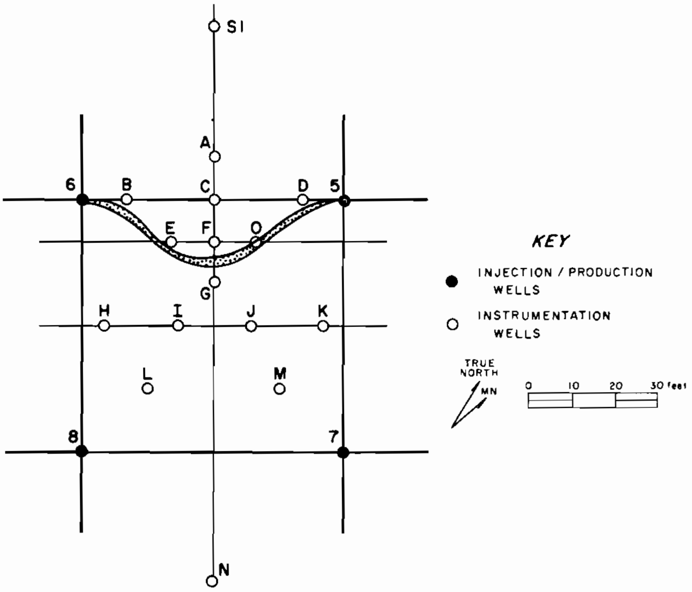

Figure 4. Estimated linkage path, Hanna II, phase II.

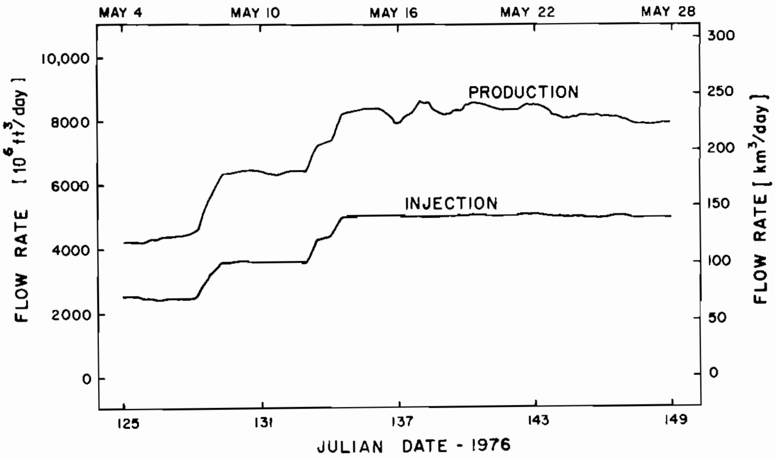

Figure 5. Injection and production rates, Hanna II, phase II.

The total coal utilized during both the linkage and gasification of the 5-6 system was 2520 s. tons. This value is based on a carbon balance by using a weighted average composition determined from a core taken at the Hanna II site. This compares

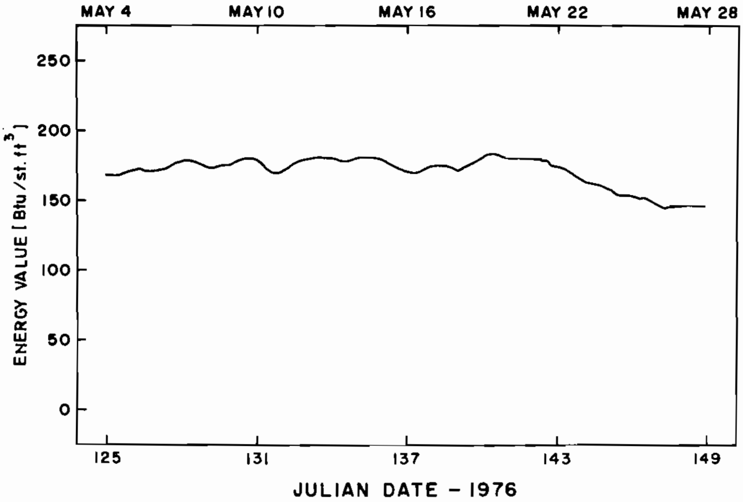

Figure 6. Dry product gas gross energy value, Hanna II, phase II.

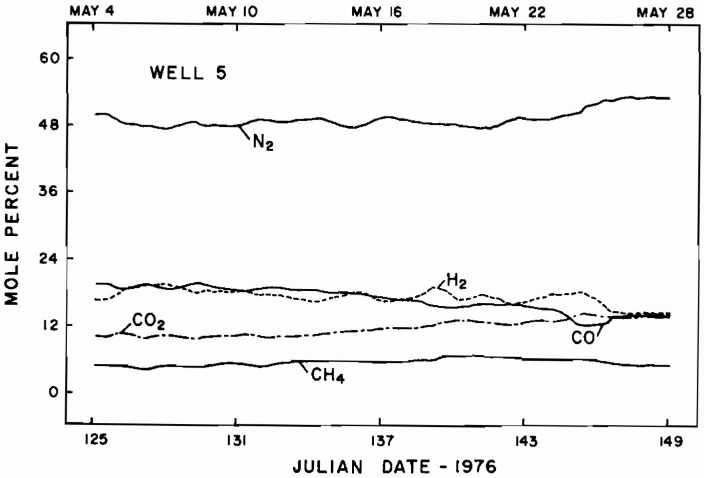

Figure 7. Product gas composition, Hanna II, phase II.

to 1260 s. tons utilized during gasification between two wells on a 52.5 ft spacing during Phase I. The improved utilization during Phase II is postulated to result from the higher injection rates, the positioning of the link at the bottom of the coal seam, and from holding 30 to 50 lbf/in^2 above atmospheric backpressure on the production side. The estimated gasified area based on thermal data from the instrumentation wells and on modeling efforts conducted at LERC [27,28] is shown in Figure 8. Thermal data indicate that at the midpoint of the 5-6 line the gasification zone was almost as wide as the 5-6 spacing.

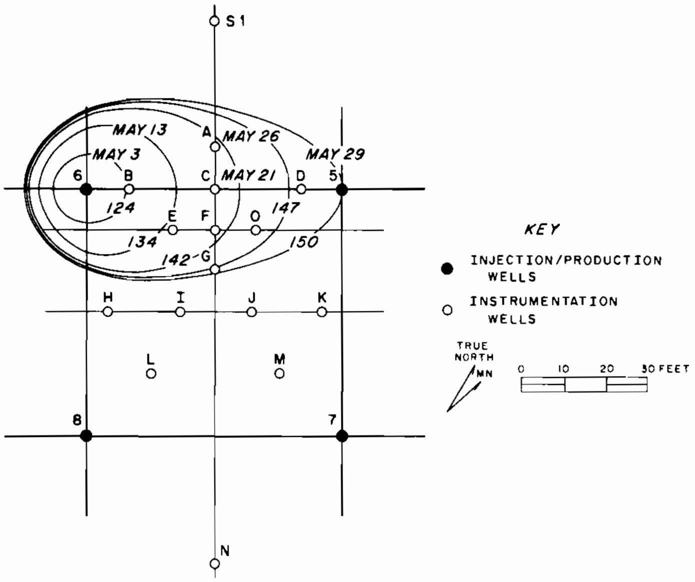

Figure 8. Estimated gasified area, Hanna II, phase II.

Phase III consisted of gasification from Well 8 to Well 7 through the previously completed linkage pathway. Again three preplanned injection rates were used. These rates were 2500, 3500, and 4500 st. ft^3/min, respectively. In addition, backpressurizing the system was conducted to determine the effects of reservoir pressure changes on the gas composition.

Figures 9 to 12 show the injection and production rates, injection and production pressure, product gas gross energy value, and product gas composition for the five major components. Significant differences are seen in the energy value and composition when compared to data from the 5-6 system. The energy value dropped off much more rapidly during the lifetime of the 7-8 system.

The explanation for this difference is shown in Figures 13 and 14. Figure 13 shows the gross energy value, cold gas thermal efficiency, and ratio of water produced to coal utilized during the 5-6 gasification period. As can be seen, the energy value and cold gas efficiency were stable until Julian Day 142 (May 21, 1976) followed by a gradual decline.

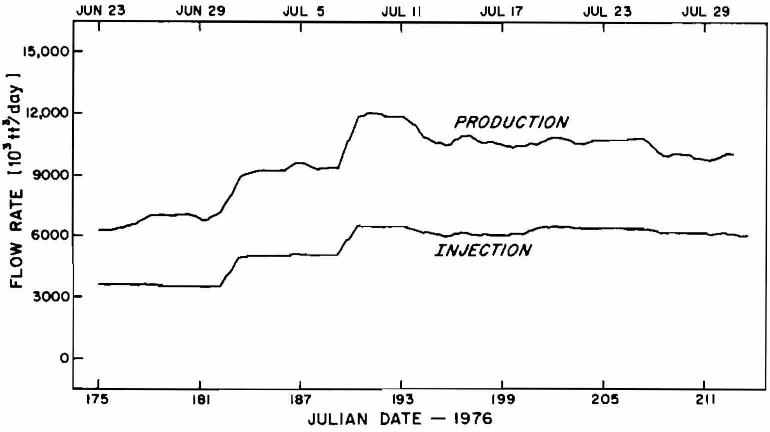

Figure 9. Injection and production rates, Hanna II, phase III.

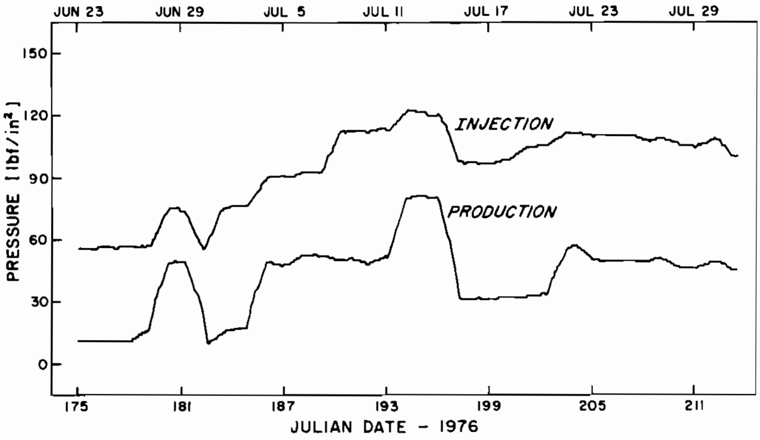

Figure 10. Injection and production pressure, Hanna II, phase III.

In contrast, Figure 14 shows the same variables for the 7-8 gasification period. The energy value and cold gas efficiency show a steady decline from the beginning of the 7-8 gasification period with the most dramatic drop occurring around Julian Day 196 (July 14, 1976). This drop coincided with a planned decrease from 80 to 30 lbf/in^2 above atmospheric in the backpressure held on the system. The ratio of water produced to coal utilized also increased sharply at this time. Compared to the 5-6 period, this ratio was approximately twice as high during the early stages of the 7-8 burn and six times as high after relieving the backpressure on Julian Day 196. This dramatic increase in water would be expected because groundwater influx should increase as the

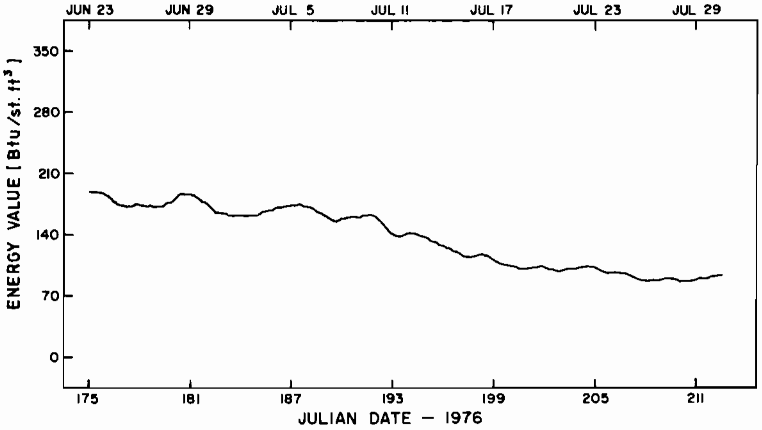

Figure 11. Dry product gas gross energy value, Hanna II, phase III.

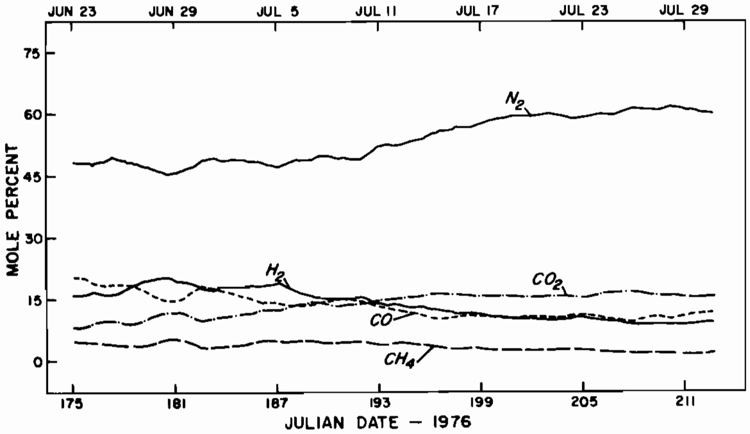

Figure 12. Product gas composition, Hanna II, phase III.

surface area of the cavity in the seam increases. In addition, decreasing the reservoir pressure further increased the water influx rate.

Increasing the air injection rate toward the end of the 5-6 burn would have stabilized the product gas energy value and coal gas efficiency since excess water does not appear to have been the cause of the decline in these two values. Also, an increased injection rate and higher backpressure during the last 20 days of the 7-8 burn would have improved the results of the 7-8 burn, but maximum air compression capacity had already been achieved.

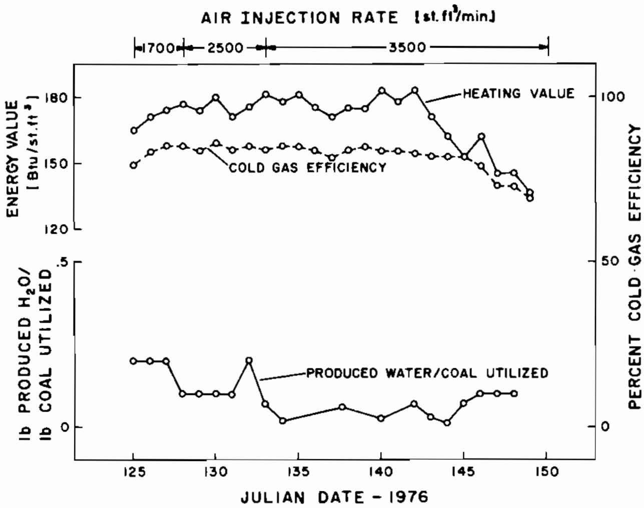

Figure 13. Effects of groundwater influx on Hanna II, phase II.

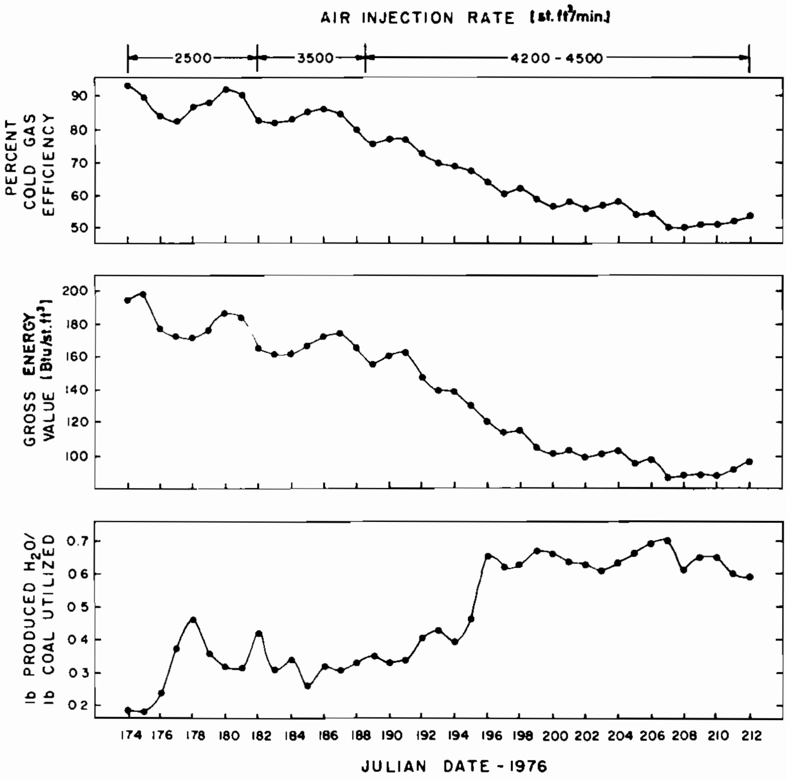

Figure 14. Effects of groundwater influx on Hanna II, phase III.

The unique character of Phase III was the excellent resource utilization. The amount of coal utilized during Phase III was 4200 s. tons (Figure 15).

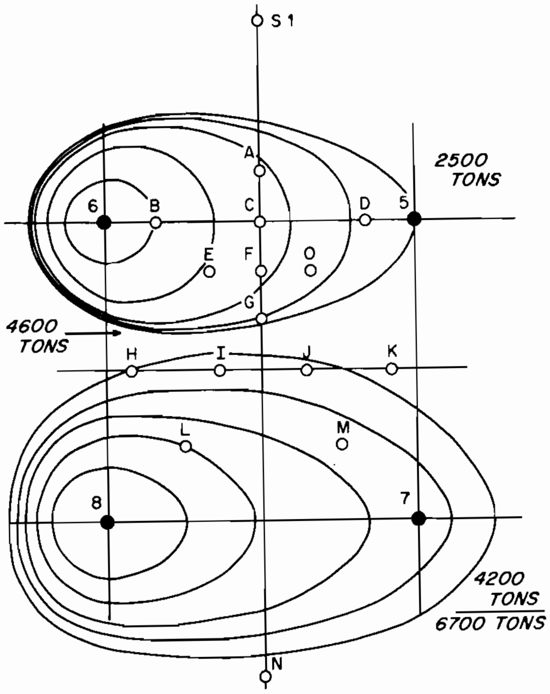

Figure 15. Estimated gasified area, Hanna II, phases II and III.

Overall, Hanna II is considered extremely successful. The total coal utilized was 6690 s. tons. This is compared to the available 4600 s. tons contained within the 60 ft by 60 ft square of the 5, 6, 7, 8 well pattern. Obviously, coal was utilized outside this arbitrary boundary but exceeding this artificial total by such a margin indicates high resource utilization efficiency. Determination of the actual efficiency awaits coring and seismic surveys of the gasified area to finalize the true boundaries of the gasification zone, but there can be little doubt that UCG can achieve high resource utilization efficiencies under controlled conditions.

Three different energy balance calculations for Hanna II have been previously reported [29]. The results of these calculations are shown in Table 1.

Table 1. Energy balance results for Hanna II.

	Phase		
	I	II	III
Energy Return Ratio	5.3	4.5	4.5
Overall Process Efficiency (%)	71.5	74.3	65.3
Thermal Efficiency (%)	82.7	89.0	76.3

Hanna II yielded several outstanding accomplishments in the field of UCG by using air injection. These were the following:

- Production of the highest gross heating value product gas over the longest duration ever reported.
- Operation at the highest thermal efficiencies ever reported.
- Highest production rate from any UCG test in the Free World.
- High overall sweep efficiency for parallel two-well patterns.
- The most thoroughly instrumented UCG test ever conducted.

Hanna III

The Hanna III test was designed as an environmental test of UCG. It was designed to determine the impacts of UCG on groundwater quality which is the major environmental concern associated with the technology. It also offered further opportunity for refining the process. The objectives of Hanna III are shown in Table 2.

The well pattern used during Hanna III is shown in Figure 16. Wells 1 and 2 were the process wells at a spacing of 60 ft. Wells 3, 4, 5, and 14 were completed into an overlying aquifer situated approximately 20 ft above the coal seam. The remaining wells were completed into the coal seam. The Hanna III site was approximately 700 ft updip from the Hanna II site. The depth to the top of the Hanna no. 1 seam was approximately 160 ft at this location.

Hanna III was conducted during June and July 1977. The objective of maintaining constant product gas energy value was not achieved due to insufficient groundwater influx. This lack of groundwater resulted in high product gas temperatures at the production wellhead and a substantial decrease in product gas energy content. Injection of water with the injected air was initiated to overcome the water deficiency but resulted in only temporary improvements in product gas energy value. A steam generator was not available thus necessitating water rather than steam injection.

Table 2. Hanna III objectives.

Environmental

- Characterize the properties of the coal seam aquifer and of an overlying aquifer.
- Determine water quality in both aquifers before the test.
- Determine water quality after the test.
- Determine impacts of UCG on groundwater quality based on any observed compositional changes.

Process

- Improve the mathematical model.
- Test process control techniques.
- Demonstrate constancy of product gas energy value by controlling the air-water ratio in the gasification zone.

During the 38 day gasification period approximately 2800 s. tons of coal were gasified with production rates as high as 10×10^6 st. ft^3/day. The product gas energy value ranged from 180 Btu/st. ft^3 early in the test down to 100 Btu/st. ft^3 at termination. A wellhead temperature of 620 °C necessitated termination in order to avoid surface piping failure.

Upon completion of Hanna III, the system was bled down. In the near future a known quantity of water will be added to the cavity to reestablish pretest water levels, and pumping will be initiated at Wells 13 and 14 to establish flow from the cavity toward the downdip monitoring wells. Both aquifers appear to be stagnant with no natural flow [30] necessitating pumping. Water will be added because natural groundwater influx after Hanna I and Hanna II took up to a year to refill the cavity. Sample collection and analyses will be conducted on a monthly basis for at least 18 months after pretest water levels have been reestablished. From these analyses data the amounts of inorganic and organic constituents disseminated to the two aquifers and the magnitude of changes in the groundwater quality will be established to demonstrate whether UCG will have serious environmental impacts on groundwater resources.

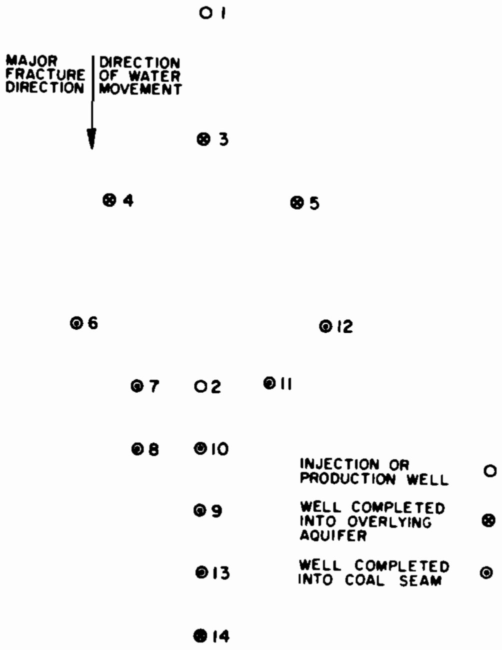

Figure 16. Hanna III well pattern.

Hanna IV

Hanna IV will represent a significant scale up of UCG. The well pattern is shown in Figure 17 consisting of three process wells with 100 and 150 ft spacings and 31 instrument wells to be instrumented by Sandia Laboratories [31]. The objectives of Hanna IV are shown in Table 3.

The Hanna IV site is located approximately midway between the Hanna I and II sites. The depth to the top of the Hanna no. 1 coal seam is approximately 330 ft. The line of process wells is oriented along the dip direction. The estimated initiation of Hanna IV is October 1977. Table 4 shows predicted results of Hanna IV.

The sequence of events for operating Hanna IV will be ignition at the middle process well (Well 2), reverse combustion linkage to the updip well (Well 1), gasification from Well 1 to 2, initiation of linkage from Well 2 downdip to Well 1 during the gasification from Well 1 to 2, and relaying gasification from the Well 1-2 system to the 2-3 system after completion of the 1-2 system.

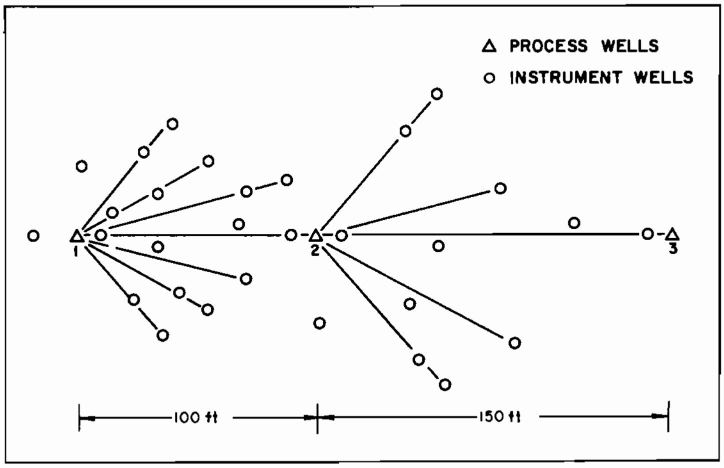

Figure 17. Hanna IV well pattern.

Table 3. Hanna IV objectives.

Determine relationship between injection rate, well spacing, and sweep width.
Determine the potential for gravity override of the link at these spacings.
Define void shape and gasification front inclination with time.
Determine in situ pressure and gas compositional gradients during linkage and gasification.

Table 4. Hanna IV predictions (maxima).

Duration [months]	6
Resource Utilization [s. tons]	28,000
Air Injection Rate [10^6 st. ft^3/day]	16
Gas Production Rate [10^6 st. ft^3/day]	27
Energy Value [Btu/st. ft^3]	170

Hanna V

The final design of Hanna V must necessarily await the results of Hanna IV but the preliminary design consists of a nine-well pattern as shown in Figure 18. The objectives of Hanna V are shown in Table 5.

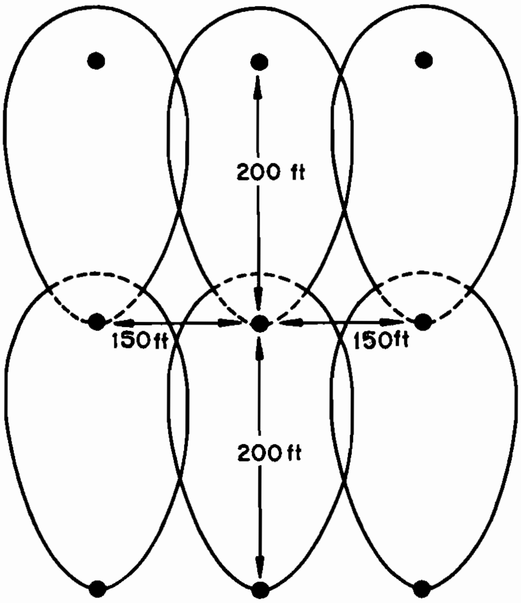

Figure 18. Proposed Hanna V well pattern.

The proposed Hanna V site is located approximately 1000 ft downdip from the Hanna I site. The depth to the top of the Hanna no. 1 seam is approximately 470 ft at this proposed site.

The well spacings will be at least 150 ft if Hanna IV is successful and may be expanded to 200 ft. Table 6 shows predictions for Hanna V based on 200 ft well spacings.

Hanna V is currently scheduled for initiation early in fiscal year 1979. Successful completion would be followed by construction and operation of a pilot plant for electrical generation to demonstrate the totally integrated technology.

Table 5. Hanna V objectives.

Demonstrate expansion of technology to smallest process unit.

Demonstrate operation of multiple-channel system.

Determine impacts of subsidence on the process.

Demonstrate an automated process control system.

Develop baseline information for pilot plant design.

Develop data for commercial scale economic analyses.

Table 6. Hanna V predictions (maxima).

Duration [months]	12
Resource Utilization [s. tons]	100,000
Air Injection Rate [10^6 st. ft^3/day]	65
Gas Injection Rate [10^6 st. ft^3/day]	110
Energy Value [Btu/st. ft^3]	170

CONCLUSIONS

The US program to develop UCG to the commercial phase is in its preliminary stages. The successes achieved by LERC at its Hanna site offer encouragement that UCG can be developed to the commercial stage. Future tests at Hanna to expand the test size and other work planned by MERC and LLL will determine whether this viewpoint is justified.

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UNDERGROUND COAL GASIFICATION

P. Ledent

INTRODUCTION

Coal deposits are the most important of the world's reserves of fossil fuels. The reserves that can be worked by conventional methods down to 1000 to 1200 m are generally assessed at 10 or 12×10^{12} t, but this is but a small part of the Earth's total coal resources. Deposits are known down to 4 to 5000 m and the development of a technology enabling the working of these deep deposits would multiply by ten the reserves of solid fuels and make available a source of energy capable of meeting our needs for thousands of years.

However, for the past 20 years, the coal industry of the industrialized countries of the Western world has known a marked recession due to the extension of oil and natural gas production. The reasons for this change are numerous: gas and oil deposits can be worked from the surface and the labor cost has little effect on the cost price; they are easy to transport; and they can be transformed and used in largely automated plants.

The recent increase in oil cost and the continuous increased demand for energy in the Western world have led to a new interest in coal. In order to meet our future needs, the coal industry has to solve two major problems:

- the reduction of labor underground because of the difficulties in recruiting miners, the cost, and the numerous technical limitations resulting from the presence of men underground;

- the transformation of coal into a fluid fuel to benefit from the latter's cleanness and easiness.

A solution is in progress in those coal-producing countries that have large virgin coal deposits available for open-pit mining. For example, the amount of coal being won by open-pit mines rose in the USA from 25 to 55% of total production within a few years and ERDA (the Energy Research and Development Administration) supports a vast R&D program for gasification and liquefaction of

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mined coal. Another solution would be a new technique of underground gasification applicable to deep deposits which could produce lean gas, synthesis gas, or substitute natural gas.

UNDERGROUND GASIFICATION AT SHALLOW DEPTH

The first attempts at applying this 19th century idea were in the 1930s. Since then, the USSR has been playing a pioneer role in its development. Of the various methods that have been tried, only two seem to have prevailed: drilling very steep seams and air filtration between boreholes drilled from the surface. Both avoid all underground manual work.

Figure 1 shows how air is injected through oblique holes drilled in the floor of the steep seam and the product gases are recovered by means of boreholes in the seam. In the filtration process (Figure 2), communication is set up between two adjoining holes 20 to 30 m apart, by increasing the natural permeability of the deposit with high pressure water or air followed by widening by retro-combustion through the fissures. Then much more important air flows can be blown in to achieve the gasification.

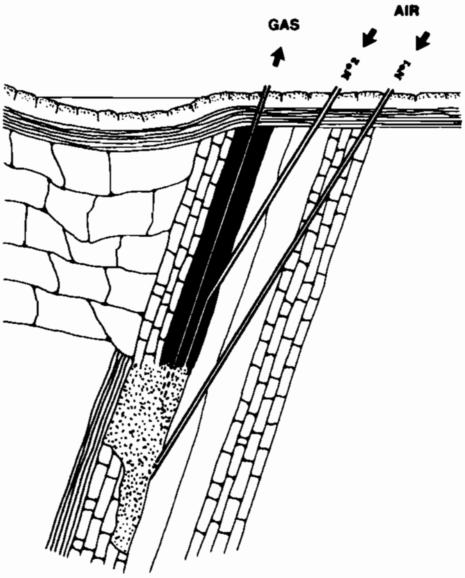

Figure 1. Gasification of a steep seam through inclined boreholes.

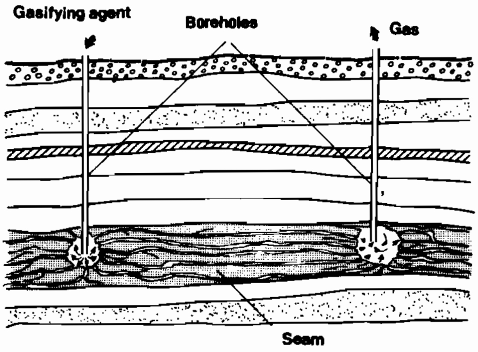

Figure 2. Underground gasification by filtration.

Four to five installations have been developed in the USSR at depths varying from 100 to 300 m. Some of them have been exploited for 10 to 15 years and the stability of their production shows that the Soviet technicians have mastered the problems involved. However, the amount of gas produced so far is much less than had been foreseen in 1955 to 1960.

The lack of large scale industrial development can be explained by the modest performances, the limitation to seams at least 2 m thick, and the low energy value of the gases of between 900 and 1000 kcal/Nm^3. The latter prevents long distance distribution and represents only about 50% of the potential of the deposit. With account taken of energy spent on production of compressed air for gasification, the net energy efficiency is only 40%.

The lack of air tightness of the underground gas generator results in an exploitation of the Soviet type, of about 10% loss, rising to 20-30% under unfavorable circumstances. This removes all possibility of production of a rich gas through use of oxygen and prevents all development in populated areas.

The effect of water infiltrations on the results of exploitation is well shown in an American study of Soviet data [1]. Figure 3, taken from this study, establishes a correlation between the opening of the seams, the water inflow, and the lower resultant energy value of the gas produced.

The results obtained in Wyoming, on the experimental Hanna site, are much more favorable [2]. The product gas regularly has 1350 kcal/Nm^3 and in the last experiments over 1500 kcal/Nm^3. The gross energy efficiency is 82.7% and the net, 70 to 71%, after subtracting the energy spent for producing compressed air. Unfortunately, the conclusions from this Hanna experiment have no general value, since the exploitation still covers a very small area and water inflow problems and gas leakages could occur later when extension of the works might bring about breaking and subsidence of the rocks covering the underground gas generator.

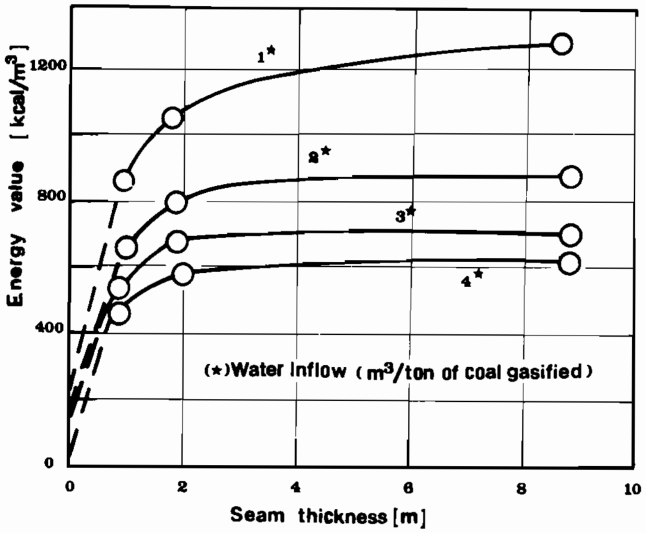

Figure 3. Variation of the heating value of the gas in function of the thickness of the seams and water inflow.

Source: [1]

The potentials of underground gasification at shallow depth and its possible economic development in Western Europe have been dealt with in an important economic study carried out by the UK National Coal Board [3]. From the USSR results and those obtained in the UK a little more than 20 years ago, underground gasification at shallow depth seems less profitable than conventional mining; besides, its utilization would be of little interest in densely populated countries because of gas leakages and the need to protect the superficial water-bearing layers that supply cities.

Only in unusual geological conditions, when the deposit to be exploited is covered by a layer of clay, both flexible and impervious, does it seem that underground gasification could be of interest and even then the gasification pressures likely to be used remain very limited.

GENERAL CHARACTERISTICS OF UNDERGROUND GASIFICATION AT GREAT DEPTH

Characteristics of Deep Deposits

Unlike shallow deposits, where conditions are damp and much pumping out is necessary, deep deposits are usually dry. Absorbed gases are present in larger amounts and instantaneous outbursts can occur in the vicinity of zones that have been subject to major tectonic movements.

At shallow depth, the roadway sections remain practically constant and support can be limited to simple protection against the fall of stones; at great depth, the roadways are deformed as soon as they are driven, their section gets narrower rapidly through floor-heave and through the convergence of the walls. Permanence can only be achieved through the use of very strong linings of a cylindrical form--really tubings to control the creep of the rocks.

Thus, the point at which the coal shales reach a plastic behavior is the dividing line between shallow and deep deposits and from this point they can oppose the passage of gases and liquids and, through their deformation, quickly seal fissures produced during exploitation. The depth of this limit depends to a great extent on the geological conditions of the deposit and on the composition of the beds. With the soft shales of the northern part of Belgium, it is 500 to 600 m, whereas it can be 1000 m or more in the deposits containing more metamorphosed coal shales sometimes mixed with sandstones.

Whereas passage to greater depths constitutes a big handicap for conventional mining, it can bring three major advantages to underground gasification:

- the lack of water,
- the tightness of the rocks, and
- their capacity to withstand very high pressures.

Objectives of Underground Gasification at Great Depth

Starting from these considerations and the preliminary studies achieved by the Institut National des Industries Extractives, Professor Wenzel's team at the University of Aachen, Belgium and the FRG have reached an agreement at governmental level for a common research program aimed at developing underground gasification at great depth and its industrial application.

This program has two objectives:

- to widen the application of existing techniques of underground gasification, by working under high pressure in a deep, dry, and tight gas generator, which should allow the achievment of air gasification for the production of lean gas, oxygen and steam gasification for the production of synthesis gas, or hydro-gasification for the production of SNG (if the pressure of the underground gas generator can be increased to a sufficiently high level);

- to extend the exploitation of coal deposits far beyond the depth limits of conventional mining methods, by using a "manless" oil extraction type technique, the development of which is not held back by rock pressure or high bed temperature.

General Layout of the Underground Gas Generator

Figure 4 distinguishes three depth zones:

- a superficial zone of loose or fissured rocks full of water;

- an intermediate zone mainly consisting of coal shales kept tight by the pressure;

- a deep deposit comprising a number of coal seams, which are to be exploited, one by one, in descending order.

The first zone may be considered a hydraulic guard and the second one the gas tight lid of the gas generator being developed. The gasification pressure within the underground gas generator can be selected at will provided it does not exceed the hydrostatic pressure at the foot of the overburden.

The injection of the gasifying agent and the recovery of the gasification gas can be at constant flow, or with cyclic variation of gas or gasifying agent flow to provoke large pressure changes within the gas generator. The advantages of this are:

- Improved gas-solid contact by penetration of the gases into the fissures of the strata and into the heaps of wastes that would otherwise remain outside the active zones;

- The possible storage of energy, which would increase the flexibility of operation of the gasification plant and make it possible to adapt to fluctuations of demand.

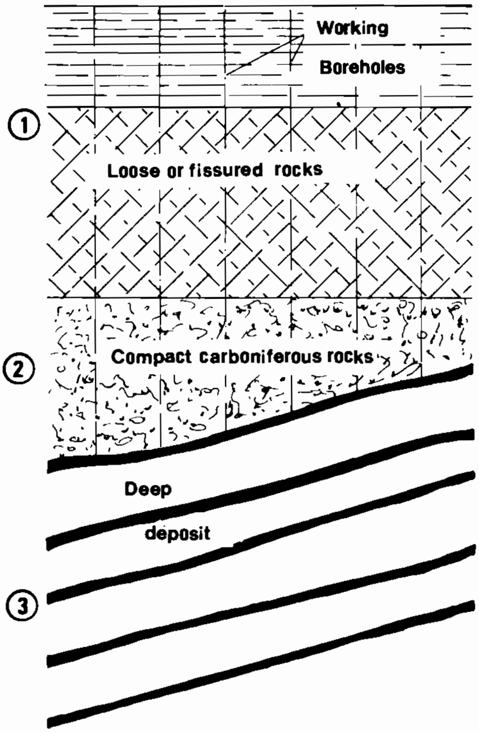

Figure 4. Scheme of an underground gas generator at great depth.

TECHNICAL AND ECONOMIC CONSEQUENCES OF OPERATION UNDER HIGH PRESSURE

Consumption of Gasifying Agent, Energy Values, and Efficiencies

Table 1 summarizes the operating characteristics of a few types of installations, working underground or at the surface.

All these values are relative to the gasification of coals of a high volatile matter content (> 30%) and, in the particular case of Angren, to a metamorphosed lignite (low energy value: 3500 kcal/kg). The values for Angren and Yuznho-Abinskaya are averages obtained on an industrial scale over several years. The values for the Hanna site are only for the first months of a new experimental phase, when the water inflow is still very small.

The results obtained at the surface in Lurgi gas generators could foreshadow the results of gasification achieved under pressure in a dry and gas-tight underground gas generator. The underground gasification will probably consume less steam than

Table 1. Energy values, consumptions of gasifying agents, and efficiencies obtained from coals of a high volatile matter content (> 30%).

Method	Underground gasification			Extracted coal gasification		
Gasifying agent	Low pressure air			Air + steam Low pressure	Air + steam High pressure	O_2 + steam High pressure
Site	Angren USSR	Yuznho-Abinskaya USSR	Hanna USA		Lünen FRG	
Pressure [bar]	2 to 3	2 to 3	2 to 3	~ 1	~ 20	~ 20
Composition of the gas [% by vol.]						
CH_4	1.9	2.3	4.0	2.6	4.9	10.1
C_mH_n	0.3	0.2	-	-	1.8	0.3
CO	6.0	14.2	18.0	28.0	15.5	19.5
H_2	18.7	14.7	18.0	14.5	24.3	40.7
H_2S	0.4	0.05	n.a.	n.a.	0.3	n.a.
O_2	0.4	0.1	-	-	0.0	-
CO_2	18.6	10.65	12.0	3.9	13.7	28.9
N_2	53.7	57.8	48.0	51.0	39.5	0.5
Energy value [kcal/Nm^3]	900	1050	1350	1450	1800	2550
Theoretical consumption of air or oxygen						
[Nm^3/Nm^3 of gas]	0.67*	0.72*	0.60	0.64	0.49	0.134
[Nm^3/Gcal]	740	685	445	440	272	52
Steam consumption						
[kg/Nm^3 of gas]	-	-	-	0.12	0.29	0.86
[kg/Gcal]	-	-	-	83	160	340
Gasification efficiency [%]**	60.0	60.0	82.7	83.5	79.0	91.3

*Actual consumption 0.90 to 1.00 Nm^3/Nm^3.
**Of the coal actually gasified.

gasification at the surface, for the risks of excessive temperatures and the drawbacks that can result from a local fusion of ashes are less restraining in an underground gas generator of a very large volume, where the gas velocities are low and where the coal is gasified without having to undergo any displacement. The advantages of gas-tightness of the gas generator and of limited water inflows are obvious when we compare the data of the Angren or Yuznho-Abinskaya installations to those of Hanna and of a surface lean-gas generator. They are:

- an increase in gasification efficiency,

- an increase in the energy value of the gas, and
- a decrease in air consumption.

Switching from operation under atmospheric pressure to operation under high pressure displaces the chemical balance in favor of higher production of methane and carbon dioxide and brings about two striking consequences: an increase in the energy value of the gas and an important decrease in the consumption of air or oxygen per unit of energy of the gas produced. These advantages explain the success of Lurgi gas generators over the last 40 years and the US endeavors over the last decade to develop new processes of gasification under very high pressure.

Cost of the Boreholes

In a recent study [4], an attempt has been made to assess the influence of pressure on the cost of the boreholes and on the energy consumed for carrying out gasification. If we assume the flow of a gas borehole, Q_G is 10,000 or 20,000 Nm^3/h, and the flow of gasifying agent through a borehole, Q_A is 0.75 Q_G in continuous working and 1.50 Q_G for 50% of the time in intermittent working at variable pressure, the distribution of pressures along the circuit are as shown in Table 2.

Table 2.

Working	Outlet compressor	Underground gas generator	Arrival power plant
Continuous	$P_c = 2.9\ P_u$	$P_G = 2.5\ P_u$	P_u
Pulsating	$P_c = 4$ to $5\ P_u$	$P_G = 2.5$ to $4\ P_u$	P_u

The hydrostatic pressure at the base of the overburden is assumed to be 50% of the hydrostatic pressure calculated from the depth of the deposit (L meters) and the underground gas generator is presumed to work at this maximal pressure, i.e.:

$$P_G = 0.5 \times \frac{L}{10} + 1 = \frac{L + 20}{20} \text{ (bar)} \quad . \qquad (1)$$

The cost of each borehole is related to its length (L) and its internal diameter (D_i) by an empirical formula from a study of conditions of Belgian deposits:

$$C = \left(92 + 1925\ D_i^{1.75}\right) L \qquad (2)$$

C being expressed in US \$; D_i and L in m.

Figures 5 and 6 show the variation of the diameter and cost of boreholes in the two extreme cases of $P_u = 1$ bar or the maximum pressure allowed by the depth of the deposit. In the first case, the diameter of the boreholes increases with the depth to compensate for the effect of lengthening the underground circuit. In the second case, a small decrease of diameter of the boreholes is possible as the effect of lengthening the circuit is more than compensated for by the reduction of the gaseous volume due to the high pressure of the gas generator; hence the increase of cost of the boreholes is rather less than the increase of depth and the investment needed is much less than the investment that would be needed if the gas were produced under low pressure. The cost of the boreholes per unit of energy extracted can be calculated. If we suppose that each cubic meter of coal in situ represents a potential of 10 Gcal and that 65% of this can be found in the extracted gas [5], we have:

$$p = C/6.5\ V\ (\$/\text{Gcal}) \qquad (3)$$

where p is the fractional cost of the borehole (\$/Gcal extracted),

C, the cost of a borehole (\$), and

V, the average volume of coal exploited from a single borehole (m^3).

Figure 5 shows that development of gasification at great depth could be achieved by selecting tubing of uniform internal diameter of 0.125 m; then C = 143 L. Introducing this value into the equation (3) we get:

$$p = 22\ L/V\ (\$/\text{Gcal}) \qquad (4)$$

which makes the very great importance of the volume exploited from a single borehole obvious. If it reaches 10,000 m^3, the fraction of the cost of the borehole (for a deposit 800 to 1000 m deep) would be about 2 \$/Gcal, similar to the cost of coals extracted in open-pit mines; at 5000 m^3, about 4 $/Gcal, which can still be favorably compared to the price of the coal extracted in shallow underground mines.

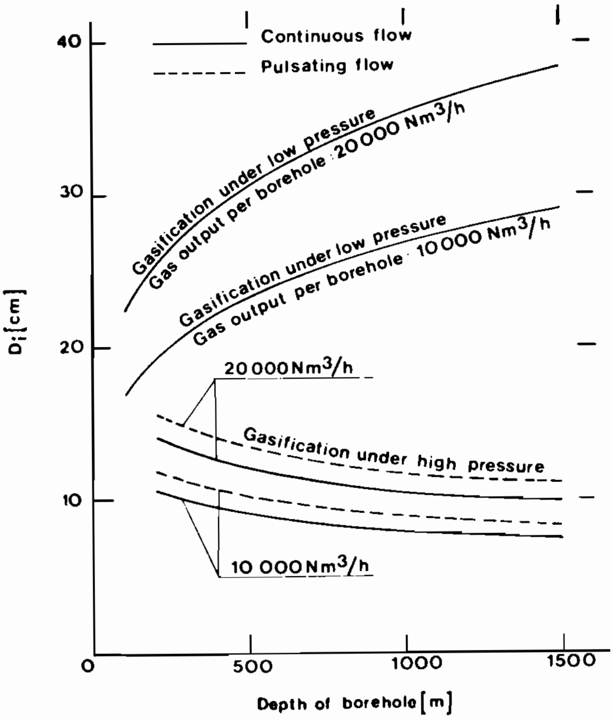

Figure 5. Evolution of the useful diameter of the boreholes in function of the pressure and the depth.

In practice, to maximize the volume exploited from each borehole will necessitate:

- increasing the spacing between boreholes to a maximum value of 50 to 70 m;
- the utilization of a single network of boreholes for the successive exploitation of several seams--this second measure being economically necessary if the gasification is in deep deposits consisting of a succession of relatively thin seams.

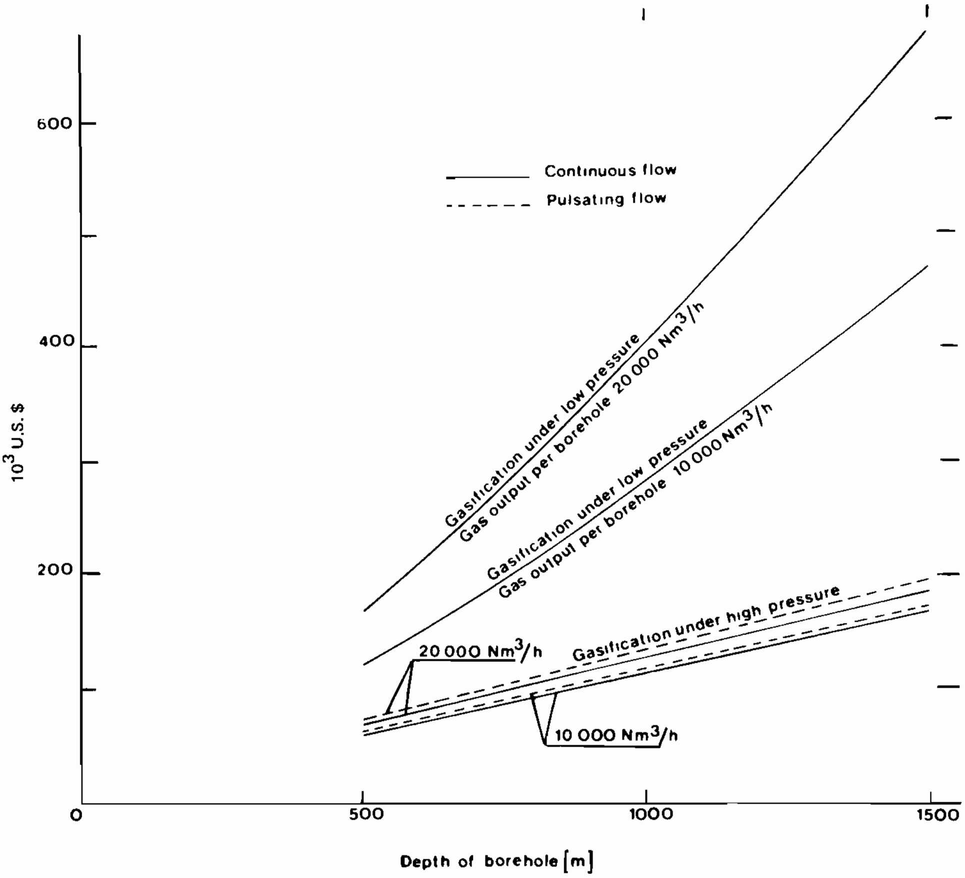

Figure 6. Evolution of the cost of the boreholes in function of the pressure and the depth.

Compression Energy of Air or Oxygen

Under low pressure, the compression energy of the gasifying agent is entirely spent on overcoming the load losses in the underground circuit. Under high pressure, the energy spent is the difference between the compression energy of the gasifying agent and the energy consumed to bring the gas to its utilization pressure. Hence:

$$W_p = \frac{P_a V_a}{\rho_c} \left(\alpha \ln \frac{P_c}{P_a} - \ln \frac{P_u}{P_a} \right) \qquad (5)$$

where W_p is the lost energy (kcal/Nm^3 of cleaned gas);

P_a, the pressure at compressor inlet (101,325 N/m^2);

V_a, the volume of 1 Nm^3 at the inlet temperature (assumed to be 20 °C);

ρ_c, the isothermal efficiency of the compressor (assumed to be 0.75);

α, the air (or oxygen) consumption (Nm^3/Nm^3 of cleaned gas).

The results of the calculation are given in Figure 7, the values of the ratio P_c/P_u being supposed to be as given in the above paragraph. They show that working under pressure always brings about a major economy in energy and that, in the most favorable cases (small α and high P_u), the underground gas generator behaves like a real thermal machine, supplying more mechanical energy than it consumes.

Recovery of the Thermal Energy of the Steam

The enthalpy of the saturated steam varies slightly with the pressure: it is about 650 kcal/kg for pressures of 3 and 100 bar and goes through a maximum of about 670 kcal/kg around 30 bar, i.e. the energy cost of steam production is virtually independent of the working pressure of the gas generator.

For a low pressure gas generator, steam consumption does not produce mechanical energy. However, for an underground gas generator at high pressure feeding a combined-cycle electrical power plant, the steam increases the gaseous volume going through the expansion turbine and its useful effect is equal to that of a similar volume of dilution air. If the efficiency of the power plant is 39%, a comparison of the thermal energy used to produce the steam and the compression energy to produce the same amount of dilution air, gives a recovery efficiency:

$$R = 0.167 \ln P_u/P_a \quad . \tag{6}$$

Figure 8 shows the variation of this efficiency as a function of the pressure. This recovery of energy applies not only to the fraction of gasification steam that goes through the underground gas generator without being broken down, but also to steam coming from the inherent dampness of the fuel and, possibly, to the steam produced from the sensible heat of the gas, through the working of a pulverization device used to protect tubing against an excessive increase of temperature.

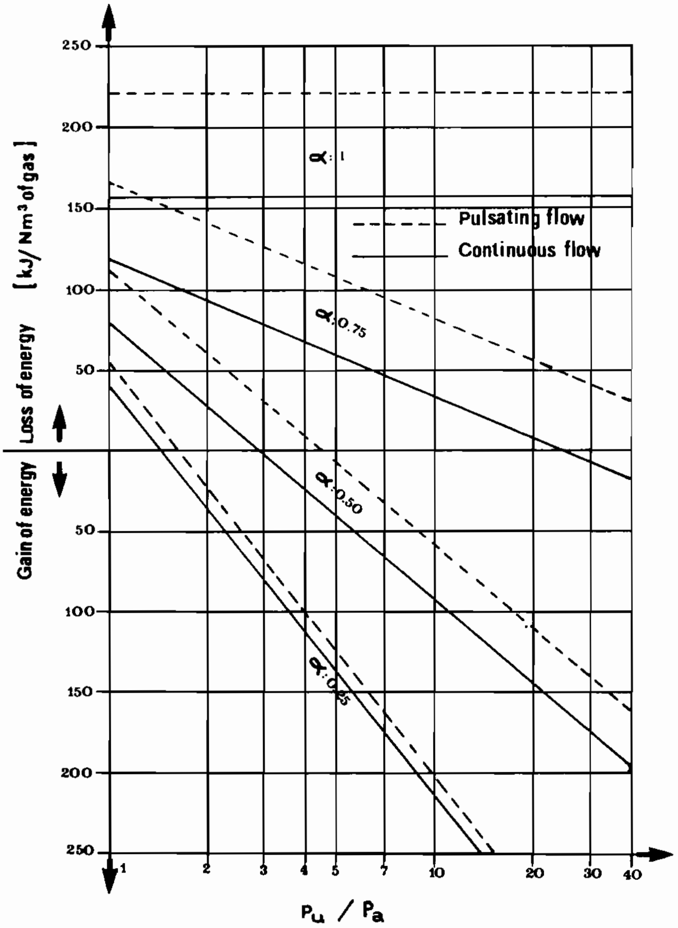

Figure 7. Loss of energy.

A CASE OF APPLICATION

Figure 9 shows an underground gasification installation with air and with steam that could feed a combined-cycle electrical power plant: gas turbine + steam turbine.

The mixture of air and steam, under high pressure (30 to 50 bar), is injected through the injection borehole and filters through the seam; it is taken again as lean gas by the productive borehole. The latter is equipped, at its base, with a device for direct cooling of the gas by water spraying, so as to protect the lining of the borehole against the excessive temperatures. The lean gas arrives at the surface under a pressure of 10 to 15 bar and at a temperature nearing 200 °C, it is cleaned in a scrubber, then burnt in a combustion chamber under pressure. The combustion gases expand in a gas turbine coupled to an alternator and,

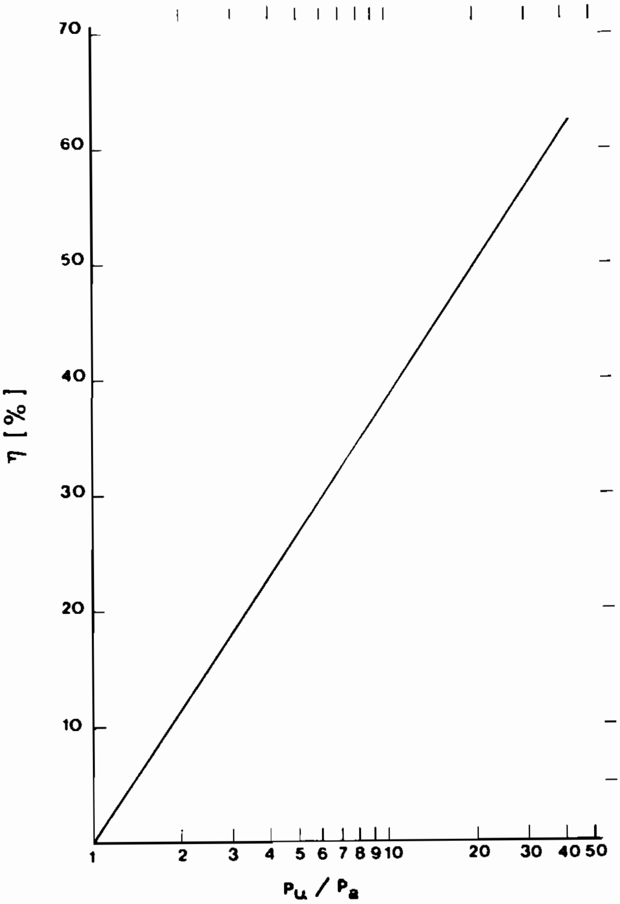

Figure 8. Recovery efficiency of the thermal energy of the steam.

at the outlet of the turbine, they pass through a recovery boiler. A fraction of the steam produced is mixed with the injection air and the rest is expanded in a steam turbine coupled to an alternator. This is, of course, an extremely simplified scheme; the supply to an electrical power plant of 300 MW would require 30 to 40 pairs of boreholes working in parallel.

Such an underground gas generator can work continuously, or with cyclic variation in pressure so that advantage could be taken of the huge volume of the cavities created by the gasification to store energy in the form of compressed air. For a power plant of 300 MW, the power used to compress the gasification air would be about 80 MW. If we adopted the variable pressure process, this would be increased to 160 MW enabling us to

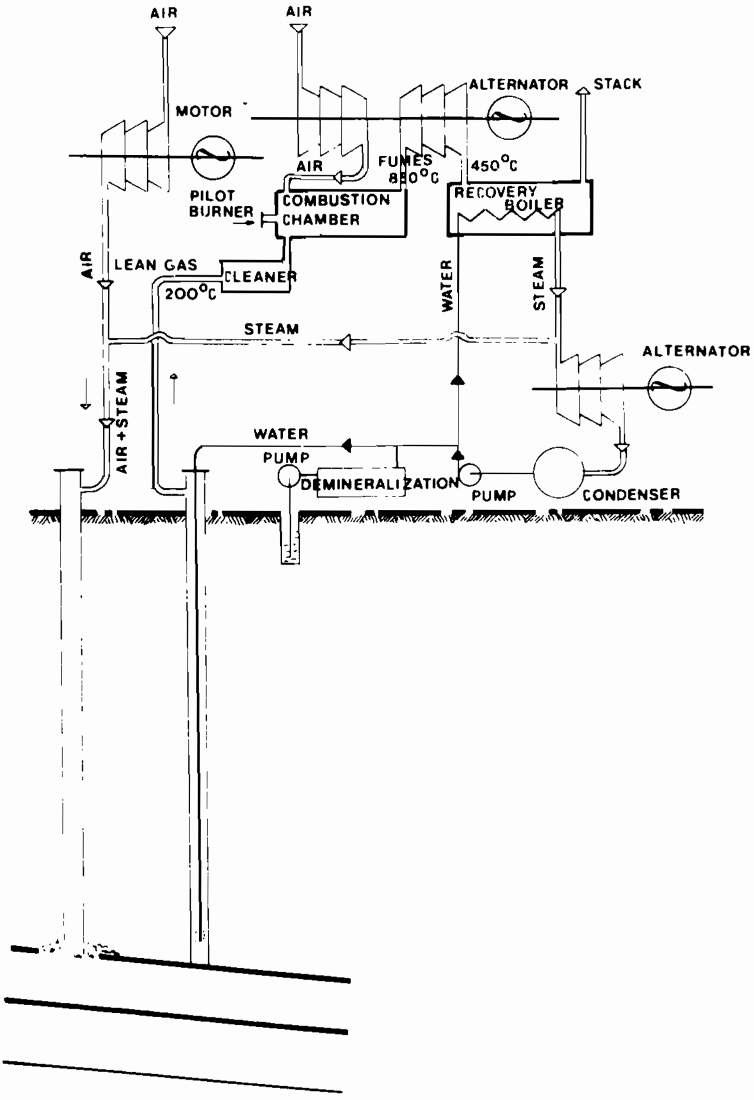

Figure 9. Scheme of the gasification method under variable high pressure for the generation of lean gas.

use it only half the time (at night); the output power of the power plant could thus vary between 380 MW (during the daytime) and 220 MW (during the night time) without modifying the maximum gas consumption level or the turbine working conditions.

The surface installation shown in Figure 9 is very similar to the combined-cycle power plant, built at Lünen (FRG) by the STEAG Company, which is fed by a battery of five Lurgi gas generators working under a pressure of 20 bar. The present investment needed to build such a power plant with a useful power of 300 MW is 140 million dollars, a third of which is for the gas generators (including cleaning) and two thirds for the conversion of gas into electric energy. About the same investment would be necessary for a power plant supplied by a high pressure underground gasification system: the gas cleaning installation is identical and the cost of the pipes and ancillary surface installations necessary for underground gasification is about the same as the cost of the gas generators used to gasify the extracted coal. The economics of either solution will in the end depend on three factors: the cost of a unit of energy extracted as coal or as gas, the efficiency of conversion of coal into gas, and the utilization rate of the power plant.

Underground gasification could compete per unit of energy with coal won in open-pit mines unless the cost per unit energy of coal is increased by 25 to 26% to take into account the gasification efficiency. It could be very competitive compared with coals from underground workings--particularly from European workings at medium and great depths [6]. Underground gasification at high variable pressure is obviously very interesting because of the possible energy storage during the night time.

A last important point is the unusually low investment needed to industrialize the method. When a new colliery is opened up, millions of dollars have to be spent to drive shafts and roadways well before the first coal is extracted and, at best, this is paid off in the next 20 to 30 years. In underground gasification, the boreholes are drilled as needed, their exploitation lasts only a few months, and their cost can be paid off as soon as exploitation of the first seam is completed. This allows the exploitation of the following seams to be done under unusually favorable economic conditions.

CONCLUSIONS

The possibility of achieving the exploitation of deep deposits by means of underground gasification under variable high pressure remains to be proved experimentally and we hope a first in situ experiment will be carried out soon by cooperation between the FRG and Belgium. The preliminary studies now in progress show that the method is economically attractive, as the drawbacks resulting from the depth are compensated for by obvious technical advantages:

- lack of gas leakages,
- lack of interference with the superficial water-bearing layers,

- possibility of working under high pressure and to use gasification with air, oxygen, or (if the pressure of the underground gas generator can be made sufficiently high) hydrogen.

The industrial success of exploiting deep deposits by underground gasification would result in freeing man from the hard labor of present-day mines and would make available in fluid form the huge reserves of solid fuels which constitute the main energy resource of the Earth's crust. Thus underground gasification could contribute to the progressive change from petrochemistry to carbochemistry, necessary because of the rapid decline in gas and oil reserves. It could constitute an alternative to nuclear energy so often put forward as the unique, urgent, and unavoidable solution.

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COAL TRANSPORTATION

ECONOMICS OF MINERAL AND BROWN COAL PIPELINE HYDROTRANSPORT

S.N. Baibakov, B.N. Belych, L.L. Morozov,
J.P. Olophynsky, E.J. Rukin, and B.S. Stepin

Today in the USSR and elsewhere investigations are being carried out and industrial facilities constructed for pipeline transport of coal as a water-coal mixture.

The pipeline system for coal delivery consists of the following main parts: a plant for preparation of the water-coal mixture, the pipeline, coal dehydration and water clarification systems, and combustion system.

At the water-coal mixture preparation plant, coal is crushed to fragments of less than 3 mm, which are mixed with water to a given concentration (optimally, 50% or less) and held at transport standard in accumulating vessels.

A steel pipeline for delivery of the water-coal mixture is laid in a trench underground to prevent the mixture from freezing in winter. The trench in the coal transport system to be constructed from the basins of the Kansk-Achinsk and Kuznetsk regions to the central regions may be up to 2.5 to 3 m deep. The pipes used are readily available, commonly serving for the construction of oil and gas mains.

The pumping stations are equipped with special positive displacement pumps for pumping abrasive mixtures, with protective locking hydro-fittings, and with baths for water and the water-coal mixture. The pumps and fittings are selected for pressures of 75 to 120 atm. The pumping stations are located at intervals of 80 to 120 km. The mixture receiving and storage facilities are constructed at the electric power station.

Combustion of the water-coal mixture received at the electric power station is generally possible at the standard transport concentration, but dehydration degree and combustion technology are determined by the coal grade and type of boiler equipment.

Pipeline delivery of the water-coal mixture in principle is no different from oil pumping and has all the advantages of continuous pipeline transport: line process, possibility of full automation, minimum losses of the material being transported, high capacity with small transport equipment size, few maintenance personnel. However, from the point of view of selection and provision of the technological regimes, water-coal mixture pumping is a very complex problem. Extensive investigations are required, depending on the material being transported, to select the mixture velocity, equipment, construction materials, parameters to be measured, and control devices, and to fix the physical and chemical properties (concentration, stability, viscosity, etc.) of the mixture.

The hydrotransport system, comprising the transport, preparation, and servicing of the system components, is an integrated mechanism in which variation in some technological parameters automatically results in a change in others. The main technological parameters defining the economic efficiency of the hydrotransport system as a whole are: granulometric composition, i.e. maximum particle size and size distribution, mixture concentration, delivery velocity, pumping pressure, and level of automation. Depending on the physical and chemical surface properties of bulk solids, it may be possible to select chemical reagents such that the economic efficiency of the hydrotransport system can be increased by means of decreasing the mixture's water content, hydraulic resistance, maximum particle size, and so forth.

The experimental data on application of surface-active substances for changing water-coal suspension properties indicate that the choice of reagent and the method of its introduction decisively depend on the nature of the coal and are different in the main for hard and brown coals. Metamorphosis stage, petrographic composition, percentage of ash, charge polarity and magnitude, granulometric composition, hydrotransport parameters, ion composition, and water pH value must all be taken into account.

Thus reagents that make the coal surface more hydrophilic are recommended for mineral coals [1]. They must be of high molecular weight and have a high content of polar groups to promote the formation of hydrate shells around the coal particles. These weaken coagulative contacts between particles and decrease the mixture viscosity. A large number of preparations produced on an industrial scale have been investigated. It was found that introduction of for example finely ground oksil, liquid glass, coal alkali reagent, and sulfite grains (barda), decreases head pressure losses two- or threefold. The reagent costs are between 14 and 60 kopeks per ton of coal. Optimal particle size for hydrotransport is in the region of the largest particles, and investigations suggest that decreased resistance can be attained in this region.

Brown coals are characterized by high water content and well developed hydrate shells, weakening the connections between coal particles. Brown coal suspensions thus have a very low sedimentation stability and a tendency to form high viscosity sediments during stratification. Reagents that make the coal surface more hydrophobic [2] and promote the development of coagulative contacts between particles are recommended for the stabilization of brown coal suspensions. These reagents destroy hydrate shells transfer part of the water content into the free state, stabilizing the system and making a decrease in viscosity possible. The best results have been obtained by treating coal (before mixing it with water) with silicone liquids--in particular GKI-11, with a consumption of 1 kg/t [2,3]. The cost of 1 kg of this reagent is 65 kopeks.

In 1975-1977 a number of preliminary theoretical and experimental investigations were carried out at VNIIPItransprogress on the definition of the technical and economic parameters of the main coal pipelines, and on ways of optimizing these and increasing economic efficiency. A comparison of the economic efficiency of the main coal pipelines with that of rail coal transport systems was conducted. The investigations of rail systems and efficiency of fuel use were carried out by VNIIKTEP and IKTP of GOSPLAN. The technological parameters of pipeline transport (velocity, mixture concentration, and granulometric composition) as well as economic reference and normative information of analogous coal pipelines are the main base data for the comparison.

The main oil pipelines, if one takes account of pipeline additional wear from erosion by solid particles, can serve as an analogue for the linear part excluding pumping stations [4].

The standard reference books on preparation plants were used as the basis for the design of analogue plants for slurry preparation and dewatering systems [5-8].

Cost estimates on the construction of pumping stations for conveying the water-coal mixture were developed for lack of satisfactory analogues. These stations were equipped with positive-displacement feeders driven by the NPP-2 type water pump developed by UkrNIIGidrougol for various capacities.

At VNIIPItransprogress* a special method was developed for selecting technological regimes, using the test data of UkrNIIGidrougol** and the results of studies conducted with experimental hydraulic benches of 100 to 150 mm diameter pipe and tubular viscometers at VNIIPItransprogress with the coal of the Irsha-Borodinsky region. From the calculations it appeared that for pipelines of 600 mm diameter the distance between pumping stations may not be less than 80 km for a pump pressure of 75 kgf/cm^2. Transport velocity is 1.5 to 3.5 m/s depending on pipeline diameter and type of solid fuel. The water content of the water-coal mixture is 50% or less.

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*All-Union Research, Development and Design Institute for Capsule Pipeline.

**Ukrainian Research, Development and Design Institute for Underground Hydraulic Coal Production.

The operating experience of US slurry pipelines shows that pipe wear during exploitation is negligible. Only some elements of the pumping equipment are subjected to wear. In some US projects the wear is less than 17 μm. We have reckoned with a wear of 1 mm during five years, i.e. one order greater.

Based on the calculations made we have found that the main coal pipelines are more effective than rail transport in the European part of our country when carrying considerable quantities of coal. The comparison was made for the capacity of 100 Mt/year of the Kuznetsk coal basin. Under these conditions transport costs for the delivery of a ton of coal from the Kuznetsl basin to the center of the country are 13.1 roubles by rail and 6.8 roubles by slurry pipeline. The metal quantity used in pipeline. The metal quantity used in pipeline transport is somewhat below that in rail transport.

The advantage of a coal pipeline is especially great with respect to the manpower used during the construction and exploitation periods.

Figures 1 to 8 show the results of calculations of some technological parameters for 50% water-coal mixtures (Figures 1 and 6) and construction and exploitation costs of pipeline transport systems (Figures 7 and 8)*. The economic efficiency of pipeline transport is increased due to the rise in freight traffic volume (Figure 3). Since the costs of slurry preparation plant construction (Figure 4) and slurry preparation for combustion, i.e. dewatering costs (Figure 5), do not depend on transport distance and since net transport expenses increase with distance, the share of total expenses for the initial and final operations decreases, while the overall efficiency of the system increases with distance (Figure 7). Expense analysis (Figure 8) shows that with a line length of 2000 km and an annual freight traffic volume of more than 40 Mt of coal, the share of initial and final operation expenses is less than 20%, with the dewatering expenses being two to three times the slurry preparation mixture expenses. It is clear that the reduction in expenses for, first, construction and operation of the linear part and, second, the dewatering system will have the most economic effect. One of the main problems is the purification and utilization of the coal-carrying water, since reversibility of water supply under conditions of long-distance transport requires heavy capital and industrial costs. The widespread adoption of pipeline transport is impossible without solution of this problem.

In principle it is possible to solve this problem by direct burning of the water-coal mixture without prior dewatering. However, in this case the heat output of the fuel drops (by 4 to 11%), although the burning technique is simplified substantially and an electric power station becomes like a liquid fuel

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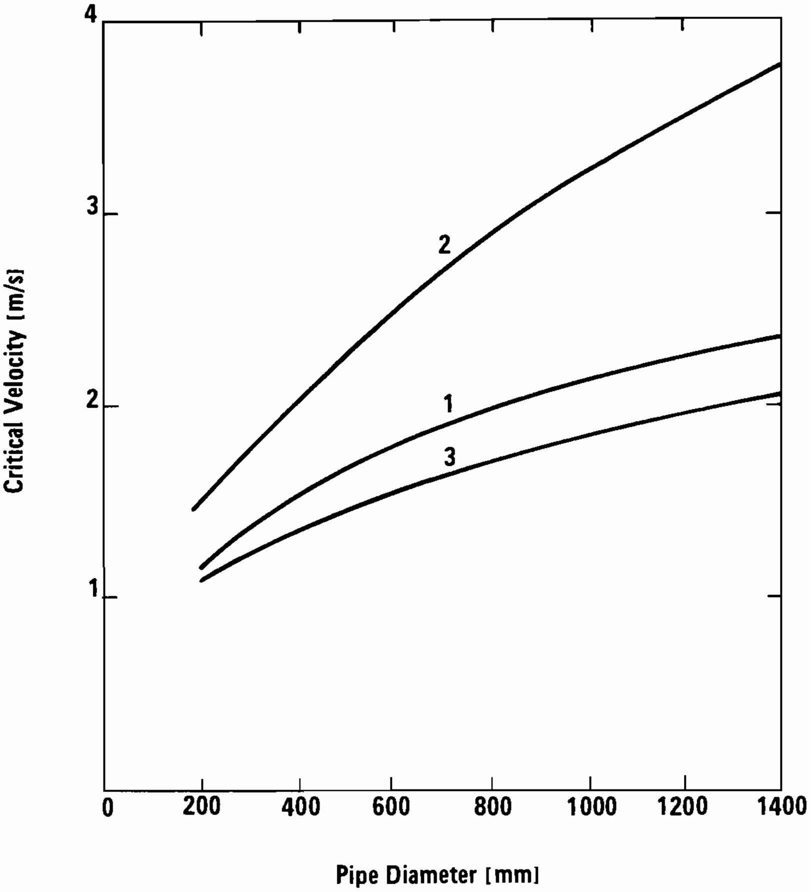
*The calculations were made without taking account of the reactants in the mixture transported that reduced hydraulic resistance.



1 Kansk-Achinsk coal
2 Product of hydrogenous coal processing (koksik)
3 Kuznetsk coal

Figure 1. Dependence of critical velocity on pipe diameter.

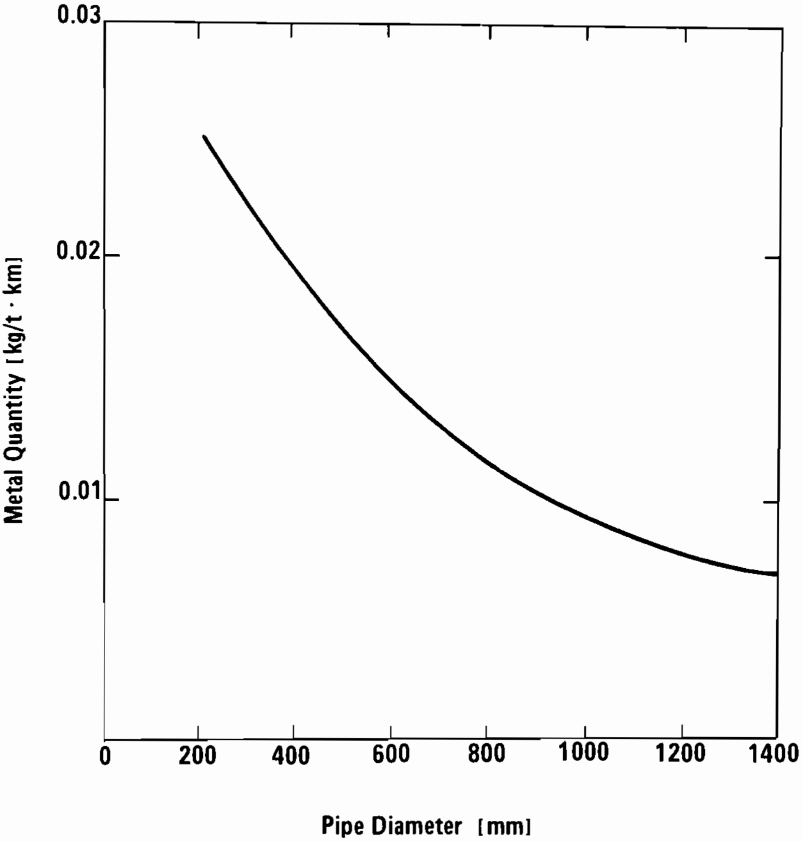


Figure 2. Dependence of metal quantity on pipe diameter.

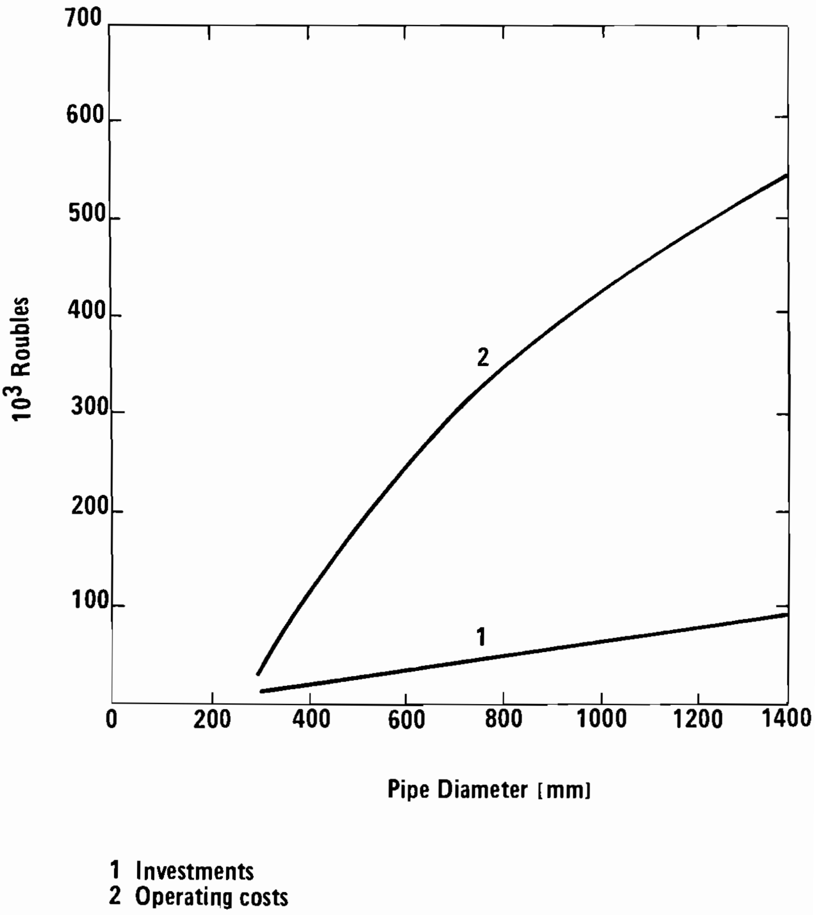
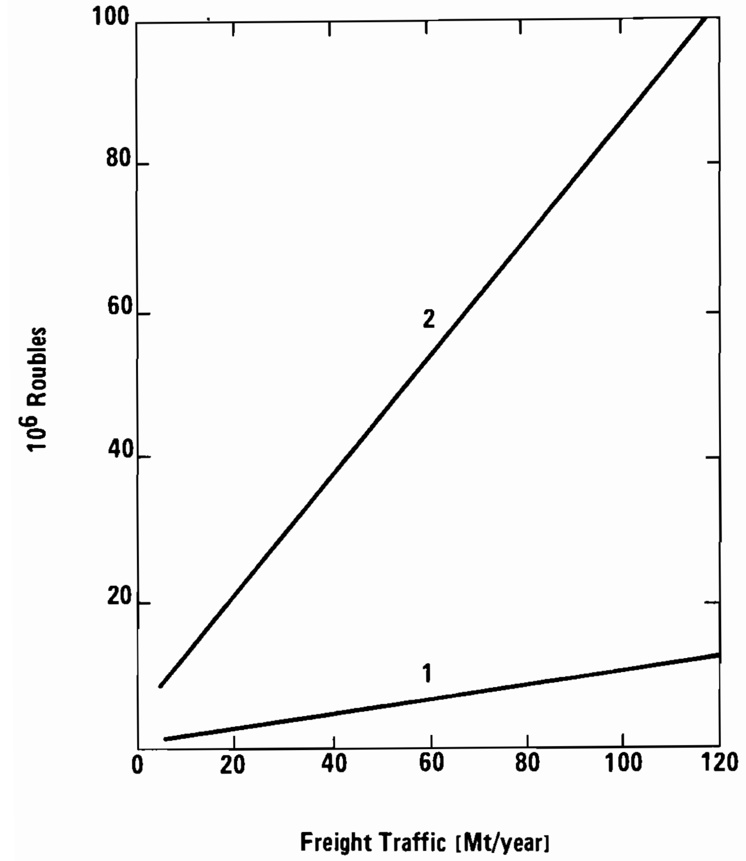
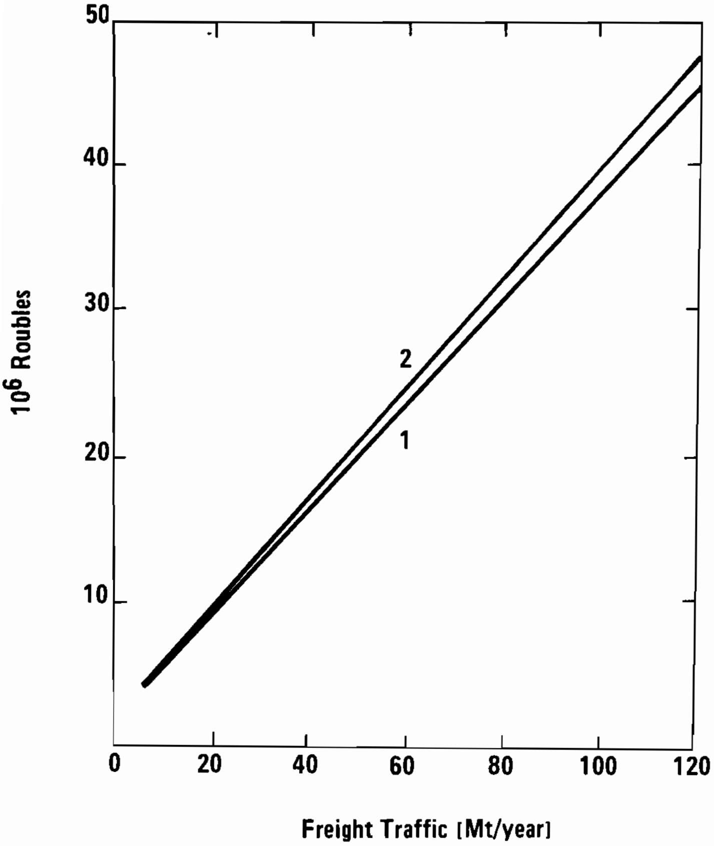


Figure 3. Dependence of investments and operating costs per km of the slurry transport system on pipe diameter.



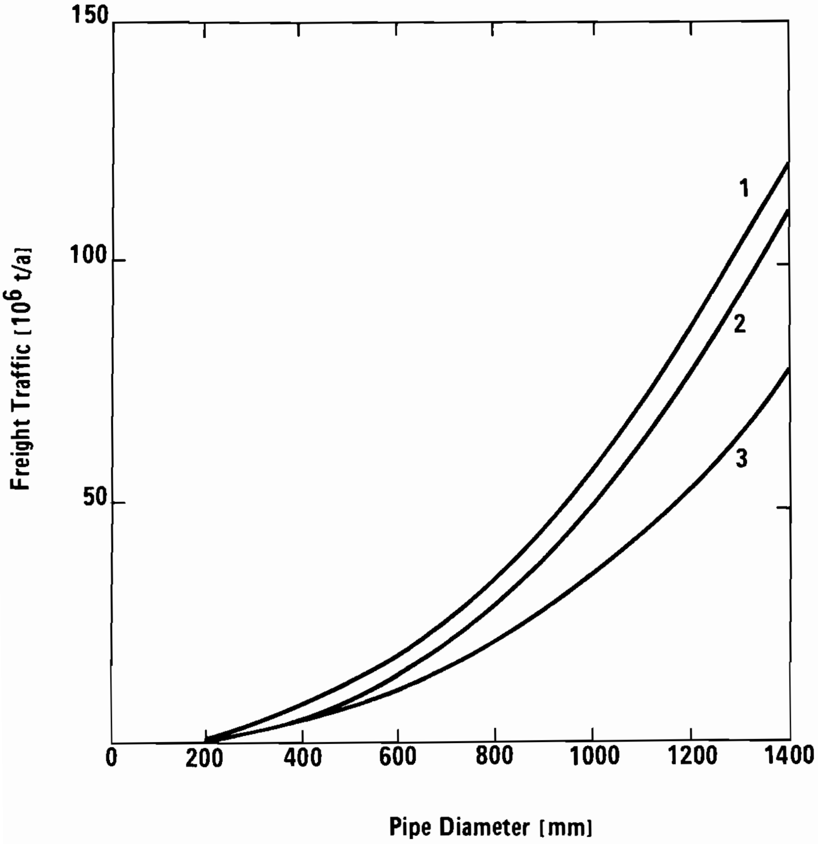
1 Investments
2 Operating costs

Figure 4. Dependence of investments and operating costs on freight traffic volume for a slurry preparation plant.



1 Investments
2 Operating costs

Figure 5. Dependence of investments and operating costs on freight traffic volume for a slurry preparation system for burning.



1 Kansk-Achinsk coal
2 Product of hydrogenous coal processing (koksik)
3 Kuznetsk coal

Figure 6. Dependence of pipeline capacity on pipe diameter.

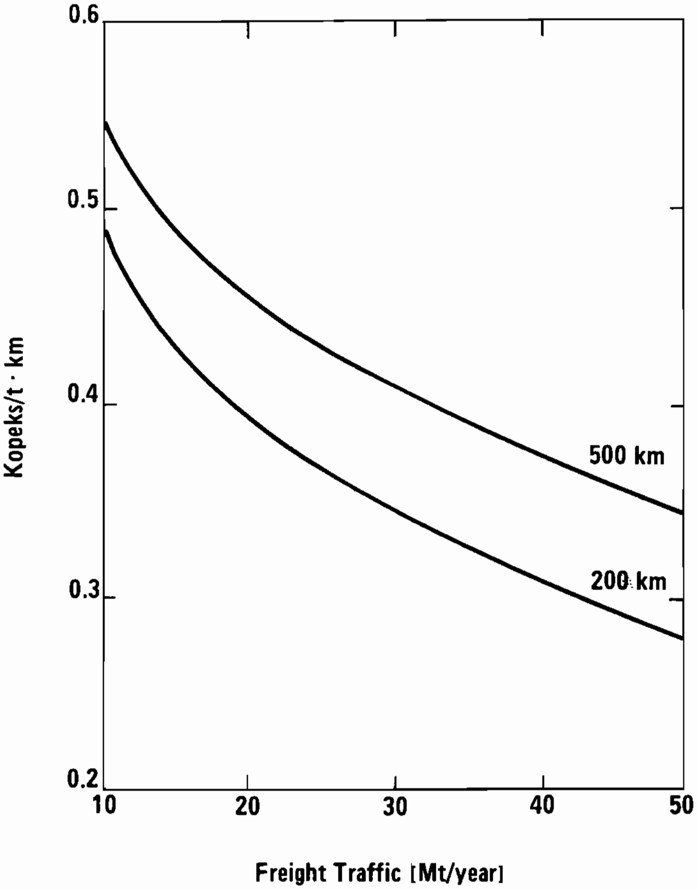
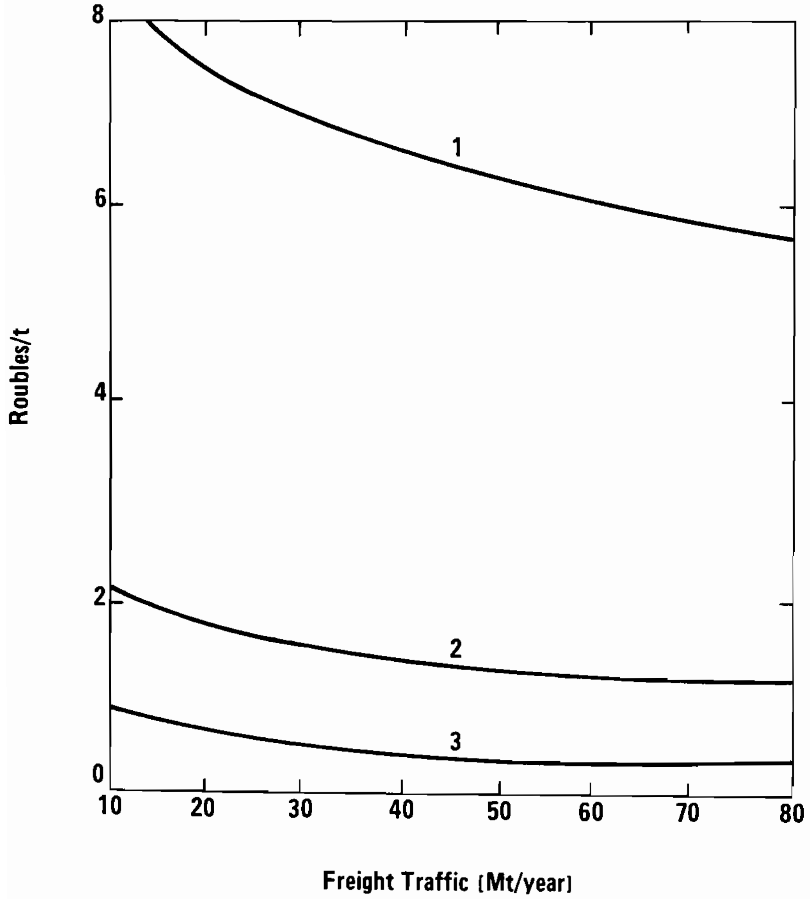


Figure 7. Cost of hydraulic transport of Kansk-Achinsk coal (including preparation for transport).



1 Transport part
2 Slurry preparation system for burning
3 Slurry preparation plant

Figure 8. Dependence of transport costs versus the pipe capacity over 2000 km.

one. As the water content is reduced (partial water-coal mixture dewatering) the heat output is increased, but at the same time the fuel preparation system for burning is complicated and plant transport costs rise.

The characteristics and efficiency of dewatering systems depend on fuel chemical and physical properties, degree of fineness, liquid phase composition, and other factors. Partial dewatering is of some interest (especially the experience of the operational pipeline "Black Mesa").

The dewatering process may be regarded as mechanical dewatering by filters or centrifugal devices and chemical treatment of drainage waters with subsequent gravitational, magnetic, or supersonic condensation.

As the coal industry has great practice in dewatering and clarification of coal slurry, this report presents the results of slurry water clarification obtained after mechanical dewatering of the brown coal suspension. The experiments were carried out with the brown coal of the Irsha-Borodinsky deposit.

The brown coal of the Kansk-Achinsk basin is characterized by a very high moisture content, up to 33 to 39%; the maximum water capacity reaches 32%, a large part of the moisture being in a bound state [9]. The chemical properties of the coal and their high porosity create great difficulties for preparing a concentrated suspension and for dewatering. The investigation of water-coal combinations, methods of water transfer from the bound to the unbound state, and thinning or destruction of the hydrated coatings of coal particles are conditions for the control of water-coal suspension characteristics at the preparation and dewatering stages.

The experiments were conducted with brown coal slurry, 60% of whose particles were thinner than 50 μm, the solid particle content reaching 60 g/l. The cation-active and nonionic high molecular polymers were tested mainly because of the negative charge of the brown coal and the high degree of water retention at the water clarification stage.

Anion-active flocculants (polyacrylamide, Metas*, Comet**, Magnaflok-156) had no flocculation activity and did not help to clarify slurry waters, even in contact up to 1 h, with a consumption of 15 to 300 g/t. The results of nonionic and cation-active flocculant experiments are the following.

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*A methacrylic acid and its copolymer, m. wt. 3 × 10^5, produced in the USSR.

**A sodium polymethacrylate, m. wt. 3 × 10^5, produced in the USSR.

- The nonionic polyxyethene is effective only at a molecular weight of over 600,000, but cation-active flocculants give satisfactory results at a molecular weight of 40,000 to 80,000.
- As the molecular weight of a flocculant increases its consumption decreases and the rate of the water clarification grows, but the coal content in the condensed deposit drops. This shows that brown coal slurry condensing takes place according to the bridge type of flocculation.
- The clarification rate and the clarified water transparency are highly dependent on the consumption of all flocculants being tested; this means that the flocculant excess gives the slurry stability.
- The condensed deposit density after sedimentation by gravity is dependent on the flocculant molecular weight, consumption, and the flocculation duration is not changed appreciably by variations of the coal content (40 to 160 g/l) in the initial slurry.
- As the coal content increases in the initial slurry from 8 to between 60 and 80 g/l, the water clarification and slurry sedimentation rate increases too, but further increase of the coal content to between 160 and 200 g/l results in a sharp drop in slurry sedimentation rate at the expense of drainage water transparency.
- With a polyxyethene consumption of 10 to 100 g/t coal the coal content in the slurry drops from 40-120 g/l to 100-200 mg/l, a condensed deposit of 200 g/l density being formed. With the increase of slurry sedimentation times 5, 10, and 40 min, the condensed deposit density rises to 260, 320, and 350 g/l respectively.

The results obtained show that the brown coal slurries may be dewatered by drainage and that a sufficiently dense deposit is formed with the amount of flocculants normally used in preparation plants. The suspended particle content in the drainage water does not exceed the level assumed for preparation plants. The slurry condensation process may be intensified by magnetic or ultrasonic treatment of the slurry or by centrifuation.

CONCLUSIONS

Pipeline hydrotransport of coal is highly efficient and has some economic advantages over rail transport especially for large distances and volumes.

The economic efficiency of coal pipeline hydrotransport systems is mainly due to the high output of the line part as well as dewatering and clarification devices.

At present the technological scheme and the economic efficiency of coal preparing and burning after the coal had been delivered by hydrotransport are the least studied problems.

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TRANSPORT OF COAL BY PIPELINE

H. de Ruiter*

BACKGROUND

As world oil and natural gas resources are gradually being depleted and prices escalate, incentives and pressure to use fuels such as coal are increasing.

In many parts of the world, coal deposits are located in areas remote from the energy consuming regions, and the transition in fuel usage will present a transportation problem in moving the coal long distances to their markets. An example of this future logistic problem is the transportation of extensive coal deposits in the western USA over distances up to 2000 km to the industrialized areas on the West Coast, Gulf Coast, and in the central areas of that country. Other large deposits of coal are available in remote areas of Canada, southern Africa, Australia, and eastern USSR and will have to be moved long distances to the consuming world markets.

The cost of transporting coal is high and is normally a significant portion of the delivered coal cost (Figure 1). Therefore, it is imperative to investigate all methods for coal transportation to minimize the coal cost to consuming utility and industrial users. One of the feasible options is a coal slurry pipeline representing a modern development in coal transportation technology and being available at a time when new methods are required not only to expand transportation capacities, but also to keep current and future costs down. Transporting solids in slurry form is now supported by substantial technology and is backed by the experience of numerous commercial installations, as evidenced by existing long distance pipelines for transporting iron, copper, phosphate concentrates, and limestone.

The system is also suitable for domestic transportation of large quantities of coal from a mine to a power plant. The Consolidation Coal slurry pipeline and the Black Mesa coal slurry pipeline in the USA are examples of this type of system. In particular, the 18 inch Black Mesa pipeline in Arizona (USA) with a length of 381 km which has been in operation since 1970 with an annual design throughput of 4.8 Mt, has proven the technical feasibility and the economic benefits of such a system for supplying coal to a power station.

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*Paper presented by L.J. van der Toorn.

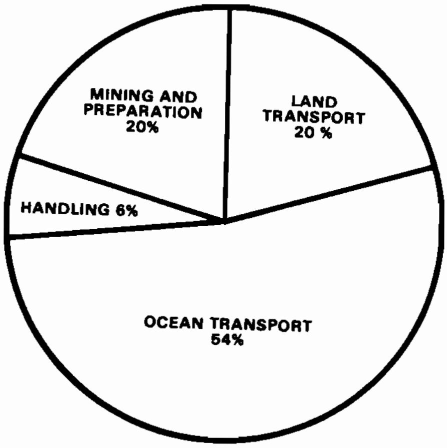

Figure 1. Approximate distribution of mining and transport costs for 500 km land transportation and 7000 sea miles sea transportation.

To cope with the increase in demand, four major coal slurry pipelines have been projected in the USA. But besides expansion of domestic use of coal, the forecasted increase in demand will cause a sharp rise in world coal trade and thus in the demand for transport of large volumes from existing or new overseas coal producing areas to the energy markets of, for example, Europe and Japan. This is bound to pose considerable problems to the use of coal slurry pipelines; first, since it is not intended to serve a single captive user who can gear the design of his equipment to the particular characteristics of dewatered pipeline coal, the marketing of such a product of unconventional specification in a competitive overseas market is likely to be impossible but at best would necessitate significant price discounts; and secondly, safe transport in dry-bulk carriers could not be guaranteed since the relatively high percentage of moisture in the product (up to 25%) could cause layers of cargo to behave as a plastic material as a result of water migration during transport, while at the same time the penality of transporting water instead of coal could add so much to the cost of an integrated pipeline/ ocean transport system that it would no longer be economically attractive.

This paper deals with process aspects of pipeline technology that have been the subject of extensive Shell research and development (R&D) work, and endeavours to indicate the circumstances under which it can be expected that a slurry pipeline either for domestic use or for export purposes is attractive in comparison with conventional transportation of coal by rail.

SLURRY PIPELINE SYSTEM AND PROCESS DESCRIPTION

The selection of a pipeline system and its design are governed by the location of the coal source and destination, the quantity, quality, and number of grades of coal, the location of water sources and water quality, the customer acceptability of the dewatered pipeline coal, and environmental considerations (see Figure 2).

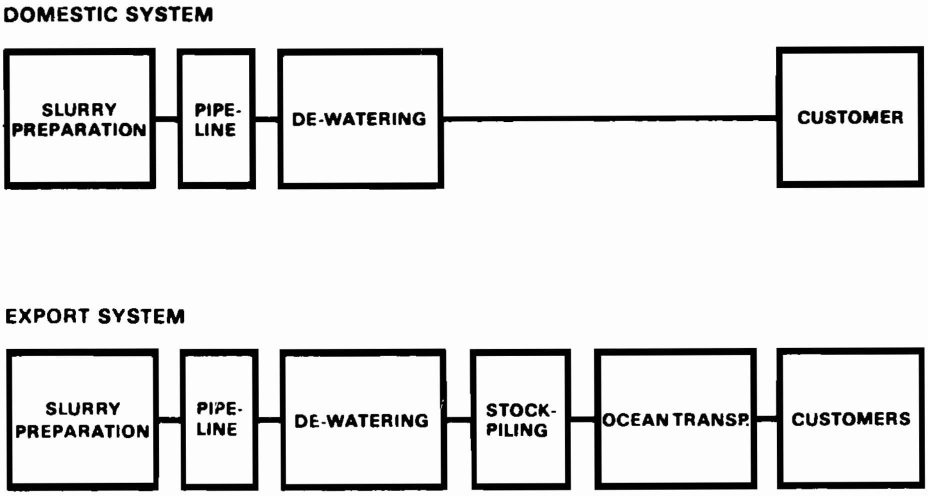

Figure 2. Schematic comparison between domestic and export coal transport systems that use slurry pipelines.

Domestic Projects

In the case of a captive mine to power plant project the envisaged transportation system is relatively simple since its objective is to transport as cheaply as possible one grade of coal from a mine to a power station which will be designed in accordance with the dewatered coal properties.

To be practical, such a long distance pipeline must handle well graded, small size particles that will stay in suspension within the normal range of pipeline liquid velocities, 4 to 6 ft/s. Such a grind is necessary to produce a concentrated slurry that settles uniformly and can be restarted after shutdown. Over the years, Shell research has confirmed that a "conventional" particle top-size of about 1.2 mm and a proportion of the fraction below 44 µm of some 20 to 30% by weight has the required operational characteristics. Therefore, coal is ground to that particle size distribution and subsequently mixed with an equal amount of water to obtain the slurry required for piping. After storage of the slurry, during which a final check on size distribution and concentration is carried out, it is pumped through the pipeline in turbulent flow to the dewatering plant near the power station. In order to maintain the required slurry velocity, pump-stations are installed in the trunk pipeline to overcome the pressure losses. In order to transport solids successfully as a slurry enough energy via turbulence must be transmitted to the slurry to keep the solids in suspension. Hence, the minimum operating velocity must be high enough to cause this turbulence. On the other hand, at very high velocities, wear and excessive pumping power are problematic. This implies that every slurry pipeline with a certain diameter has its own range of acceptable velocities. Since the average velocity is given by the annual throughput, selection of a pipeline is basically determined by its inside diameter. For instance, in the case of 5 Mt coal per year a pipeline diameter of 18 inches would be selected and for 10 Mt per year a diameter of 22 inches. The steel pipeline is generally laid underground with a minimum cover of 1 m. Slopes of up to 10° are acceptable for the selection of the pipeline route; this limit is necessary to prevent sloughing which causes sags to fill with over-concentrated or thickened slurry. From the pipeline the slurry is fed directly into the dewatering plant, where screen bowl centrifuges are used to dewater the slurry mechanically. This process gives a product with a total moisture content of 17 to 19% by weight. In order to reduce the moisture content of pipeline coal further, the slurry can be heated before entering the centrifuges. Heat exchanges should then be included in the dewatering system and the waste heat of the power plant could probably be used to supply the necessary energy. Conveyor belt connections will be used to transport the final dewatered coal product to the power station. The overflow water from the dewatering plant will be pumped to the water treatment plant, from where it will be disposed into the sea, or else it could be used for water supply to the power plant.

Export Projects

The primary objective of the development of a slurry pipeline system for an export project has been to obtain an end-product that could be generally and universally marketed. By this is meant that the product can be shipped, handled, stored and combusted in existing and conventional equipment, and that to all intents and purposes the product should equal the characteristics of conventional coal as it is currently marketed (see Figure 3).

Dewatered pipeline coal has poor flow properties. As a result, blocking of bunkers and transfer points at customer installations would occur. This is caused by a combination of high moisture content and a large proportion of small particles. Therefore, in order to be able to handle the pipeline product in an export system (a necessity if the product is to be successfully marketed) the moisture content should be reduced and/or the proportion of fine particles decreased.

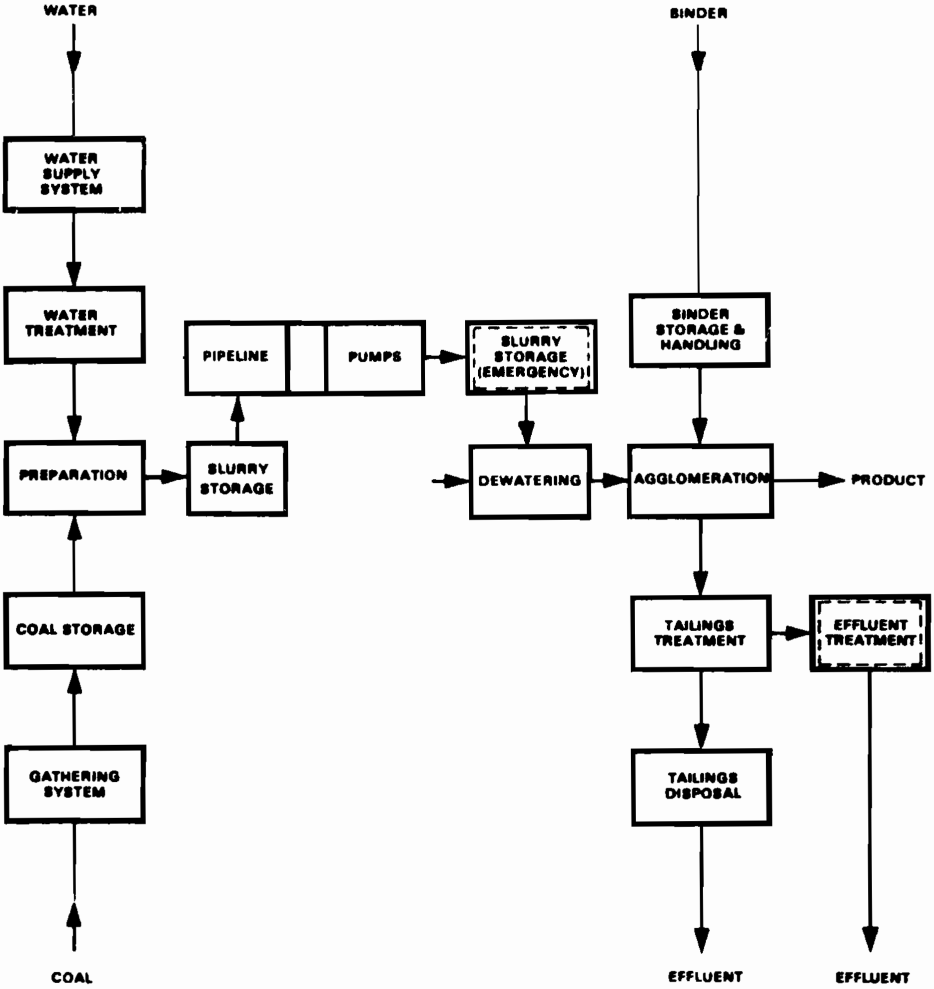

Figure 3. Elements of the complete slurry pipeline system.

Reducing the moisture content by mechanical means (centrifuging) of a slurry containing the full particle size range cannot give a moisture content below 15 to 16% by weight. A further reduction would require the very expensive method of thermal drying. Therefore, improving the flow properties has to be attempted via reduction of the smallest particle fraction. This can be done by increasing the average particle size to be pipelined (i.e. making a coarser slurry) and by agglomeration of the finest material in the slurry.

Shell research in the last two years has centred on defining an acceptable pipeline product that could be made in the most economic way out of a coarser slurry by means of mechanical dewatering and agglomeration.

The research subjects covered include:

- Influence of particle size distribution (PSD) on the flow properties of dewatered coal;
- Hydraulic behaviour of slurry with the adopted PSD;
- The behaviour of the mix of agglomerates and fine coal in power-station mills (necessary because the agglomeration process requires the addition of a hydrocarbon binder);
- Additional problems relating to the transport of slurry and the dewatered pipeline product.

Although this R&D program is still continuing, a few results can be mentioned here:

Pipelining of Coarser Slurries

The resulting PSD is different from the "conventional" one used in the Black Mesa system and therefore tests were conducted in Shell's Pipeline Laboratory to assess the hydraulic behaviour of a range of coarser slurries. The results have been encouraging and showed that such coarser slurries can safely be pumped under certain conditions at reasonable velocities. The tests gave no indication of any danger of plug formation (caused by the settled bed in inclined pipeline sections after an involuntary shutdown) or of difficulties with subsequent restart. It was also established that Shell's computer program for predicting the friction loss per unit of pipeline and the critical deposition velocity of particles is valid for the slurries. Further tests indicated that no appreciable pipe erosion or particle attrition is to be expected.

Internal Corrosion of Pipeline

The conventional method of controlling internal corrosion by addition of inhibitor is very expensive. Therefore, the possibility of lining the pipe with a suitable material was investigated and it was concluded that applying a concrete lining in site would give adequate and reliable protection at acceptable cost, even though the rougher surface somewhat increases the friction loss and thus the power requirement.

Slurry Dewatering and Agglomeration

Tests carried out in a screen bowl centrifuge on a slurry with conventional PSD showed that when dewatering the total size range a moisture content of 16 to 18% could be reached, whilst dewatering of the plus 200 µm fraction leaves only 10% surface moisture in the cake. (See Figure 4.)

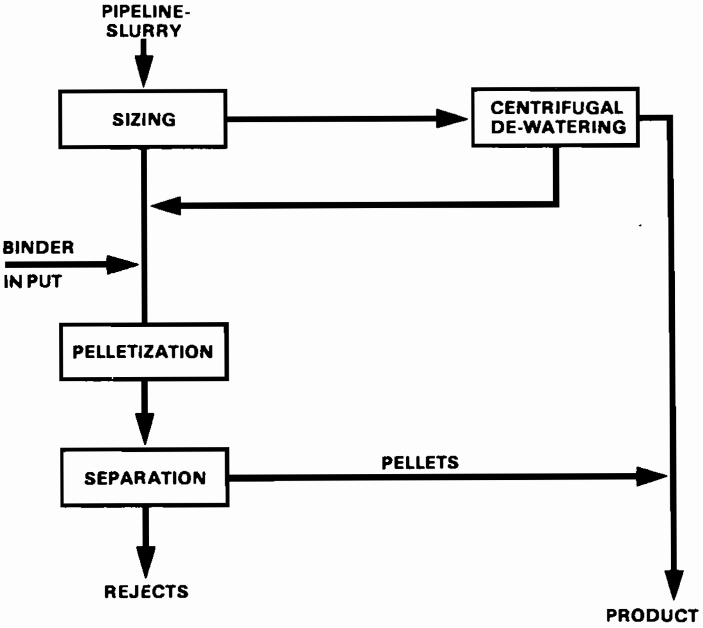

Figure 4. Process scheme for coal slurry dewatering.

A promising method of reducing the finest fraction is a screening operation and subsequent agglomeration. This has the advantage that the coarser fraction can be dewatered in the centrifuges more deeply. The agglomeration can be done by, for example, the Shell Pelletizer Separator (SPS). The SPS (Figure 5) consists of a horizontal, cylindrical vessel with a rotating shaft on which there are a number of impellers. The coal slurry and the hydrocarbon binder are fed in at one end of the cylinder and vigorously stirred.

The principle of the operation is that the hydrocarbon binder preferentially wets the coal particles which subsequently agglomerate to form pellets with sufficient strength and a low moisture content. The coal pellets can easily be separated from the ash and water in a wet screening operation at the outlet of the SPS unit. An additional advantage of the operation is that the free ash is not agglomerated, resulting in lower ash content of the product than the slurry feed to the SPS.

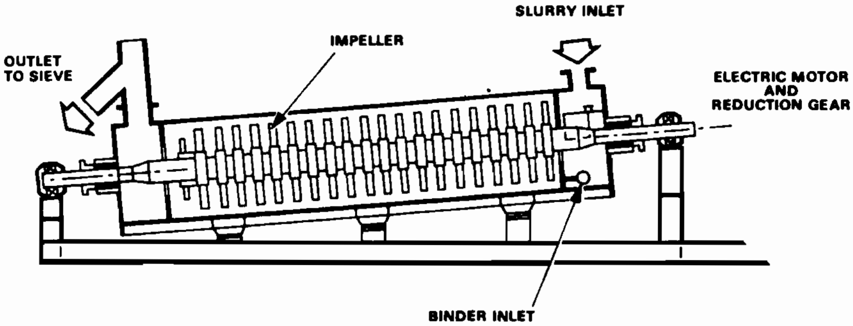

Figure 5. Section through Shell Pelletizer Separator (SPS).

Fryston Pilot Plant

In order to assess the technical feasibility of the proposed dewatering and agglomeration process and to provide large bulk samples of selected blends for handling, pulverizing, and combustion trials on a commercial scale, it was decided to build a demonstration plant (Figure 6). The site chosen for this facility was determined by the availability of a suitable source of coal slurry. This was found at a coal preparation plant of the National Coal Board at Fryston, UK. The process applied in this pilot plant consists of three parts. The first produces, from the solids source, a slurry with a PSD comparable to a pipeline slurry: the second part dewaters the slurry and produces a stream of pellets and a stream of coarse fines. In the third part these two streams are blended in the required ratio, and subsequently stored. Construction of the Fryston plant was started towards the end of 1975, and it was first commissioned in August, 1976. Following some start-up problems, a number of necessary design modifications were implemented. The plant is now operating satisfactorily and is producing batches that can be made available for large scale customer trials.

Resulting Coal Properties

Flow Moisture Point

The flow moisture point of a dry bulk material is the surface moisture content at which the lower layers of material in a ship's hold tend to reach a level of saturation at which they become plastic. This can lead to shifting of the cargo. Tests have shown that the surface moisture content of the proposed coarse/pellet mix is well below the flow moisture point.

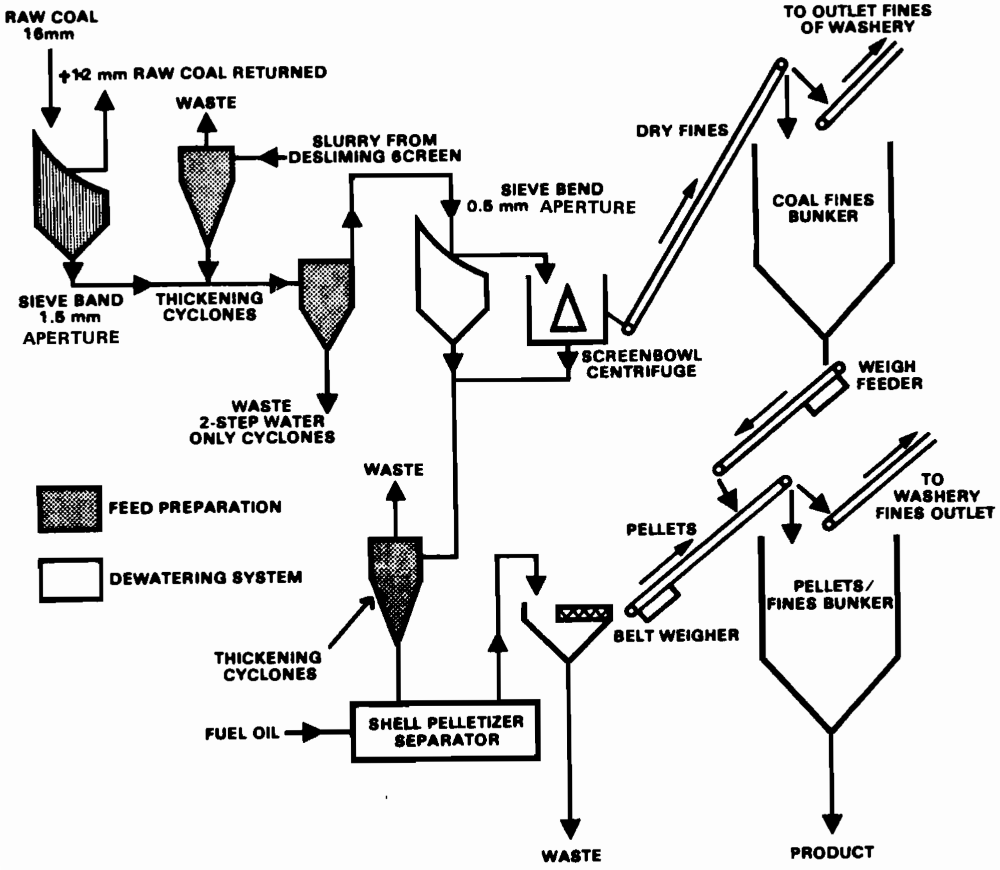

Figure 6. Process flow scheme of Fryston pilot plant.

Behaviour in Power Station Pulverizers

Tests, carried out at elevated temperatures on a "coarse"/ pellets mix containing fuel oil as a binder and up to 30% by weight pellets, showed that this mix is as easy to pulverize as coal without pellets, and that there were no detrimental side effects. In particular, the tests, so far, indicated that the fuel oil present in the pellets does not increase the explosion risks that may be present in a pulverizing mill.

Freezing of Stockpile

The strength of a frozen surface of a stockpile of pipeline coal is so low that it can easily be broken up the equipment normally available in the storage yard of power stations.

Environmental Aspects

Dusting

Results of tests on the dusting tendency of pipeline coal containing the full size range of particles indicate that dust pollution in the air downwind of a coal storage yard is mainly attributable to the amount of very fine material present. Since this fraction is eliminated by pelletization, problems with respect to dust pollution are expected to be at least not greater than with railed coal.

Self-Ignition

Coals transported by long distance pipeline are at least one order of magnitude smaller than most coals transported by railway and therefore can form more compact stockpiles. Calculations have shown that the permeability of a stockpile of pipeline coal is very low and that air sufficient to maintain a fire cannot enter the stockpile. Hence, problems concerning self-ignition are not expected to occur.

Effluent Treatment

The underflow of the sieve after the SPS, consisting mainly of water and ash, must be treated to remove the suspended solids from the water, in order to comply with generally accepted standards for effluent disposal. It should be noted that there is no residual oil in the sieve underflow. Laboratory tests indicated that the only process that appears to consistently satisfy these standards is flocculation/sedimentation.

OUTLOOK FOR COAL SLURRY PIPELINE SYSTEMS

Looking at the long-term benefits the question arises whether it has been and still is worth while to execute a very costly R&D program on coal slurry pipelining (Shell has spent so far approximately US $4 million on research activities in this field). To answer that question one has to look at the economics of a coal slurry pipelining system not in isolation but in comparison with other modes of transport, principally with what appears to be its major competitor, railroading by unit train.

A coal slurry pipeline requires an enormous investment. Being capital intensive, this could be at the same time one of the keys to its economic attractiveness: studies indicate that 70 to 80% of the pipeline tariff is needed for capital recovery, the remaining 20 to 30% are for operating costs consisting of labour, materials, and electricity charges.

This is, of course, particularly relevant in the context of comparison with coal transportation by rail where the ratio capital cost to operating cost is the reverse, i.e. 30:70 as a result of the much larger labour and fuel cost elements.

On a replacement value basis the proportion of cost that is needed for capital recovery will increase with the general trend of inflation. In many countries wage inflation and fuel cost increments will escalate more rapidly than the general inflation indicator and under those circumstances rail transport costs will rise faster than slurry pipeline costs.

The major problem in comparing the cost of transporting coal by unit train with slurry pipeline costs lies, however, in the fact that railway costs are highly variable depending on availability of new or existing railroad bed, spare traffic volume capacity, proportion of future coal traffic in total traffic volume, and, not the least, tariffs for existing railways are negotiated (established individually) with the railway companies.

To circumvent this problem two extreme cases have been considered for an economic comparison with slurry pipelines:

- costs of a new railroad, only transporting coal by unit train operation,

- tariffs for unit train operation of all types of bulk commodities based on a regression analysis of published tariffs, assuming that this is a fair representation of average conditions of general purpose railways.

Figure 7 presents the results in comparison with slurry pipeline costs of a project supplying coal to a local power plant (domestic project) and of a project for delivery of coal into overseas markets (export project). Although extracted from generalized data, the graph clearly demonstrates the dilemma facing the responsible parties when contemplating the introduction of a slurry pipeline:

- if no alternative of transport already exists, pipeline transportation of coal is of great potential importance. Under these circumstances a direct comparison between a coal slurry pipeline and unit train operations on a *dedicated* new railroad favours the former, *even for short distances*.

- in cases where railroad bed is already available or where in addition to the potential coal project more industrial developments or population centres can be linked together, the reduction in rail transport cost (or tariff) can make slurry pipelining unattractive, particularly for smaller volumes and shorter distances.

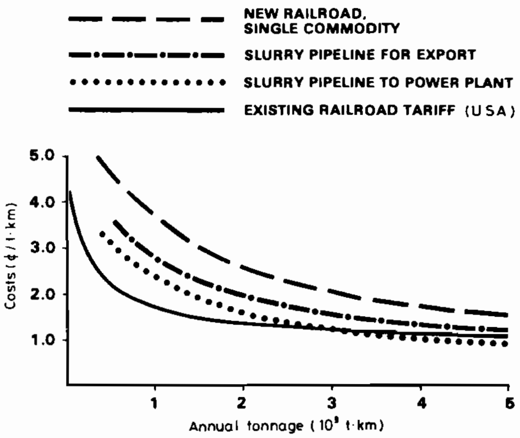

Figure 7. Cost comparison of slurry pipeline with railways.

The most important reservation about this straightforward analysis of capital and operation costs is that they do not take into account the socio-economic consequences of the construction of a major transport route. The introduction of a new slurry pipeline or a railway can have quite different impacts. It is not suggested that it is the responsibility of industry to choose one kind of transport over the other merely on the basis of the ultimate impact upon the social circumstances of the producing country, but undoubtedly it should be kept in mind while planning transport systems that regional population density and (lack of) infrastructure have a big stake in the type of system chosen.

Factors favouring the introduction of a coal slurry pipeline are:

- Normally being laid underground, it is silent and invisible and has no impact on surface activities.

- Being highly automated and immune from surface effects (weather damages), its operational reliability is very high. The Black Mesa pipeline, for example, has shown so far a pipeline availability of 99%.

- Allowing a maximum pipeline inclination of 10 to 15°, it can be constructed over terrain that is impossible for railways.

- Requiring only a modest area, it has limited impact on the surface it uses. The land requirements for a total system, including 180 km slurry pipeline and a water supply line of 120 km are approximately 1100 ha of which 900 ha right-of-way area will be restored after completion of construction.

Factors that could limit the future use of slurry pipelines are:

- Impossibility of transporting other commodities.
- Sufficient water should be available near the mine. If the required water volume cannot be acquired locally a water supply line will have to be constructed.
- Effluent disposal after dewatering. Local requirements will dictate the solution: either the construction of a return water pipeline which has the additional advantages that only "make up" water will be required at the mine, or a disposal water treatment plant.

It looks as if the environmental impact of coal slurry pipelines is generally less severe than transporting coal by rail, whereas the additional benefit in terms of infrastructure favours a railway.

However, the actual balance of strict economics and socio-economic considerations is completely dependent on local circumstances. This can probably be best illustrated by three iron-ore projects all in the volume range 30 to 40 Mt/year with a distance of approximately 400 km between mine and coast:

- W. Australia (desert conditions)--decision: railway
- Brazil (abundant water resources and railway available) --decision: slurry pipeline
- Labrador (Canada) (subzero conditions)--decision: railway

SUMMARY

Shell's current thinking is that the future transport of coal far exceeds the current availability and will require an enormous increase in transport capability in the producing countries. And although not attractive under every geographical and political set of circumstances there appears to be sufficient scope for the construction of coal slurry pipeline systems for domestic as well as export purposes that will provide an attractive, dependable transport system and will result in long term economic benefits to the users of coal.

METHACOAL ENHANCES THE TRANSPORTATION AND USE OF COAL RESOURCES

R.M. Jimeson

INTRODUCTION

In recent years the rise in the price of oil and its unstable market conditions have intensified the desire to utilize other energy sources. For stationary combustion sources the trend has been toward the use of coal and nuclear energy. The shift to greater coal utilization is not easy, for natural gas and petroleum have been in great demand due to their former low cost, convenience in handling, and environmental attributes. However, many nations have large coal resources that if put to use could supplant their petroleum imports and augment short domestic oil and gas supplies. Coal could be used by direct combustion or by various coal conversion schemes. The increased use of coal and the choice of the appropriate coal utilization technology is sensitive to conversion efficiency and the environmental situation. Some of the coals are naturally low in sulfur content and can be burned within prescribed limitations for sulfur oxide emissions. Others require removal of sulfur and mineral matter from the coal before combustion or from the flue gas afterward. The technology for "cleaning" coal or for removing sulfur oxides and particulate matter from flue gases resulting from coal combustion is available and being improved. Thus, an opportunity exists to burn coal within acceptable air pollution requirements. Unfortunately, an additional environment concern may constrain the availability of coal for use in various technologies. The development and conversion of coal to usable energy requires water resources, and water is scarce where many of these highly desired coal deposits are abundant. The amount of water varies with the technology employed. Thus, in scarce water regions the consideration of the water requirements of the various technologies is equally as important as their conversion efficiency and economics.

Many systems have been designed or proposed to utilize the coal resources. Some systems convert the coal at the mine to synthetic pipeline gas or to liquid hydrocarbons for transport by pipeline to remote energy use centers. Another system burns coal at the mine site to produce electricity which is transmitted long distances to major cities. Projects such as these require the consumption of large quantities of water on site. Yet another type of energy technology requires the interregional transfer of water along with the coal. In the USA, one such coal-water slurry pipeline exists and another one is proposed.

The coal-water slurry originates at western mine sites that are deficient in water and proceed to energy producing facilities located in water sufficient areas. Concern has been expressed about the depletion of water in arid regions for the production of energy. Whether the depletion is by local consumptive use or interregional transfer, the result to those in arid regions is the same. Regional differences of resources and interregional competition for them is a vital issue begging for a solution that is satisfactory to all.

A new energy systems concept, Methacoal, has appeared which is reported to conserve both water and energy. At the same time it provides an opportunity for low sulfur fuels to be made available in areas with high pollution potential. Methacoal is claimed to be competitive with other "clean" fuels and with flue gas desulfurization.

In light of the need in many parts of the world for development, transportation, and use of coal resources under conditions of maximum energy and water conservation plus acceptable environmental restraints, the author has examined the features of the Methacoal system and compared them with those of other energy technologies. The paper first describes the Methacoal process including energy and water balances, secondly it compares the characteristics of Methacoal with coal-water slurries for transporting energy, next it lists conversion efficiencies and water use for Methacoal and other energy technologies, and finally enumerates the advantages of Methacoal as a new system for developing, transporting, and using coal in an environmentally acceptable manner.

THE METHACOAL PROCESS

Methacoal is a trade name for a new type of fuel composed of coal or other carbonaceous materials and a mixture of lower alcohols, predominantly methanol. The founder* of the process holds the patents. The term Methyl Fuel** is given to this mixture of crude alcohols containing one to four carbon atoms. Methacoal is a pseudo-thixotropic suspension of particulate coal in Methyl Fuel. The alcohols may be produced from coal, lignite, natural gas, or other hydrocarbons, such as solid waste and biomass. For the case being considered in this paper, the Methyl Fuel is produced from coal.

In the process, shown in Figure 1, coal is mined by strip or underground methods, as appropriate to the deposit. The

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*Leonard J. Keller, President, Methacoal Corporation, 2650 Northaven Road, Dallas, Texas.

**Tradename assigned to Wentworth Brothers, Inc., Cincinnati, Ohio.

coal is transported to bins or piles. It is next crushed and screened to a size of less than 1.2 mm and cleaned by conventional coal preparation methods. A minor portion of the coal is gasified to produce carbon monoxide and hydrogen whose composition is adjusted by a shift reaction to a hydrogen to carbon monoxide ratio that is thermodynamically favorable for the production of methanol. The adjusted synthesis gas is passed over a catalyst to produce the Methyl Fuel.

The second major fraction of coal is dried in commercial drying apparatus with either coal-fired heat or waste heat from the production of Methyl Fuel. It is dried to 8% or less moisture. Lignite and subbituminous coals are generally high in water content, with some having as much as 40% moisture. Thus, considerable water is evaporated in reducing their water content down to less than 8%.

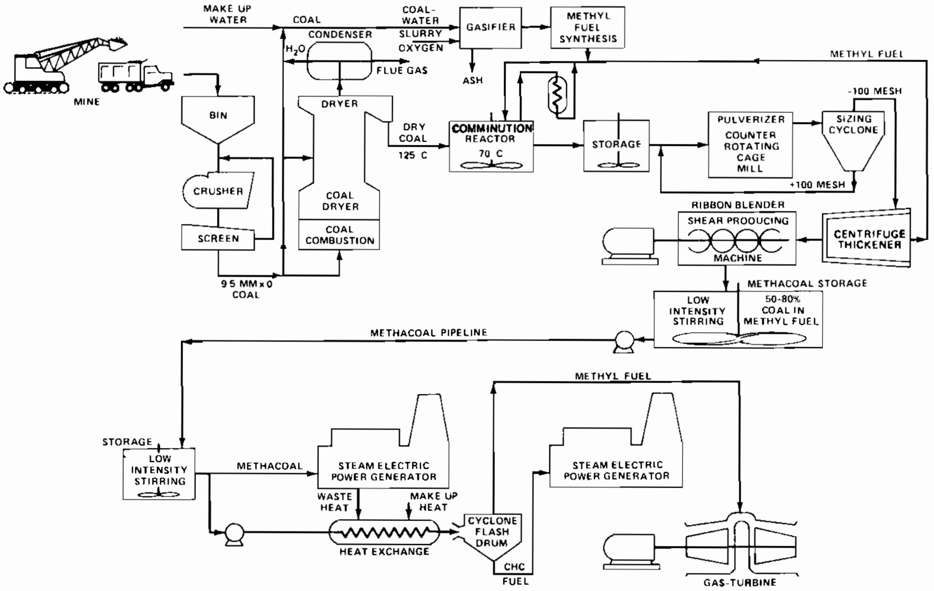

Figure 1. Simplified diagram of Methacoal concept.

In a water deficient area the evaporated water can be condensed and recovered as the coal is dried. The recovered water can be used in the manufacture of the Methyl Fuel. A coal with about 30% moisture, after being dried to 8%, will provide all the water needed for the production of the Methyl Fuel.

The hot, dried particulate coal is sent to a comminution reactor where it is mixed with Methyl Fuel at about 70 °C. The vessel is closed, and its operating pressure is the vapor pressure of Methyl Fuel. The concentration of coal in the liquid is approximately one part in three. In the reactor Methyl Fuel dissolves water and other alcohol soluble impurities in the coal which frequently enables further direct reduction in the size of certain grade coals by chemical comminution or fracturing along natural fissures. At this stage the slurry is unstable at rest, and coal would separate in a relatively short time. It is not a slurry recommended for pumping over long distances.

Small quantities of various gases will be generated in the reactor. They are removed along with some Methyl Fuel vapors at a rate required to control pressure near one atmosphere. The gases pass through a condenser where heat exchange occurs which preheats combustion air for the dryer. The noncondensable gases are utilized as a part of the fuel for the dryer. The condensate is combined with the Methyl Fuel makeup stream and pumped into the bottom of the reactor to assist in agitation. After a residence time of up to perhaps 30 min, depending on the coal, the slurry of the coal in Methyl Fuel is pumped into a closed, agitated storage vessel.

From storage the dilute slurry is sent to multirow counter-rotating cage mills for further reduction in size of the coal particles. The mills are closed. Vapors exit through a condenser and are utilized as those from the reactor. After grinding, the mixture is pumped into a cyclone separator designed to make a separation at 150 μm. The oversize coal from the separator is returned to the pulverizer for further grinding. The light fraction from the separator passes to another cyclone designed for maximum separation of coal particles and gangue material. The heavy fraction is sent to the gasifier to utilize the fuel valve associated with the gangue and to remove noxious polluting elements such as sulfur. Such elements can be recovered from the synthesis gas leaving the gasifier by using existing technology.

The light fraction from the cyclone, containing the undersized coal and Methyl Fuel, flows to a centrifuge thickener where excess liquid is removed as an overflow. The overflow, predominantly Methyl Fuel, is returned to the reactor. The thickener may be either a solid bowl or a perforated bowl centrifuge. The concentrated coal-Methyl Fuel mixture remaining is called Methacoal. Methacoal can contain 50 to 75% by weight of coal particles. Most of the work to date has been with a 66% concentration of coal.

After thickening, the material flows to a shear producing machine, such as a ribbon blender. In this device energy is imparted to the concentrated fluid to effect a stable surface coating of the processed coal. The working of the coal particles in the various steps in the presence of Methyl Fuel is apparently necessary to activate and wet the surface of the coal particles to make the unique Methacoal mixture. The reasons for the processing imparing the resulting characteristics are not fully understood.

Following the adjustment of the solids to liquid ratio and activation of the fluid, the Methacoal is ready for storage. In storage it is gently stirred to provide the blending that assures continuous homogeneity of the fluid. The Methacoal from storage can be transported by pipeline, ship, barge, railroad tank car, or tank truck. The most efficient method is by pipeline.

Methacoal can be pumped in a pipeline system similar to that used for coal-water slurries. It could be pumped from one station to another with no storage at intermediate pump stations. The same type of pumps can be employed.

The technology of coal-water slurry pipelines is well established. In the United States the technology first came into recognition as a viable method in 1957 when the Cadiz to Cleveland pipeline within the State of Ohio entered into service. The length of the line was 110 miles. It operated until 1963 at a capacity of 1.3 Mt per year and was shut down when Unitrain rail rates became competitive.

In 1970 the Black Mesa pipeline, the largest and longest slurry system yet built, began operation. It is 273 miles long. The pipe is 18 inches in diameter and traverses mountainous northern Arizona terrain. In the last 12 miles the pipe is reduced to 12 inches in diameter to impede the flow during a drop of 3000 ft in elevation. The pipeline system has a capacity of 660 short tons of coal per hour. The coal-water slurry is 48% solids by weight. The system has successfully completed more than 6 years of operation. Pipeline availability has exceeded 99%.

The successful experience with the coal-water slurry pipelines augurs well for a Methacoal pipeline because they can be identical. Professor R.R. Faddick of the Colorado School of Mines conducted rheological tests on coal-methanol slurries at four concentrations, namely 55, 60, 64, and 70% solids. Although the mixtures were not truly Methacoal, the results should indicate the worst conditions expected with Methacoal. He observed that at room temperature the viscosity of coal-methanol slurries were about the same as the coal-water slurries. He noted that methanol had a somewhat greater carrying capacity for coal than did water. Thus, since Methacoal properties should be better than those of a coal-methanol slurry which in turn are about the same as those of coal-water slurries, the Methacoal pipeline operation should be better than either of the slurries.

At the terminus of the pipeline, Methacoal is pumped to sealed conventional liquid storage tanks from which it can be distributed by various transportation modes or processed for various uses.

In one case the Methacoal may be burned directly as a fuel in power plant boilers.

In another option the Methacoal may be separated into powdered CHC fuel (processed coal particles) and alcohols. The separation is performed by pumping the Methacoal at an elevated pressure into a tube heat exchanger where it is heated to the desired temperature for subsequent separation. Most of the heat could be provided by waste heat from a power plant. Additional heat is generated by burning noncondensable gases leaving downstream of the separation plant or by burning CHC fuel itself. The pressure of the Methacoal in the heat exchanger is sufficient to prevent vaporization. As the fluid passes from the heater through a venturi into a cyclone separator the particulate material separates as the liquid phase vaporizes from the Methacoal. The particulate matter consists of CHC particles. The cyclone is controlled at a pressure slightly above one atmosphere to control vapor lost at the particulate discharge while also preventing air from entering the process.

Once the alcohols are separated from the CHC particles the products can serve several applications. The CHC fuel can be handled by conventional methods used for dry, powdered, and hygroscopic materials. It is highly reactive with oxygen and can be burned in pulverized coal-fired boilers or combination coal or oil-fired units.

The alcohols may be marketed as fuel for various engines. The market could include gas turbine fuel, fuel additive for gasoline, fuel for direct use in automotive engines, and a natural gas supplement in place of propane or butane.

The separated alcohols may also be returned to the Methacoal processing plant through a second pipeline running parallel to the main line. Then the Methyl Fuel plant need only have a capacity to provide makeup. Methyl Fuel loss has been estimated to be less than 5%. The return line for the alcohols is about 20% of the capacity required for returning water for a coal-water slurry system.

Other options and opportunities exist. For example, the CHC fuel may be used as a feedstock for low energy gas plants, synthetic natural gas plants or ammonia plants in areas where water is readily available for gasification. In addition, the alcohols separated from the slurry may be further separated into methanol, ethanol, normal propanol, and isobutanol and marketed accordingly.

Incidentally, the Methacoal can be used directly as pipeline fuels when burned in a gas turbine. The overall efficiency of the pumping process would be approximately 50% greater than electrically driven equipment. Its use as a prime mover fuel appears to render the Methacoal pipeline as the most energy efficient mode of long distance coal transportation.

COMPARATIVE CHARACTERISTICS OF METHACOAL AND A COAL-WATER SLURRY

Methacoal is described as a stable pseudo-thixotropic suspension. Thixotropic means that the shear stress of a material decreases with time at a constant shear rate. At rest, the Methacoal appears to be a moist solid. Its consistency is reduced when subjected to any type of agitation. It then displays a low effective viscosity.

Keller, mentioned earlier as the founder of the Methacoal process, reported to the author that the flow characteristics of Methacoal are typically viscous, rather than turbulent which is necessary to maintain a slurry of coal in water. In viscous flow the coal particles can be visualized as traveling in parallel straight lines. Methacoal could be pumped through pipes at velocities ranging from zero to some maximum velocity, limited only by power requirements. The coal would essentially not separate at rest or any velocity. Coal-water slurries, however, must be pumped above a critical velocity to maintain an internal fluid turbulence which keeps the coal constantly mixed and suspended in the water. At too high a velocity the water is pushed ahead of the suspended coal and separation ensures. The proper velocity for a 50% coal-water slurry is 5.8 ft/s (4 miles/h). Slurries in turbulent flow would cause greater erosion of the pipe walls than encountered with viscous flow.

As indicated earlier Methacoal can be composed of coal to alcohol ratios ranging from 50 to 75% coal by weight. The concentration depends primarily on the characteristics of the particulate coal. In contrast, the coal-water slurry is limited to concentrations between 50 and 60%. The coal-water slurry pipeline in the United States operates at 50%. Since all the material in Methacoal is fuel, the cost per unit of fuel delivered is about one half that of a coal-water slurry.

Since Methacoal was found to be a relatively stable suspension, it should be possible to store essentially as a liquid fuel in conventional tanks. The degree of stability depends to some extent on the nature of the carbonaceous material used. Keller recommends minimal stirring, but not agitation, to maintain homogeneity of the fluid over extended periods. Tanks are sealed to prevent the evaporation of the alcohols.

WATER REQUIREMENTS FOR METHACOAL AND OTHER ENERGY ALTERNATIVES

Most of the energy processes consume surface or underground water. Such consumption is undesirable in areas that are deficient in their supply. The Methacoal process, however, can utilize the associated moisture within the coal as its water supply. When the moisture in the coal is 23% or greater, no other water is needed if dry cooling towers are employed. Thus, in many locations no apparent flowing surface or underground water is consumed in contrast with other energy processes. At the greater moisture content clean water may be discharged to a stream. At lesser contents water withdrawals would be conserved by the amount of moisture in the coal. A comparison of the water requirements for Methacoal and those of other energy alternatives is shown in Table 1. The Methacoal was produced

Table 1. Energy processes water requirements and conversion efficiencies.

Process	Consumptive Water Use		Efficiency
	[US gal/10^6 Btu]		[%]
Electric Power Generation[1]	Fossil	Nuclear	
Once through cooling	95	135	40-33
Wet cooling tower	220	315	36-29
Cooling pond	126	212	39-32
Dry cooling tower*	0	0	35-28
Coal Gasification[2]	28		65
Oil Shale Surface Retorting	28		-
Coal Liquefaction	33		75
Coal-Water Slurry [55% coal]	4-6.5		54
Solvent Refined Coal (SRC)	0*-6		80
Solvent Refined Coal-Water Slurry [55%]	6*-12		-
Coal to Methyl Fuel	6*		56
Methacoal			
70% coal	(0.80)* Net gain		78
60% coal	0.15*		74
50% coal	0.57*		70

*Dry Cooling Towers Employed

[1] *Waste Heat Disposal in Power Plants* by R.M. Jimeson and G.G. Adkins, Cooling Towers, Chemical Engineering Progress Technical Manual, American Institute of Chemical Engineers, New York, NY, 1972.

[2] *Western Coal Gasification Draft Environmental Impact Statement*, US Department of Interior, Bureau of Reclamation, Washington, DC, 1976.

from a typical western US coal containing 30% moisture, 7% ash, and an energy value of 8000 Btu/lb. The coal was dried to 8% moisture. It could be dried to 1% moisture and additional water accumulated. The marked conservation of water which can be attained per unit of energy with the Methacoal process is apparent upon examination of the Table.

COMPARISON OF ENERGY PROCESS EFFICIENCIES

Feasibility studies for the Methacoal process installed in the western USA include the utilization of a Texaco gasifier to feed a Wentworth Brothers Inc. methanol unit employing dry cooling towers. Wentworth[1] estimates the yield would be approximately 5 bbl/t of completely dry coal fed to the unit when the ash is about 7%. He also reports that the cost of Methyl Fuel in 1976 dollars would be around 20 cents per US gallon with coal at 35 cents/10^6 Btu. A typical US western coal could contain 30% moisture, 7% ash and have an energy value of 8000 Btu/lb. The Bureau of Mines reports that 4.5×10^6 Btu will evaporate a ton of water from western coal. The energy value of the completely dried coal would be about 11,415 Btu/lb. The conversion efficiency of energy in the coal to Methyl Fuel is approximately 56%. About 0.64 lb of Methyl Fuel with an energy content of 10,000 Btu/lb would be produced per pound of dry coal. For those interested in changing to volumetric units, Methyl Fuel has a relative density of 0.78 (48.7 lb/ft^3; 6.5 lb/US gal). At the above prices the author estimates the price of a 60% Methacoal at about 1.43 \$/10^6 Btu.

Relative to other coal conversion processes, the efficiency of converting coal to Methyl Fuel is low. This poor efficiency is offset, however, when Methacoal is produced, since less than half the Methacoal mixture is composed of Methyl Fuel. Thus, the overall conversion efficiency to Methacoal is much greater. A comparison of the efficiencies of various processes is shown in the last column of Table 1.

A schematic flow diagram for the Methacoal process using a subbituminous coal is shown in Figure 2. The capital letters at specific points on the diagram are at locations where weight and heat content figures have been calculated. The values computed at each of the points are shown in Table 2. The first set of lines in the Table contain the quantities for the production of Methyl Fuel only. The next three sets of lines show the values when a short ton of Methacoal is produced composed of a 50/50, 60/35, and 70/30 coal to Methyl Fuel mixture, respectively.

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[1] T.O. Wentworth, President, Wentworth Brothers Incorporated, 648 Linn Street, Cincinnati, Ohio.

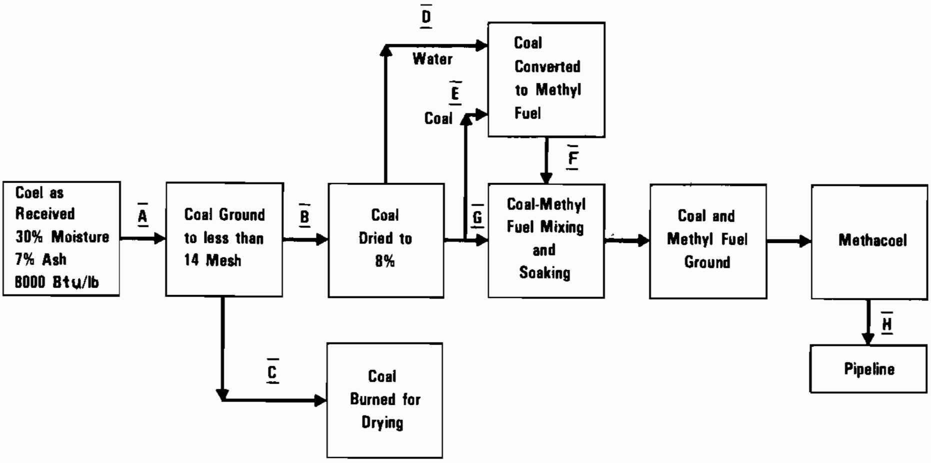


Figure 2. Schematic flow diagram of the Methacoal process.

ADVANTAGES OF METHACOAL

Producing Methacoal from coal and transporting it to the market by pipeline has a number of advantages. First, it is an efficient process with energy conversion efficiencies of 70 to 78%. It rivals the 80% conversion efficiency of the solvent refined coal (SRC) process. The coal-water slurry process, which is an alternative pipeline system for certain coals, has a much lower energy conversion efficiency of 54%.

Secondly, Methacoal uses the least water when applied to coals with high moisture content as experienced in lignite and subbituminous coals. Methacoal produced from a 30% moisture coal when dried to 8% needs no external water if dry cooling towers are used in producing the Methyl Fuel. The same applies for a 23% moisture coal dried to 1%. The processes with the next smallest water demands are SRC (0 to 6 US gal/10^6 Btu) and coal-water slurry (4 to 6.5 US gal/10^6 Btu).

Methacoal would have between 25 and 50% less sulfur content than the original coal. The magnitude of the reduction depends on the ratio of coal to sulfur free Methyl Fuel in the product. Higher proportions of Methyl Fuel will result in lower sulfur content in the Methacoal.

Other advantages appear obvious. Because of the pseudothixotropic nature of Methacoal existing pipelines could be used to transport the mixture. A Methacoal pipeline would not need to be placed underground in cold climates because the Methyl Fuel has a very low freezing point. Methacoal could be burned directly in boilers, or some portion of the Methyl Fuel could serve the gas turbines used for peak power while the coal could be burned directly in base load boilers; thus, Methacoal can simultaneously furnish two separate utility needs.

Table 2. Weight and energy values at selected points in the Methacoal process.

Location in Figure 2	A	B	C	D	E	E	F	G	H	I	J	
Methyl Fuel Mix and Units	Raw Coal Feed	Coal to be Dried	Coal Burned for Drying	Water from Coal Drying	Coal to Methyl Fuel	Water in Coal to Methyl	Reaction Water Required	Excess Water	Methyl Fuel	Coal 8% Moisture	Metha-coal	Conv. Eff. %
0-100												
Wt[lb]	4471	0	0	0	4471	1341	2347	-1005	2000	0	-	-
10^6 Btu	35.8	0	0	-	35.8	-	-	-	20.0	0	-	55.9
50-50												
Wt[lb]	3638	1314	88	314	2236	671	1082	-97	1000	1000	2000	-
10^6 Btu	29.1	10.5	0.704	-	17.9	-	-	-	10.0	10.5	20.5	70.4
65-35												
Wt[lb]	3388	1709	115	409	1564	469	821	57	700	1300	2000	-
10^6 Btu	27.1	13.7	0.92	-	12.5	-	-	-	7.0	13.7	20.7	76.4
70-30												
Wt[lb]	3305	1840	124	440	1341	402	704	138	600	1400	2000	-
10^6 Btu	26.4	14.7	0.992	-	10.7	-	-	-	6.0	14.7	20.7	78.4

SUMMARY

The Methacoal process presents an attractive alternative for developing and utilizing the energy of coals that are remote from energy use centers. The process utilizes the moisture associated with the coal as its water supply. No additional water is required when the moisture is 30% or greater. Thus, the Methacoal process is symbiotic with the water deficient coal resource regions. It is also an energy efficiency process, an important factor in the conservation of energy resources. A demonstration project is yet needed to provide design criteria of an integrated system and to establish accurate costs under various conditions.

ASSESSMENT AND EVALUATION OF COAL DEPOSITS

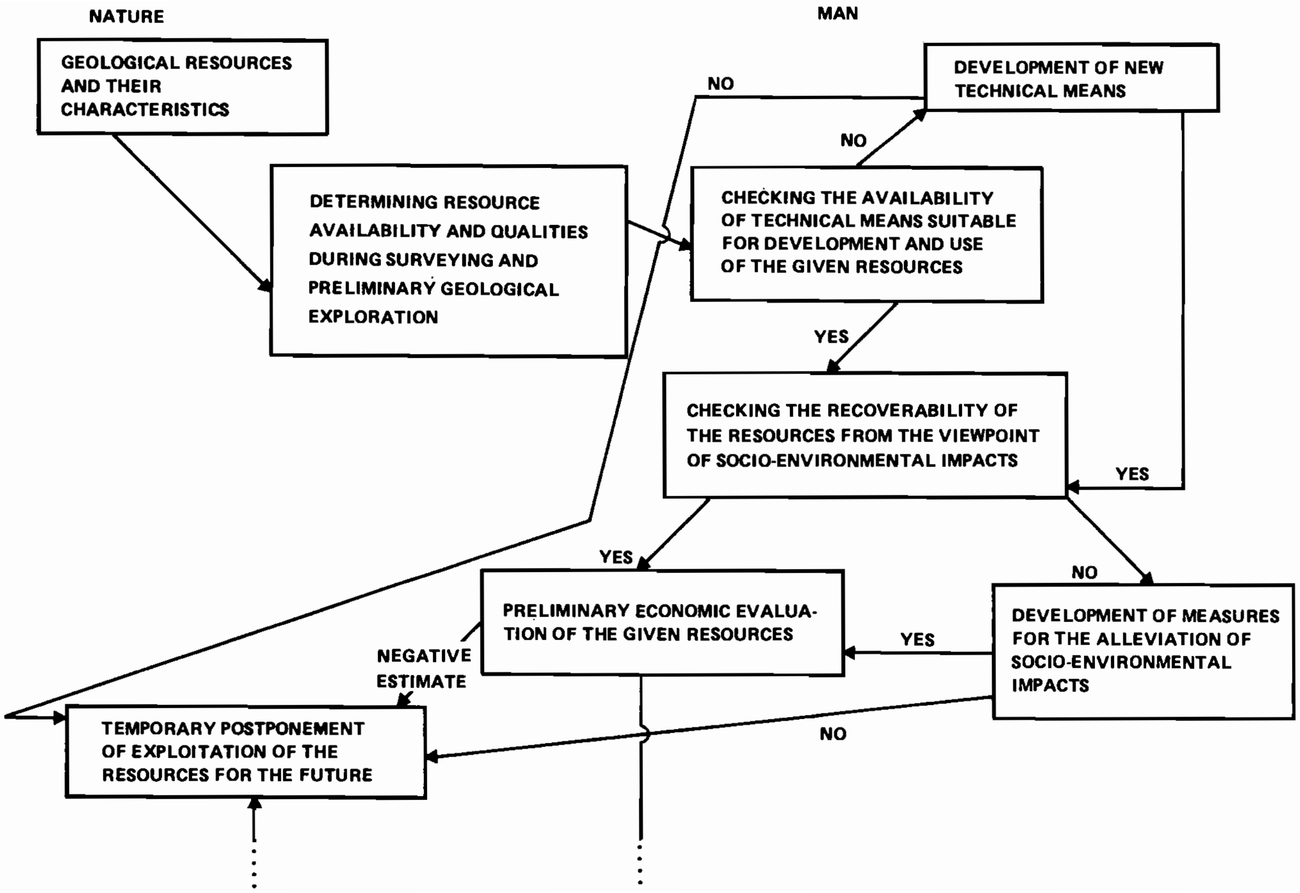
COST SIMULATION AND ECONOMIC ASSESSMENT OF COAL RESERVES AND RESOURCES

A.S. Astakhov

The role of coal in the future fuel/energy balance will greatly depend upon the level of the related costs. In this report we attempt to examine the main trends in the development of these costs and the factors determining them, and on that basis to formulate principles for designing appropriate cost models.

The most characteristic feature of coal mining is the great dependence of its costs upon the natural conditions of the deposits. However, it would be wrong to consider this dependence one-sided and fixed. The interactions between man and nature that take place in the process of mining are illustrated in Figure 1. While studying the mineral resources provided by nature, man creates and improves the technical means for mineral extraction and use. Depending upon the extent of these means, one always chooses the most economic part of the reserves. Their exploitation produces an unfavorable effect on the environment, and sooner or later measures must be taken to alleviate this effect. The costs of coal production are influenced by all these interactions. We can single out natural, social, and technical factors of these costs dynamics. Let us examine their impacts separately.

USSR coal basins and deposits exhibit a great diversity of *natural conditions*--i.e., geological characteristics and coal quality (Table 1). These conditions greatly influence coal production operational costs, and capital investments. Under unfavorable conditions the share and costs of ancillary operations per ton of coal produced grow; expensive special services become necessary, working conditions worsen, and labor productivity decreases. This results in a sharp decrease of mining intensiveness. In the Donetsk basin the cost of sinking and drivage of main workings in mine construction increases by 7 to 8% for each 100 m depth increase over 500 m, the specific capital cost increases by 6% and operational expenses by 3%, and the period of mine construction is 1.05 to 1.1 times longer. The capital costs of coal production from seams 0.5 m thick is 35% higher than that from seams 1.8 m thick. Low thickness of seams, high gas and water emission, and tectonic faulting reduce the intensiveness of mining by 2 to 3 times, which in turn sharply raises costs.


NATURE
MAN
GEOLOGICAL RESOURCES AND THEIR CHARACTERISTICS
DETERMINING RESOURCE AVAILABILITY AND QUALITIES DURING SURVEYING AND PRELIMINARY GEOLOGICAL EXPLORATION
NO
DEVELOPMENT OF NEW TECHNICAL MEANS
NO
CHECKING THE AVAILABILITY OF TECHNICAL MEANS SUITABLE FOR DEVELOPMENT AND USE OF THE GIVEN RESOURCES
YES
CHECKING THE RECOVERABILITY OF THE RESOURCES FROM THE VIEWPOINT OF SOCIO-ENVIRONMENTAL IMPACTS
YES
YES
NO
PRELIMINARY ECONOMIC EVALUATION OF THE GIVEN RESOURCES
DEVELOPMENT OF MEASURES FOR THE ALLEVIATION OF SOCIO-ENVIRONMENTAL IMPACTS
YES
NEGATIVE ESTIMATE
NO
TEMPORARY POSTPONEMENT OF EXPLOITATION OF THE RESOURCES FOR THE FUTURE

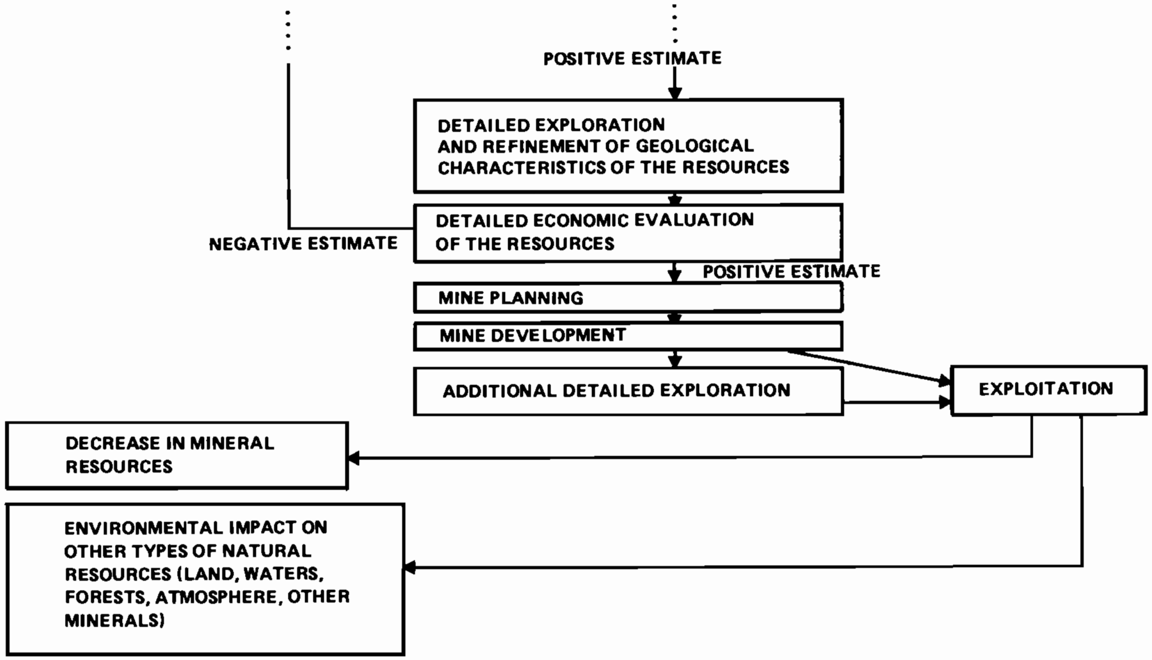


Figure 1. Interactions between man and nature in mineral resource exploration and exploitation.

Table 1. Natural conditions of the main coal basins of the USSR.

	Basins and deposits						
Indices	Donetsk	Kuznetsk	Karaganda	Pechora	Moscow	Ekibastuz	Kansk-Achinsk
Average number of working seams per mine	2.7	5.3	3.0	2.3	1.0	3.0	2.7
Workable thickness of coal seams [m]	0.5-2.0	2.19	0.7-6.7	0.8-3.9	1.1-4.5	15-138	8-70
Seam dip [°]	0-80	0-90	0-60	8-90	0-8	10-90	0-13
Average depth of working section [m]	528	246	365	471	59	70-125	30-90
Coal output [% of total]							
Virtually non-gassy mines	21.8	none	none	none	96.4	n.a.	n.a.
Mines with 1-10 m^3 of gas per t of coal produced	13.3	21.9	none	50.1	3.6	n.a.	n.a.
Mines with more than 10 m^3 of gas per t of coal produced	64.9	78.1	100.0	40.9	none	n.a.	n.a.
Amount of water pumped out per t of coal produced [m^3]	2.8	1.5	0.4	none	10.5	n.a.	n.a.
Energy value of coals							
Q_H^P [Kcal/kg]	4840- 6500	6000- 6900	3600- 5300	4300- 6000	2500- 2800	4000- 4600	2800- 4400
Average ash content of coals [%]	27.4	15.3	28.3	23.8	33.0	38.0	7-13
Moisture content W^P [%]	3.5-14	4-8.5	1.4-7	0.5-7.2	35	8.2	33-44

Our views at the possibility and efficiency of resource development change with time. Resources that were considered unrecoverable may become exploitable with technical progress. (For example, the advent of submersible pumps has made it possible to solve an acute problem of the Moscow basin mines with high water inflow; the development of degassing not only radically improves working conditions in gassy mines but allows methane to be used as a fuel, and so on.) In all traditional basins, the depth of mining increases by 3% annually, which raises rock pressure, gas emission rates, and the temperature of adjoining rocks. Stopping the exploitation of thin seams, which is a current trend, can counteract the adverse impact of these factors to a certain extent. However, in general the geological conditions of traditional underground coal mining are becoming more complicated.

The main counterbalancing factor is a growing tendency toward coal production in the eastern regions, many of whose deposits are characterized by small depth and high thickness of coal seams suitable for opencast mining. The cost of opencast mining is 4 to 4.5 times lower than that of underground mining. Thus if today's share of opencast output doubles, mining and geological conditions in the industry *as a whole* will improve so substantially that the level of costs will be lowered by 15 to 30%.

The development of costs will continue to be affected by *social measures.* The funds allocated for further improvement of safety and working conditions and for environmental control are constantly growing. The share of these costs now accounts for about 15% of the total costs of mine equipment in use; projects adopted during the last 10 to 15 years envisage far larger expenditures. Recently the permissible levels of dust content at the face and in preparation plants have been reduced by a factor of about 2.5, and standards for water consumption and lighting of working places have been raised significantly. As a result, the specific capital cost of newly planned mines has steadily increased in recent years, by not less than 1% annually. This tendency will undoubtedly continue, especially for environment control costs (reclamation, anti-pollution measures). While these measures have a beneficial effect at the national level and for society as a whole, they have become an additional, ever growing financial burden for the coal industry.

Technical progress accompanied by concentration of production represents the main source of savings in the expenses of the coal industry. Nevertheless, the effect of technical progress on various types of production costs differs. The maximum possible elimination of manual labor, especially in arduous underground operations, is a traditional main objective in technical reequipment. Owing entirely to measures directed at technical reequipment, labor productivity during the period 1971-1975 increased by 12% at underground mines and by 35% at open-cast mines. In addition, some reduction of materials consumption was achieved. However, so far both these objectives were reached only with the help of more expensive and energy-consuming new machinery.

The cost of new machines per ton of coal produced (i.e. the specific capital investment increases or decreases depending upon the extent of production intensification. Where the total cost of the machines grows more rapidly than their productivity, specific capital investment increases; otherwise it decreases. Efficiency assessment methods assume the growth of investment in machinery within the limits conforming to the standard payoff term. In the coal industry, the tendency toward growth of specific capital investments is virtually predominant. During the period 1971-1975, capital investment per ton of coal in operating underground mines increased by 1.34 times, that in open-cast mines by 1.12 times, and that in coal preparation plants by 1.15 times. Depreciation costs correspondingly increased in the course of technical progress: during the period 1971-1975, from 1.91 to 2.65 roubles/t for underground mines, and from 0.52 to 0.62 roubles for opencast mines. The grand total of technical progress is some reduction in production costs and a substantial change in their inner structure. It would be interesting to consider all these data for a long historic period. While it is hardly possible, of course, to eliminate all the changes in value factors that have taken place, the analysis of shifts in the inner structure of costs nevertheless would be useful.

Nearly 140 years ago, in 1840, when manual labor predominated in the Donetsk basin, the share of labor accounted for 92% of total coal production costs. By 1900 this share had decreased to 75%, and by 1950 to 68%; and in 1975 it accounted for 55%. The ratio of labor cost to depreciation cost has changed from 6.7:1 in 1913 to 2.6:1 in 1975. If we consider only the period following World War II, we can see that the greatest changes in the level of mechanization have taken place for coal-winning operations. In the pre-war years the share of coal-winning operations accounted for more than 30% of total labor consumption but for only 2 to 3% of specific capital investments. The specific costs of face equipment increased consecutively from 0.06 roubles/t with manual labor; to 0.19 roubles/t for faces worked with coal-cutting machines and primitive chain conveyors; to 0.47 roubles/t for wide-web power loaders; and to 0.62 roubles/t for faces worked with narrow-web power loaders and single props. For modern completely mechanized faces in the Donetsk basin, these costs account for 1.2 to 2.5 roubles/t. All these changes were accompanied by a substantial decrease in the total cost of one ton of coal at a longwall face.

The payoff term for all these techniques did not exceed three years, though in the course of mechanization it did increase sharply. Analysis of some highly mechanized mines of the Donetsk basin showed that complete mechanization raised daily output per mine by 1.5 times; labor productivity increased by 1.7 times, but capital investments also increased by 15% (including the growth of equipment capital cost by 1.5 times). Exploitation expenses decreased by 10%. Wage costs per ton decreased by 1.9 roubles, i.e. by 25%; materials costs remained unchanged, depreciation costs increased by 0.7 roubles/t or by 1.4 times, and energy costs increased by 0.1 roubles/t or by 1.3 times. A fivefold increase of capital costs at faces (from 0.5 to 2.5 roubles/t) was accompanied by a decrease in winning expenses from 3.5 to 3.2 roubles/t. Underground transport capital costs increased by 1.4 roubles/t, and expenses decreased by 0.8 roubles/t. The driving of workings showed no improvement in terms of any of these indices. For all the ancillary processes, both expenses and capital consumption have decreased, but not to the substantial extent expected from production intensification. Among these processes we can clearly distinguish capital-intensive and energy-consuming processes on the one hand and labor-consuming ones on the other. The ratio of depreciation and energy costs to labor costs illustrates the progress already made along the path toward "full exhaustion" of the technical potential for replacing manual by mechanized labor. This ratio for the highly mechanized mines considered constitutes only 0.54:1 for coal winning and 0.25:1 for driving of workings, while for underground transport and other processes it reaches 1.15:1 and 1.32:1 respectively. Thus, we can see that further improvement of coal face operations must continue to concentrate on a decrease in manual labor costs, while the development of other processes must be aimed at a substantial capital cost decrease. Naturally, both factors must be reinforced by operation intensification.

In general, the technical development of traditional underground methods during the last decades was characterized by labor savings but at the same time by a growth in capital cost. This trend was probably inevitable in view of the development level of the industry at the beginning of that period: capital equipment costs grew from "zero" level as manual labor was progressively replaced by mechanization in many of the main processes.

Technical progress affects the capital costs of a process at the various stages of its development as follows. (a) Initial mechanization of a manual process as a rule increases its capital costs. (b) In the course of extending equipment use to ever more complicated production conditions, capital costs continue to increase; but at the same time the equipment is being exploited with more increasing success due to accumulated experience, and the degree of its use is growing. On the whole, these two opposed tendencies nearly neutralize each other, and the total specific capital cost becomes practically stable. (c) Further improvement of the equipment as a rule leads to more complicated design and a corresponding growth in machine cost. If this improvement leads to more intensive mechanization, the specific capital cost decreases; if not, it continues to increase. (d) When machine design becomes highly sophisticated, the main objective of further technological research shifts to simplification and increased capacity, and thus the capital cost becomes lower. (e) Fundamental new discoveries sooner or later lead to new technological developments, which in turn lead to a sharp drop in specific capital cost. From here on, the cycle returns to its (b) through (e) stages in a new turn of the dialectical spiral.

Because the technical development phases of various mining operations do not coincide in time, we cannot place the entire industry within a given development stage; but we would not go far wrong in saying that during the last decades, underground mining in the USSR has been in stages (a) through (c) of its technical development. Within the next few years the transition to the (d) stage will presumably take place; that is designers' efforts will be directed toward creating both labor- and capital-saving techniques. Drastic simplification of mining systems and mine surface layouts can play a role here: let us remember that during the last decades, underground mining systems have undergone no radical change, so that workings account for more than half of the total capital cost of underground coal production. A substantial intensification of operational processes--to our mind, by no less than 2 to 3 times--will be equally important. (The average daily output per longwall face at present is 1.3 to 1.5 times lower than the results achieved by advanced teams under similar conditions, and the share of time used for pure coal-winning operations does not exceed 35%.) Intensification here means a growth in output per productive unit, unconnected with intensification of workers' labor.

If we consider the shifts described, we may think that the increasing capital costs typical of the past few decades will gradually give way to stabilization and possibly a certain decrease of this index. Here we should recall some obvious facts. First, the principles of mining technology have not yet been affected in practice by the revolutionary impact of fundamental scientific achievements in the fields of chemistry, biochemistry, electronics, laser techniques, nuclear physics, and so on. This impact will certainly take place. Moreover, major reconstruction of the coal industry offers opportunities for a transition to quite new organizational patterns uniting coal production, conversion, and use for energy and for a wide range of chemical by-products. While realization of these opportunities will give a powerful new impulse to the development of coal industry economics, there is no doubt that it will take a long time.

An approach to further analysis, which could become the first prerequisite for coal production cost forecasting, is outlined below.

1. Substantial differences in the cost levels and the dynamics of different basins makes it impossible to build a satisfactory unique model for the whole industry. Such models should be constructed on the basis of the costs calculated for separate basins.

2. Conditions and possibilities for cost forecasting differ considerably for coal reserves and resources. As a rule, information on costs in a base year is available for coal reserves; if it is not, the cost can be calculated using the geological

characteristics that are known in detail. For resources, on the other hand, no cost figures or detailed geological characteristics are normally available; calculations thus have to be based on more aggregated models. The objects of cost calculations also may be different for these two cases: for reserves they will generally be a mine or a seam, while for resources an entire deposit or basin may be the object of estimates.

3. In models simulating the costs for the immediate future it is necessary to take account of trends in technical progress in the industry and of the specific conditions of underground and opencast mines; rough calculations for groups of mines with similar mining and technological conditions are also possible.

3.1. The main initial directions of technical progress for underground mines will probably entail the completion of full mechanization of face and ancillary operations; coal transport by conveyors; hydraulic mining development; widespread introduction of automated control systems; and substantial intensification of operations. For opencast mines, the main prospects for technical development include the extended use of transportless systems for overburden removal (direct overcasting of overburden), continuous mining techniques for coal-winning operations, and use of cyclic-continuous techniques for working hard overburden.

3.2. It is advisable to build simulation models separately for new mines, mines under reconstruction, and operating mines, as both the capital expenditures and the operational costs differ. For new mines and those under reconstruction, costs are established by projections. For operating mines, annual costs are calculated by base cost correction, taking into account (a) completion of full mechanization of the main operations, (b) trends in technical progress in other operations taken as a whole, (c) the trend toward further worsening of mining and geological conditions, (d) the trend toward further increases in costs due to improvements in the fields of safety, working conditions, wages, and environmental control. Each of these tendencies can be calculated by the methods of mathematical statistics and later used as a correction factor for base costs. These costs are then corrected (lowered additionally) by taking account of the planned intensification of mining connected with the factors mentioned above.

3.3. Costs calculated by such a method for each operating mine and each possible new project serve as input to an optimization model for development of the whole industry. This model is based on linear programming principles. In addition to exploration and coal preparation costs, the optimized criterion of the model comprises costs for transport and use of coal and its by-products. With the help of special constraints, the model reflects the level of the national economy's demand for coals and their by-products; technically feasible levels of production for different deposits; and throughput of transport facilities and funds. The coal industry model in its turn is a component of a more general model of fuel/energy complex development. Using these models, one can determine the most efficient coal production in the country and the shares of individual basins in total production. One can also determine the optimal ratio of new mine construction, reconstruction, and maintaining of existing mines. Average cost indices for the whole industry and for separate basins are one of the results of such an optimization.

3.4. The optimization model can serve also for calculation of marginal costs per ton of additional coal production for the industry as a whole and for any individual basins. Marginal costs demonstrate the objectively determined national economic limit for admissible production costs per ton of coal of a given grade.

3.5. The difference between marginal, M, and individual, I, costs may be considered as a certain "economic value" of given resources/reserves. If $M > I$, the resources have positive economic value; the higher this value, the greater the economic importance of the given resources. If $I > M$, then the "economic value" is negative; this means that the development of the given resources in the period considered is economically inefficient. It is also possible to compare marginal and individual costs in the form of M/I ratio. The resources are economically recoverable if $M/I \geq 1$. Using this ratio, the resources and reserves may be arranged in a row according to their efficiency; this is convenient for practical purposes. Such rows should be composed separately for each group of noninterchangeable grades of coal.

4. In forecasting costs for the more remote future, we are faced with the problem of basins and deposits unexploited at present. The potential costs for such deposits must be assessed in order to examine the efficiency and priority of their detailed exploration and further development. In this case, models of costs acquire a number of distinctive peculiarities. The available information based on preliminary geological exploration is insufficient for detailed cost calculation. Moreover, preliminary geological exploration data are always purely hypothetical, so that attempts to use them for scrupulous economic calculations would not prove very reliable. Thus the analogue method and the method of aggregated cost standards may be regarded as the two main means of cost calculation. With the former, specific costs for a new deposit are calculated on the basis of the known costs for a more extensively explored (or exploited) deposit of similar type. Specific differences between the deposits compared may be taken into account by the use of correction factors. With the second method, costs are determined from the standard reference books on aggregated costs differentiated for various combinations of mining and geological parameters (such standards may be in the form of either tables or elementary formulae). The object of calculation here should not be too small. Under relatively homogeneous coal seam conditions, the resources of the whole deposit are the object of assessment. If there is a substantial difference in overburden ratio and seam depths and thicknesses, costs may be calculated for separate but necessarily large parts of a deposit.

4.1. Initial capital expenditures are very important for assessing costs for a new deposit development. It is a feature of cost calculation for new deposits that the creation of regional infrastructure, related industries, and facilities for coal transport to distant consumers are of paramount importance. These costs are quite different for new and old deposits, even of the same geological type, and this can impede the selection of "analogues". To eliminate such difficulties it is advisable to select different analogues for (a) mining and geological conditions of a deposit, (b) qualitative characteristics of the coal, and (c) economic and geographic conditions of a region. Conditions (a) affect mainly the level of coal production costs; conditions (b) determine coal preparation and processing costs (and sometimes transport costs as well); and conditions (c) determine the costs for infrastructure and transport facilities. All three groups of costs are affected by climatic conditions, which must also be taken into account. Analogues may be selected separately for each group of factors considered; then coal production costs for a new deposit may be determined in conformity with the first analogue, coal preparation and processing costs in conformity with the second, and regional costs in conformity with the third. The difference in climatic conditions between the deposits compared may be leveled by correction factors for all three groups of costs. Total specific costs per ton of coal resources contained in a deposit will be determined by summing up the indices on the three groups. It is advisable to calculate this cost per 1 tce and to show the inner structure of costs for the three cost groups.

4.2. Cost indices for deposits as yet unexploited cannot be calculated unambiguously: according to the character of the initial information available, the results of these calculations are of an extremely probabilistic nature. Thus cost estimates for new deposits should preferably be given in the form of a range, the lower limit of which may show an "optimistic" estimate and the upper a "pessimistic" one. The difference between these two values, expressed as a percentage of their mean value, characterizes their reliability as estimated by experts.

4.3. Because of the great variety of calculated costs, natural characteristics play an important role in estimating unexploited resources. These characteristics fall into four groups:

- *Mining and geological conditions of a deposit.* These include coal seam thickness, depth, hydrogeological characteristics, seam dip, nature of adjoining rocks, degree of tectonic faulting, and the like.

- *Characteristics of coal quality.* These include moisture, ash and sulfur content, volatile matter, thickness of plastic layer, calorific value, strength, liability to spontaneous combustion, and other parameters that make it possible to determine coal grades and types and possibilities for coal preparation, higher degree of utilization, transport over long distances, and production of useful by-products.

- *Economic and geographic conditions of a region.* It is necessary to take into consideration the degree of development, remoteness from the main transport routes, and regional characteristics: relief, suitability of land for agricultural and recreational purposes, energy and water supply, labor resources, climatic conditions, availability of other mineral resources, and possibilities for complex resource utilization.

- *WELMM parameters of coal mining.* According to definitions suggested by IIASA, WELMM parameters include consumption data for some materials and natural resources expressed in physical indices, namely specific values of water demand, area of land occupied for mining, energy, labor, and material consumption.

  A substantial part of these physical indices indirectly characterizes the extent of possible environmental and social impacts of industrial development of the deposits. In assessing the prospects for development of large new deposits, this aspect of the problem is of paramount importance. It would be difficult and fundamentally wrong to reduce it to purely monetary terms. The use of physical evaluation indices allows a much more thorough exposition of different aspects of the problem.

From the facts presented, it follows that cost index calculation and economic evaluation of coal deposits occupy an important position in coal industry planning. In many respects such calculations are closely connected with technological forecasts, and they in turn determine future technical trends. Thus one should speak of a whole system of calculations based on a wide variety of models. In order to evaluate the future role of coal, one must calculate total costs for exploration, mine construction, coal production, processing, transport, and use, as well as environmental impacts of deposit development. Multicomponent calculations are possible only when using a number of different methods of statistical simulation, heuristic methods, analogue methods, rough project computation, and linear programming. Each is applied at one or another stage and level of calculation. Performing all these calculations requires a system of standards, which include predictions on the effects of technological development, specific cost standards, marginal cost standards, and others.

The author's attempt to determine the main trends in the development of costs connected with coal development has yielded the following results, which should by no means be regarded as indisputable. It appears that underground coal production costs in most traditional basins will remain roughly at their present level. The efficiency of underground hydraulic coal mining will improve. Opencast mining costs will be substantially reduced, thanks to the growing share of the highly efficient coals from the Kansk-Achinsk and Ekibastuz basins. If we manage to achieve significant results in the utilization of other minerals embedded with coal, we would substantially reduce coal production costs. There is every hope that the replacement of underground mining by the opencast method will also reduce production costs significantly Coal processing costs will increase noticeably due to the expansion of high temperature coal treatment (conversion of Kansk-Achinsk coal into transportable low-temperature coke, coal liquefaction, etc.). Coal transport costs will probably increase as a result of substantial coal production development in the remote eastern regions. Generally speaking, in comparison with other fossil fuels the dynamics of coal production costs seems to us more hopeful, and the total efficiency of coal development will depend upon the parameters of the processing technology.

USE OF COMPUTER MODELS TO ASSESS AND EVALUATE COAL DEPOSITS

T.A. Boyce

INTRODUCTION

Realizing that large-scale surface coal mines will be needed to supply the future energy needs of the USA, the US Energy Research and Development Administration sponsored a study to be better able to estimate expected costs of mining and processing coal, and to provide industry with planning and analysis models to facilitate mine design and equipment selection to meet future increased production needs. The study has resulted in the development, testing, and documentation of simulation models which:

- Estimate capital investment and annual operating cost for a surface coal mining project;
- Select equipment and estimate unit costs for each individual mining function;
- Estimate manpower, materials, and infrastructure requirements for the project; and
- Analyze coal selling price and profit relationships.

All coal mining and processing functions are included in the modeling system, namely,

- Overburden drilling and blasting,
- Overburden removal,
- Coal drilling and blasting,
- Coal loading and hauling,
- Coal handling and processing,
- Land reclamation,
- Premining, facilities and administrative expenses, and
- Economic cash flow analysis.

COMPARISON OF BROAD MACROMODELS AND DETAILED MICROMODELS

The objective of the models is to provide mine designers, policy planners, and engineering managers with the ability to analyze a surface coal mine at two levels of detail as shown in Figure 1. *Detailed micromodels* provide estimates for a detailed part of a large-scale surface mining complex. Individual models allow the user to separately analyze overburden removel, overburden drilling and blasting, coal drilling and blasting, coal loading and hauling, coal preparation and handling, land reclamation, and premining, facilities, and administrative expenses. *Broad macromodels* provide a first order estimate for an entire mining complex. All the detailed operations considered separately by the micromodels are contained as subroutines in the macromodel. In several cases simplified macromodel relationships were derived from detailed micromodel studies. Macromodels have been developed for three mining methods identified by the method of removing overburden: area stripping with draglines, area stripping with shovels and trucks, and contour mining with draglines. Both systems begin with a tract description and end with the results of a cash flow analysis. The key difference between the types of models is in the steps required to reach a solution.

The broad macromodel requires only one manual step, i.e. defining case study parameters. The computer program performs all the remaining calculations required to produce a solution. This procedure allows the user in a single step to quickly obtain first-order estimates for an entire mining operation. The macromodels are specifically designed for situations where little verified field data are available on the site or region being studied, but where cost estimates are needed for planning purposes. Each macromodel includes a file of default values that is used by the computer in the absence of user specified values to define the mining situation further.

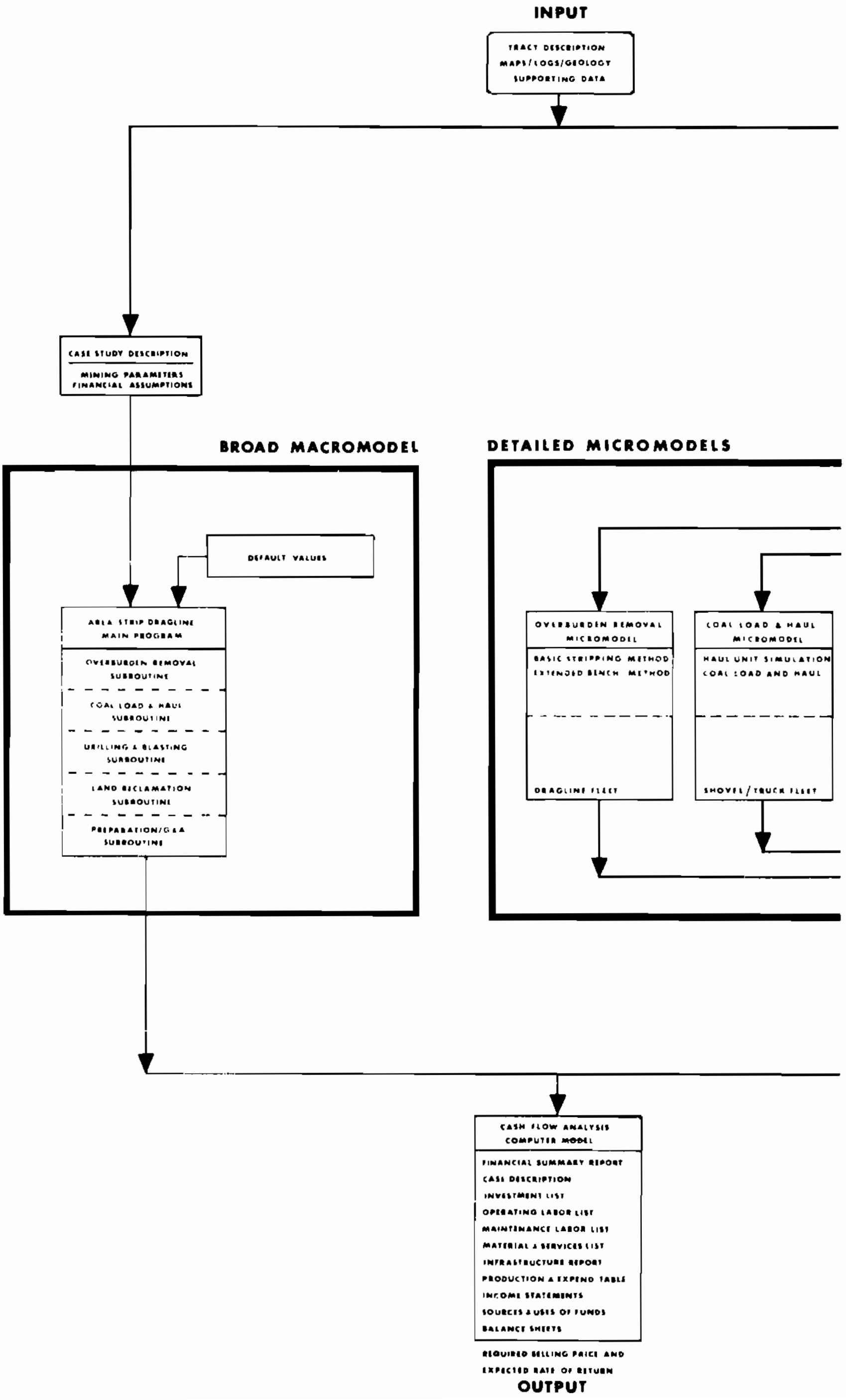
The detailed micromodels require several manual steps. Each mining function is studied separately and the results are interpreted by the user at each stage of the analysis. This procedure allows interactive use of the computer with the user involved at several decision points with the aid of detailed comparative information generated by the micromodels. The micromodels are specifically designed for situations where verified field data are available on the site being studied and where more accurate cost estimates and more detailed production data are needed.

Thus, the type of model used depends on the following factors:

- Availability of field data: if little, use broad macromodel; if great, use detailed micromodels.

- Desired interaction between user and computer: if little, use broad macromodel; if great, use detailed micromodels.

- Desired detail of analysis: if little, use broad macromodel; if great, use detailed micromodels.


INPUT
TRACT DESCRIPTION
MAPS/LOGS/GEOLOGY
SUPPORTING DATA
CASE STUDY DESCRIPTION
MINING PARAMETERS
FINANCIAL ASSUMPTIONS
BROAD MACROMODEL
DETAILED MICROMODELS
DEFAULT VALUES
AREA STRIP DRAGLINE
MAIN PROGRAM
OVERBURDEN REMOVAL
SUBROUTINE
COAL LOAD & HAUL
SUBROUTINE
DRILLING & BLASTING
SUBROUTINE
LAND RECLAMATION
SUBROUTINE
PREPARATION/G&A
SUBROUTINE
OVERBURDEN REMOVAL
MICROMODEL
BASIC STRIPPING METHOD
EXTENDED BENCH METHOD
DRAGLINE FLEET
COAL LOAD & HAUL
MICROMODEL
HAUL UNIT SIMULATION
COAL LOAD AND HAUL
SHOVEL/TRUCK FLEET
CASH FLOW ANALYSIS
COMPUTER MODEL
FINANCIAL SUMMARY REPORT
CASE DESCRIPTION
INVESTMENT LIST
OPERATING LABOR LIST
MAINTENANCE LABOR LIST
MATERIAL & SERVICES LIST
INFRASTRUCTURE REPORT
PRODUCTION & EXPEND TABLE
INCOME STATEMENTS
SOURCES & USES OF FUNDS
BALANCE SHEETS
REQUIRED SELLING PRICE AND
EXPECTED RATE OF RETURN
OUTPUT

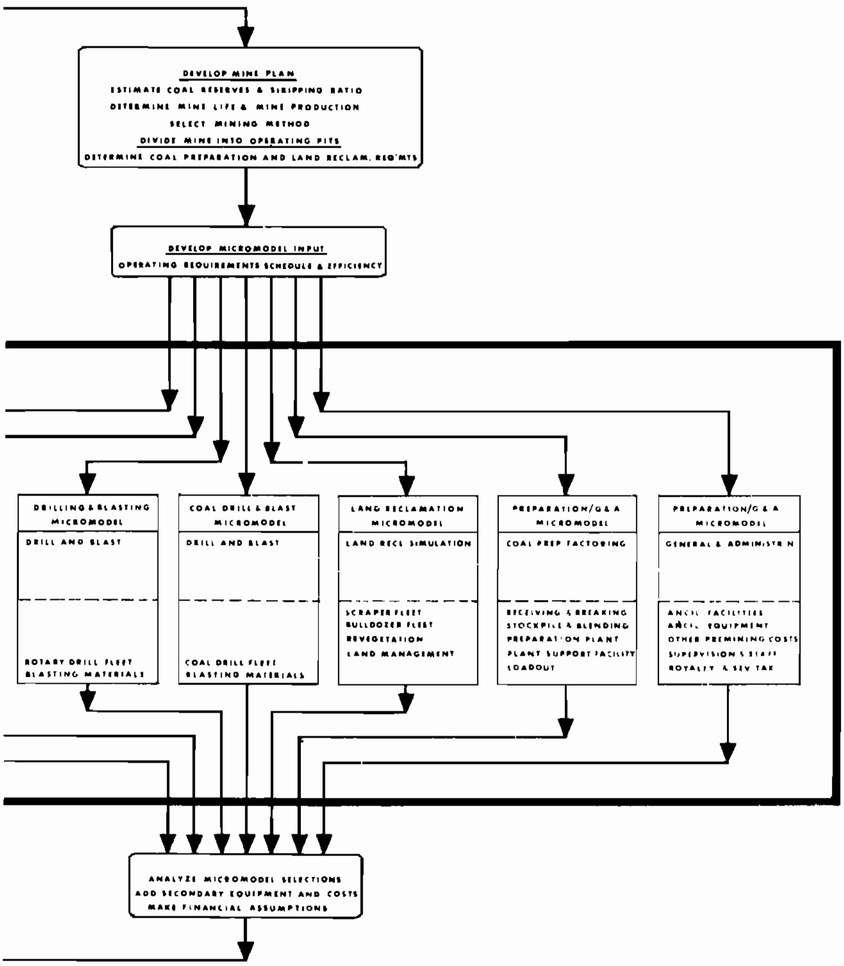


Figure 1. Comparison of detailed micromodels and broad macromodels.

In the normal progression of mine development, a macromodel would be most useful during early planning and the micromodels would be most useful at a later stage during detailed feasibility and engineering studies. Each is potentially very useful at the appropriate stage of a project or study.

DESCRIPTION OF THE SIMULATION MODELS

A total of fifteen models have been developed: eleven detailed micromodels, three broad macromodels, and one economic analysis model.

Micromodels for Dragline Stripping

Three micromodels simulate the major methods of dragline stripping illustrated in Figure 2.

The basic stripping method micromodel simulates area stripping of overburden by using a single dragline with no spoil rehandle. The model solves the geometry of the mining pit and estimates ownership and operating costs for each dragline with sufficient size and capacity to meet required production. The least cost solution is found and listed by the computer. The computer also plots the pit geometry for the least cost machine.

The extended bench method micromodel simulates area stripping of overburden by using two draglines. The first dragline removes a portion of the overburden. The second dragline, operating on a bench created by leveling the spoil from the first machine, removes the remaining overburden and rehandles a portion of the initial spoil. The model solves the geometry of the mining pit, allocates production between the two machines, and estimates ownership and operating costs for each combination of draglines with sufficient size and capacity to meet required production. The least cost solution is found and listed by the computer.

The contour stripping with draglines micromodel simulates removal of overburden by using a dragline following the contour of a coal outcrop along a gently sloped hillside. The model determines how many panels can be stripped into the hillside until the operating limit of the dragline is reached. The model tabulates the amount of coal and overburden for each panel and estimates ownership and operating costs for the totel pit with and without rehandle.

Each of the models permits more than 30 input parameters to be defined. Each model produces extensive output information for review by the user.

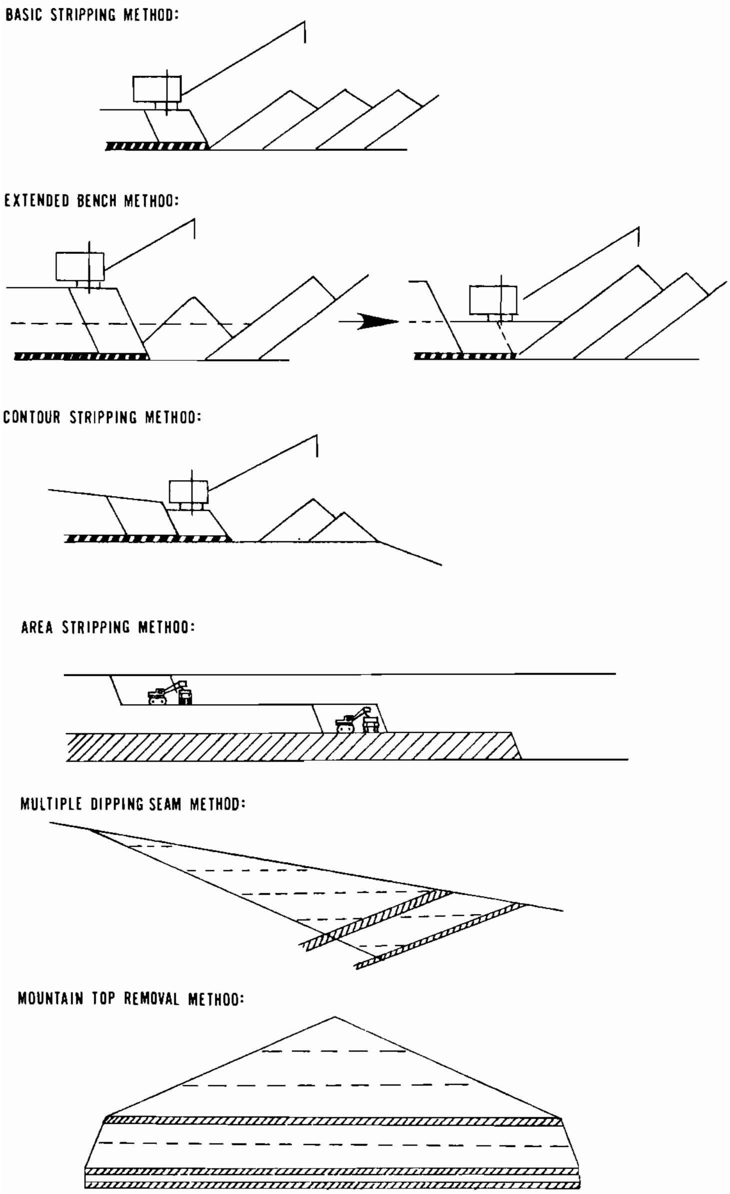


Figure 2. Micromodels for shovel truck mining and dragline stripping.

Micromodels for Shovel Truck Mining

Three micromodels simulate the major methods of shovel truck mining illustrated in Figure 2.

The shovel truck or area stripping micromodel simulates overburden removal by a fleet of shovels (or front-end loaders) and trucks operating on a series of benches. The topography and the seam are assumed to be relatively flat. The model also simulates coal loading from one or more benches and hauling to a central preparation plant. The model solves the geometry of the mining pit, divides the operation into benches, and estimates for each bench the ownership and operating cost for each available shovel truck combination. The least cost solution for each bench is found and a summary of all benches is listed by the computer.

The multiple dipping seam micromodel simulates overburden removal by a fleet of shovels (or front-end loaders) and trucks operating on a series of benches in a hillside pit. The model also simulates coal loading from one or more seams and hauling to a central preparation plant. The model solves the geometry of the mining pit, divides the operation into benches, and estimates for each bench the ownership and operating cost for each available shovel truck combination. The least cost solution for each bench is found and a summary of all benches is listed by the computer.

The mountain top removal micromodel simulates overburden removal by a fleet of shovels (or front-end loaders) and trucks operating on a series of benches on a mountain top or ridge. The model also simulates coal loading from one or more seams and hauling to a central preparation plant. The model solves the geometry of the mountain top, divides the operation into benches, and estimates for each bench the ownership and operating cost for each available shovel truck combination. The least cost solution for each bench is found and a summary of all benches is listed by the computer.

Each of the models permits more than 40 input parameters to be defined. Each model produces extensive information for review by the user.

Micromodels for Nonstripping Functions

Four models simulate the major nonstripping functions of a surface coal mining operation:

The haul unit simulation and coal load and haul micromodels together simulate loading and hauling coal with a shovel (or front-end loader) and one or more trucks. The haul unit simulation model estimates the cycle time for each size of truck to make a complete round trip on a specified haul road. This cycle time is used by the coal load and haul model to determine the number of shovels and trucks required to meet a specified production, and to estimate ownership and operating costs and list the least cost solution.

The drilling and blasting micromodel simulates drilling and blasting either overburden or coal. Ownership and operating costs for the required number of drills plus the annual quantity and cost of blasting materials and explosives are estimated by the computer.

The land reclamation simulation micromodel simulates six aspects of land reclamation: topsoil removal, spoil pile regrading, general dozing, topsoil spreading, revegetation, and land management. The model estimates equipment requirements and calculates ownership and operating costs.

The preparation/general administrative micromodel uses extrapolation from a baseline case rather than simulation. The preparation portion of the model estimates the ownership and operating costs for a complete coal handling and preparation facility including receiving and breaking, stockpiling and blending, preparation (crushing and screening, Baum jig, or heavy media), support facilities and coal loadout. The baseline values for the extrapolation were derived from a detailed study of hypothetical large-scale preconversion facilities. The user may redefine the baseline values to describe other preparation systems. The general administrative portion of the model estimates the ownership and operating costs associated with premining activities, central facilities, operating staff, and taxes and royalties. The baseline values for the extrapolation were derived from a study of general and administrative costs for a large-scale mine. The user may redefine the baseline values to describe other general and administrative approaches.

Macromodels for Broad Analysis of a Mine Complex

Three macromodels have been developed:

The area dragline macromodel selects equipment and estimates costs for all functions that comprise a complete mine complex that uses the area stripping with a dragline mining method.

The area shovel truck macromodel selects equipment and estimates costs for all functions that comprise a complete mine complex that uses the area stripping with shovels and trucks mining method.

The contour dragline macromodel selects equipment and estimates costs for all functions that comprise a complete mine complex that uses the contour stripping with draglines mining method.

These broad macromodels need only seven mining parameters and nine financial parameters as input. All other parameters are set at default values generally descriptive of the region being studied. The user who desires little or no interaction with the model can obtain an answer quickly by defining only the needed input and accepting all other parameters at the default values. The user also has the option of changing any or all the default values to match his own field data or operating experience.

Economic Model for Cash Flow Analysis

Once equipment selections have been made the next step is to develop equipment and manpower lists and investment and operating costs. These data are manually compiled when the micromodels are used but developed directly by the macromodels. The final step is the estimation of the coal sales price required to yield a specified return on investment or the return that could be expected from a specified sales price. The cash flow analysis model is used for this final step. It develops a complete discounted cash flow analysis of the project and prepares the following reports:

- The financial summary report provides economic highlights such as required investment, selling price, and rate of return.
- The case description identifies the case being analyzed, including mining parameters and financial assumptions.
- The investment list identifies all equipment, facilities, and pre-mining costs and shows total investment and replacement capital.
- The operating personnel list identifies all operating personnel, including supervision and staff and shows total manpower and payroll requirements.
- The maintenance personnel list identifies all maintenance personnel and shows total manpower and payroll requirements.
- The services and materials list identifies all services and materials and shows annual quantity of electric power, water, and fuel.
- The infrastructure report summarizes physical effects, economic impact, utility requirements, and manpower requirements.
- The production and cash expenditure table shows production and cash expenditures for each year of the project.
- The financial statements give income, sources and uses of funds, and a balance sheet for each year of the project.

These reports provide the user with a wide range of information useful in evaluating a large-scale surface coal mining project in terms of capital investment, operating costs, and profitability.

TEST CASES

Eight test cases were developed to confirm the capacity of each of the fifteen models to produce realistic and logical results for varying mining conditions and financial assumptions, and to provide examples of applications of the models for a representative (although hypothetical) mining situation for each major surface mining region in the USA. The steps undertaken in analyzing each test case were selection of regions and mining methods, development of hypothetical mining situations, generation of baseline solutions by using the micromodels, macromodels, and the cash flow analysis model, and investigation of the sensitivity of results to variation of key parameters.

The eight hypothetical test cases analyzed in detail to test the simulation models for representative situations in the regions were:

- Illinois Basin (dragline area stripping);
- Four Corners (dragline area stripping);
- Fort Union (dragline area stripping);
- Texas Gulf (dragline area stripping);
- Appalachia, Ohio (dragline contour stripping);
- Powder River (shovel truck area stripping);
- Appalachia, West Virginia (shovel truck mountain top removal); and
- Green River (shovel truck multiple dipping seam mining).

A baseline solution was first generated for each case by using the detailed micromodels; for six test cases, solutions were generated by using the broad macromodels. This served as a check between the two types of models. In all cases, baseline results were within less than ±5% of each other by the two methods. Then the sensitivity of solution values to the mining and financial parameters was determined by varying them one at a time through a range of values from extremely low to extremely high. The range of values used represents practical limits for each variable based on operating experience and field investigation.

MINE EVALUATION

Mine evaluation typically progresses through a series of steps from initial order-of-magnitude estimates through preliminary estimates, basic engineering, detailed engineering, procurement, and construction to start-up.

The broad macromodels can be used to obtain inexpensive order-of-magnitude estimates for initial reserve evaluation. As more field data are collected, preliminary estimates can be made by using the macromodels for analyzing the overall mining complex, and the detailed micromodels for analyzing critical mining functions. In the basic engineering stage the computerized models can be used to examine a wide range of alternatives for both mining and processing *before* committing large expenditures for the preparation of detailed engineering drawings, specifications, calculations, and estimates. By using the results of field investigation and by testing to refine model default values further with actual realistic data, a great many cases can be run rapidly and inexpensively to examine many alternative mining methods, mining plans, processing methods, equipment types, and equipment sizes.

AN APPROACH TO DETERMINATION OF COAL EXTRACTION MARGINAL SCALES

A.A. Arbatov and G.N. Kuznetsov

INTRODUCTION

The emergence of coal as an alternative energy source is due to the depletion and rising cost of oil and gas resources. Despite its inferior technical and economic characteristics compared to gas and oil, coal, owing to its large reserves, is assumed to be able to fully or partly replace natural hydrocarbons before the era of inexhaustible energy resources. In this connection the scale of coal extraction is determined, on the one hand, by maximizating coal use in order to prolong the lifetime of gas and oil in the spheres where their replacement is not yet feasible or reasonable, and on the other hand, by minimizing the negative effects of coal extraction and use on the environment.

Solution of this problem involves determination of the following:

- Anticipated total demand for fuel and energy;
- Permissible standards for different pollutants affecting human subsistence;
- Pollutant quantities in the environment resulting from the extraction and consumption of an "average" coal unit;
- Natural purification;
- Marginal scales of coal extraction and consumption.

Each stage requires extensive study and thorough calculations. This paper focuses attention on the last stage: determination of marginal coal extraction and consumption scales versus ecological constraints. The output data of the earlier stages used in this paper are either taken from the relevant literature or approximated. The authors aimed at obtaining not explicit values for specific recommendations, but an approximate calculation for identifying the main trends and priorities in solving the problem of marginal coal extraction.

Three main constraints are connected with large-scale use of coal resources:

- Higher costs of coal extraction and processing owing to different "conditions" of the deposits. By "condition" we mean an aggregate indicator based on the depth of coal deposits, their capacity (power), ash content, and the like;

- Volume of extraction constrained by the marginal value of coal resources. The existing estimates of practically inexhaustible resources are based on recent rates of extraction. However, if the period of transition from hydrocarbons to the inexhaustible sources of energy is extended, the problem of depletion of allegedly infinite coal deposits will arise.

- Large-scale use of coal will inevitably cause environmental problems, and the ecological constraints are likely to be stronger than the others mentioned. The main negative impact of coal extraction and processing upon the environment is the spoiling of land resources and gaseous atmospheric pollution.

The aim of this paper is to determine temporal restrictions on large-scale coal use connected mainly with the impact of ecological factors. In other words, the period of coal use until the moment when its extraction and processing begins to affect the environment irreversibly has been calculated. Coal wastes are estimated as a derivative of extraction. Maximum concentrations of those wastes in the atmosphere and land spoiling and depletion were calculated on the basis of modern standards of permissible concentrations of noxious substances.

The calculations were based on the following assumptions:

- Coal reserves 15×10^{12} t; no further significant increase is expected.

- Since 1975, world extraction of coal has increased annually by 1%, 2%, 3%, 4%.

- World coal extraction has dramatically increased by 1980 to meet overall energy demand; this hypothetical extraction will also grow by 1%, 2%, 3%, 4% per annum.

- The volume of noxious wastes, because of upward trends in cleaning technology, will decrease annually by 1%, 2%, etc.

For each combination of these variants of increased extraction and decreased noxious waste, a temporal boundary of coal use is calculated. The work is based on the mineral resources dynamic model developed at the Institute for Systems Studies for analyzing different resource strategy alternatives in connection with the weaker or stronger influence of various factors upon the volume of mineral resource (MR) extraction and processing. In the model the term resource strategy implies a change in the values of the control variables and in some initial values of exogenous variables. A schematic diagram of model MR is shown in Figure 1; it can be regarded as a generalized systems model reflecting the main stages of MR exploration, extraction, and processing. The system's poles are speculated MR stocks and economic demand for the given mineral resource. The poles are quite mobile in time due to the interrelationship of natural and economic factors, such as economic feasibility of MR development, depending on the resource condition, and decreasing volume of MR extraction and processing due to ecological constraints. Naturally this is only part of the spectrum of factors significantly affecting the system considered. A more sophisticated and improved model will be developed.

The cause-effect relationships between the basic variables of the model are illustrated in Figure 1. The computational pattern of the model is based on a method somewhat different from that of J. Forrester [4]. Because of the specificity of the system explored, probabilistic evaluations have been introduced into some equations. The model is generally characterized as (a) nonlinear, (b) probabilistic, (d) dynamic, (d) simulation.

MODEL CHARACTERISTICS

Control Variables of the Model

D	demand for final product
DD	coefficient of changes in demand
$MPR	marginal pollution extent
$MPRK	coefficient of annual reduction in wastes polluting the environment

Basic Variables of the Model

S	speculated resource volume
PE	proved economic resource volume
E	volume of annual extraction of mineral resources sent for processing
P	volume of annually processed mineral resources
C	accumulated product volume
R	accumulated proved subeconomic resource volume

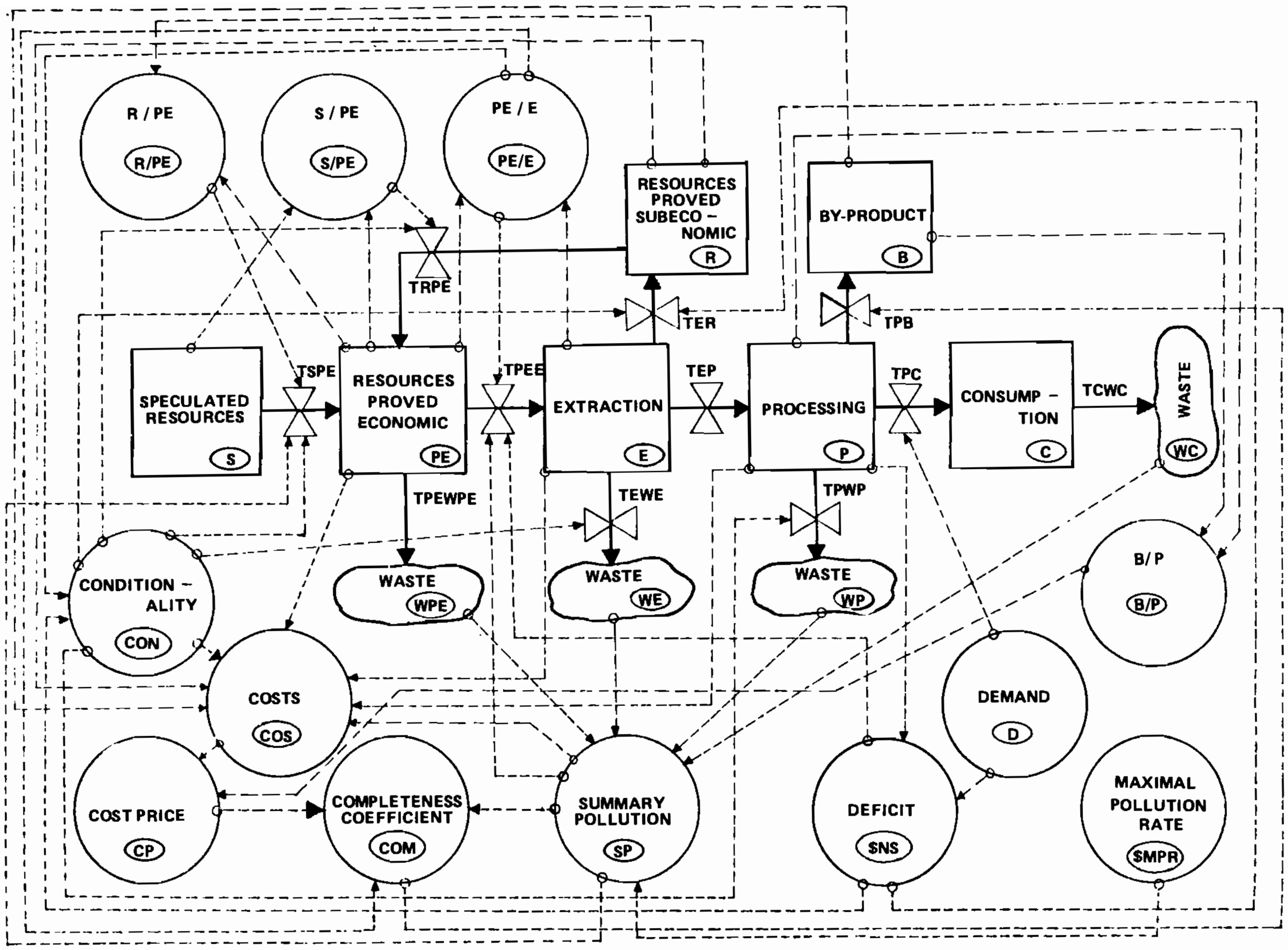


Figure 1. Common model of mineral resources.

B	accumulated by-product volume
WPE, WE, WP, WC	volumes of waste accumulated in the processing stages
$NS	nonsupplied product deficit
CON	coefficient of deposit "condition"
SP	overall volume of environmental pollution
COS	costs
COM	MR completeness coefficient (17) (nondimensional)
CP	product costs
TSPE	proved economic stock growth
TPEE	rate of extraction
TEP	rate of processing
TPB	rate of by-product accumulation
TER	proved subeconomic resource growth
TRPE	proved subeconomic product transformation into proved economic product
TPEWPE, TEWE, TPWP, TCWC	rates of waste accumulation at all processing stages.

Taking into account the specific nature of the problem investigated in this paper, some variables of the model are assumed equal to zero.

Initial Values of Variables

The world volume of coal extraction in 1970 to 1975 varied from 2.9×10^9 to 3.1×10^9 t [2]. In our calculations the volume of the initial period [1975] is assumed to be equal to 3×10^9 t. The annual extraction growth varies from 1% to 4%. The speculated coal reserves of the world are 15×10^{12} t.

If global energy demand is to be covered by coal, the present volume of extraction should be increased to 13×10^9 t. This figure is derived by simple recalculation of all modern energy resources in terms of coal equivalent. The annual growth of this hypothetical extraction was also calculated for four different rates: 1%, 2%, 3%, and 4%.

In determining the marginal volumes of coal extraction and processing, four types of coal waste pollution were analyzed as ecological constraints: The area of land spoiled by mining processes and quarries [3], and the volume of nitrogen oxides (recalculated as NO_2), sulfur dioxides, and carbon dioxide wastes from coal power stations [1].

Determination of marginal pollution standards per time unit has proved to be one of the most complicated problems. The input data for these calculations were the estimates of M.A. Styrikovitch et al. [1], who calculated the 1973 volume of these three air pollutants. However, since standards should be based on the marginal permissible volume of pollution and not the actual one, higher input data on marginal volumes of gaseous pollution are assumed than those used in [1].

Determination of the marginal land resource area that can be allotted for coal extraction is a separate and complicated problem. We hypothetically assume this margin to be equal to 10% of the calculated total area of arable land [5]. Tables 1 and 2 show the input data taken from [1, 5].

Table 1. Ecological costs of extraction and use of one ton of coal.

Land [ha]	SO_2 [kg]	NO_2 [kg]	CO_2 [kg]
41-97 $\times 10^{-7}$	42-62	7-11	0.4-0.6

Table 2. Marginal area of spoiled land and marginal volumes of annual gaseous atmospheric pollution.

Land [10^9 ha]	SO_2 [10^9 t]	NO_2 [10^9 t]	CO_2 [10^9 t]
0.68	1.50	0.50	3.00

Interpretation of the Results

Tables 3,4,5, and 6 show the results of modeling calculations for current world and hypothetical coal consumption versus annual decrease in pollutant volume. Analysis of these data proves that if the volumes of all pollutant types decrease by 3% annually, coal is likely to satisfy global energy demand in the foreseeable future without ecological constraints, even assuming that the growth in demand is 4% per annum.

The weakest links in the chain of the four pollutant types analyzed are sulfur dioxide and nitrogen oxide (Tables 3 and 4). The current standards of atmospheric pollution by these substances show that only an annual decrease of 2 to 2.5% in these pollutants will permit a 3% increase in coal extraction. Thus the hypothetical replacement of all energy resources by coal cannot be effected because of the constraints connected with pollution by these substances.

As might be expected, atmospheric pollution by CO_2 is no great obstacle to increased coal extraction. However, not only the current maximum CO_2 pollution rates, but also the climatic changes likely to occur owing to atmospheric saturation with CO_2 must be taken into account here.

The spoiled land area assumed as marginal puts no limits on coal extraction growth. The calculations (Table 6) show that this area can provide for coal extraction for quite a

Table 3. Limits of coal resource exploitation before marginal atmospheric pollution by sulfur dioxides is reached.

Initial extraction [10^9 t]	Decrease in pollution [%]	Years of exploitation for an annual production growth of			
		1%	2%	3%	4%
3	0	230	120	70	60
	1	>300	240	110	80
	2	>300	>300	220	130
	3	>300	>300	>300	260
13	0	90	40	30	20
	1	>300	80	60	30
	2	>300	>300	100	50
	3	>300	>300	>300	80

Table 4. Limits of coal resource exploitation before marginal atmospheric pollution by nitrogen oxides (recalculated as NO_2).

Initial extraction [10^9 t]	Decrease in pollution [%]	Years of exploitation for an annual production growth of			
		1%	2%	3%	4%
3	0	280	140	100	70
	1	>300	260	120	110
	2	>300	>300	290	160
	3	>300	>300	>300	260
13	0	130	80	50	30
	1	>300	140	60	40
	2	>300	>300	120	70
	3	>300	>300	>300	140

Table 5. Limits of coal resource exploitation before marginal atmospheric pollution by CO_2 is reached.

Initial extraction [10^9 t]	Decrease in pollution [%]	Years of exploitation for an annual production growth of			
		1%	2%	3%	4%
3	0	>300	>300	260	180
	1	>300	>300	>300	250
13	0	>300	>300	210	150
	1	>300	>300	>300	200

Table 6. Limits of coal resource exploitation before the marginal land resource pollution is reached.

Initial extraction [10^9 t]	Years of exploitation for an annual production growth of			
	1%	2%	3%	4%
3	>500	410	270	200
13	>500	340	230	170

long-term perspective. Naturally, subject to a lesser extent of land spoilage through coal extraction, certain constraints should emerge. The ratio of coal extraction volume to extent of spoilage can be optimized accordingly.

The results presented above should be considered as an illustration of the potential of modeling calculations and as the first tentative attempt to identify the main ecological constraints. The following conclusions emerge:

- With a dramatic increase in coal extraction, great attention should be paid to improvements in the technology of sulfur and nitrogen compound extraction in the coal combustion process;
- Coal combustion products can be extracted in such amounts that practically unlimited growth of coal mining is possible;
- CO_2 produced by combustion is not a serious direct constraint;
- With a 10% limit on the use of potentially arable land for coal extraction, land spoilage is not a serious constraint for the growth of coal extraction.

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THE WELMM APPROACH TO COAL MINING

M. Grenon

THE WELMM APPROACH

The WELMM approach (standing for Water, Energy, Land, Materials, and Manpower) was developed at IIASA to assess the qualitative and quantitative systems aspects of energy strategies [1]. It is clear that the harvesting, conversion, and further use of energy resources require other natural as well as human resources. In short, what is consumed is neither energy (a theoretical concept) nor energy resources only, but "WELMMITE", an aggregate of natural resources.

This method of resource analysis or accounting can be considered as an extension of the well documented energy analysis to other natural (and some human) resources. Also, it is interesting to compare and possibly integrate the availability of the other natural resources required to implement a given energy strategy. In particular, one must avoid shifting the burden of scarcity in one energy resource onto another scarce resource such as some metals, water, or land.

Some of the impacts of energy resource development on other natural resources can be considered minor, whereas others are already considerable--such as those of coal mining. All of them, however, are worthy of examination when energy strategies are implemented on the large scale necessary today, and even more tomorrow.

Before describing the tools of the WELMM approach, let us point out that, from the theoretical analysis point of view, the various resources considered are, of course, basically different, but that a degree of unification can be achieved, especially through generalization of the McKelvey diagram. For each resource, natural occurrence (or abundance) can be defined, and, independently "institutional" availability; combining the two allows us to define categories of "resources" and "reserves" and their relative scarcity. Two examples illustrate these points.

Water. Worldwide, about 7500 m^3 of clean, fresh water is available per capita at any given time. But the availability of clean water is becoming a problem in many big cities and some regions, such as in the western States of the USA, for coal mining and conversion and subsequent land reclamation.

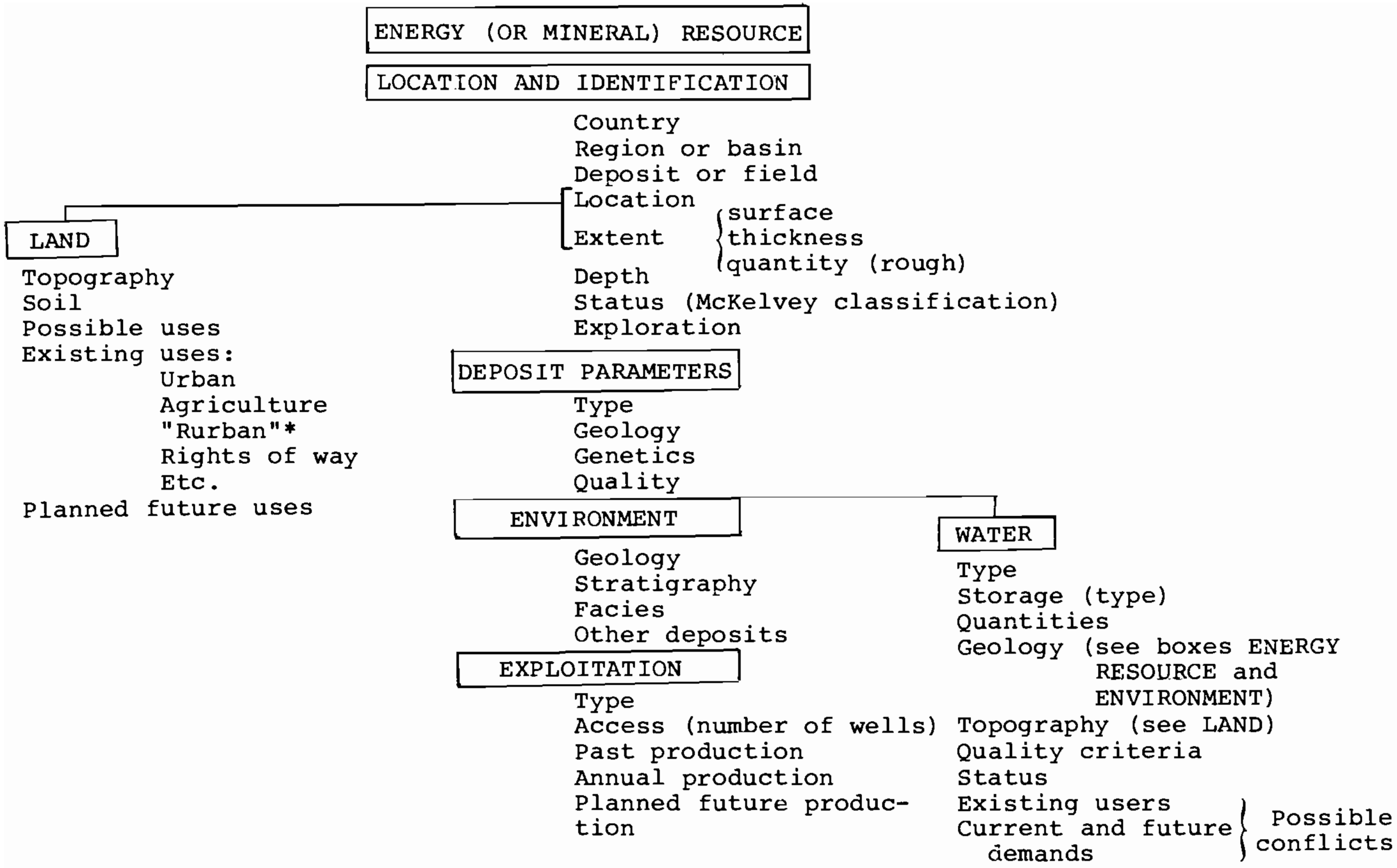
Land. Worldwide, there is about 37,000 m^2 of land per capita, approximately 10% of which is arable. If the world population were concentrated in the USA, its density would be about the same as in the Netherlands. However, it is becoming increasingly difficult in industrialized countries to open a new surface mine (for coal and/or minerals, and even for stone or gravel on the East Coast of the USA), or to find an acceptable site for a new energy facility, such as a power plant or coal gasification plant.

THE BASIC TOOLS OF THE WELMM APPROACH

The WELMM approach is implemented through three basic data files (now being computerized): the Resources Data Base, the Basic Materials and Equipment Data Base, and the Facility Data Base. The last two are used for the WELMM or natural resources accounting.

The Resources Data Base (RDB)

There seems to be a continuous trend toward larger resource extraction facilities, as illustrated by the growing emphasis on giant energy or mineral deposits; these include, for example, the Kansk-Achinsk basin in the USSR, the lignite mines of the Rhine area in the FRG, the Selby mine in the UK, and the planned large surface mines in the western USA. The RDB collects information on WELMM resources associated with large (cluster), giant, and supergiant fossil and/or fissile fuel deposits and on mineral resources. Data are gathered (Figure 1) on geographical and geometrical parameters of the deposit and its status in the McKelvey classification (speculative or hypothetical or identified resource or economical reserve); on the geological parameters--for both the deposit and its ecological environment--and on the possible simultaneous occurrence of other minerals and/or fuels, in search of possible "total mining operations"; and on potential, present, or past exploitation and production. Data on the land and water resources locally or regionally associated with the deposit are also filed, especially for the factors that would be important in truly large-scale exploitation of the energy (or mineral) resource. An example of a surface mine in northwestern New Mexico is given in Figure 2.



*New types of human settlements in rural areas

Figure 1. Basic concept of the WELMM Resource Data Base.

Land

Northwestern New Mexico, San Juan County
Navajo Indian Reservation

Arid plateau, 1675-1770 m altitude

Slight relief, numerous flats of barren shale frequently adjacent to shallow sand dunes

Several local drainage systems (generally dry) cut steep gullies

Soils: mostly alluvial or eolian; from coarse to deep

Existing use-grazeland (poor)

Total lease ~ 160 km^2

Total coal reserves 750 Mt

Strippable coal reserves 615 Mt

Stripping ratio: 4.9 Depth <50 m

Deposit Parameters

Subbituminous coal 2300 kcal/kg
Fruitland formation: shale beds interbedded with sandstones; about 75 m thick; contains at least 10 coal beds

Genetics: relatively short period of unstable conditions, alternating swamps of shallow fresh water occasionally invaded by salt water and river flood plain deposits

0.72% S; 22% ash; 17% moisture

Environment

Stratigraphy:
  Quaternary: alluvim (sand & gravel) and dune sand

  Upper Cretaceous:
  Kirtland shale
  Fruitland formation (coal bearing)
  Pictured cliff sandstone
  Lewis shale

Exploitation

Strip mining (start up>1982)

Water

- San Juan River Basin (one of the few perennial streams in this part of New Mexico)
- Principal tributaries:
  - Navajo
  - Los Pinos
  - Animas
  - La Plata

1.83×10^9 m^3/yr in 1974 at Shiprock (NM)

- Groundwater:
  - shallow: meager
  - deeper water-bearing sandstone formations
- Complex water rights Upper Colorado River Basin Compact 1948

Figure 2. Burnham coal gasification mine: location and identification.

The Basic Materials and Equipment Data Base (CDB, Components Data Base)

In these files are gathered the WELMM, or "WELMMITE", contents of basic materials--e.g., steel, metal alloys, cement, glass, and concrete (for various manufacturing processes)--and of basic equipment--e.g., pumps, turbines, and heat exchangers. These data are collected from the literature, through direct analysis with the help of materials producers and equipment manufacturers, and through input/output tables using energy or resources multipliers.

The Facility Data Base (FDB)

The basic data of the CDB are aggregated for typical energy facilities. An energy chain from the resource in the ground to final use can be divided into various steps such as mining (surface or underground); fuel cleaning, transportation, or conversion to a secondary energy such as synthetic natural gas, electricity, or methanol; distribution; and waste disposal. Each step can be characterized by a process--say, longwall or hydraulic mining--and an energy facility can be associated with each process. Fortunately, at least in the downstream parts of an energy chain there is a tendency toward size standardization, which favors WELMM resource accounting: for instance, coal gasification plants are generally considered at a level of 2.5×10^9 m^3/year (250×10^6 st.ft^3/day), and coal power plants are built or planned in the 600 to 800 MW(e) range. The situation is more complex for mining, for which most of the facilities are more or less site specific.

WELMM analysis for energy facilities gathers details on construction (for the facility as a whole and per unit of capacity) and operation of the facility (annual requirements and per unit of output), on the following:

- Water requirements	Intake, consumption and quality;
- Energy requirements	Electricity (in kWh), motor fuel and process heat fuel (in kcal or kJ);
- Land requirements	Temporary and permanent use, exclusive and nonexclusive use;
- Materials requirements	All materials problems, from consumption and handling of materials to recycling potential and

	waste production and disposal. Analysis of these requirements is generally expressed in commercial products (steel plate, copper wire, concrete, etc.), and then converted into basic metals (iron, nickel, molybdenum, cement, aggregate, etc.) and finally into the true mineral ore requirements, based either on commercial grade values or, in a longer-term perspective, on cutoff grades.
- Manpower requirements	Generally estimated for miners (or analogous or associated professions, such as geologists, drillers, etc.), in terms of skilled and unskilled workers.

Data are acquired as for the CDB, from literature surveys (of great value are Environmental Impact Statements) and directly via questionnaires. All the data are collected in standard files, which include supplementary information and all source references. The files are being published in a series of IIASA reports.

APPLICATION PROGRAMS

Numerous application programs can combine the WELMM data in a static or dynamic way to compare various energy strategies on a local, national, regional or global basis. Some of them are being developed at IIASA.* Local applications are, for instance, detailed assessments of coal mining projects, as will be shown later. The WELMM approach is also being used to compare various methods of coal mining, such as future potential in situ energy extraction (underground gasification, pyrolysis, complete combustion, quenched combustion, solvent digestion, aqueous phase liquefaction, supercritical gas extraction, chemical comminution, microbiological degradation, etc. [2]). The WELMM approach helps in making detailed energy and material balances, and in assessing the impacts of global energy scenarios, such as the 35 TW Reference Scenario being developed at IIASA. Whether we are dealing with the 12 plus 5 TW fossil fuels of that scenario or with the 8.7×10^9 t of coal assumed for the year 2020 by the Coal Resources Assessment Group of the Conservation Commission of the World Energy Conference [3], the global impacts of such large-scale mining and subsequent fuel conversion and/or use are worth a thorough examination.

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*As an institution one of whose main purposes is to advance methodologies, IIASA naturally attaches as much importance to developing the method as to its applications, which by their nature are generally shared with other institutions.

Some energy conversion facilities or the harvesting of a new energy resource like the sun require huge amounts of materials and equipment. Large-scale mining, especially surface coal mining, involves the moving and handling of tremendous amounts of material, fuel, and spoil. The 8 to 12 × 10^9 tons of coal supposed to be handled in 2020 as mentioned above compare with the calculated amount of 12 × 10^9 m^3 of solids transported annually by rivers, of which some 90% are deposited on continental shelves. This huge volume of rocks moved, added to the vast areas of land disturbed and reclaimed and the great impact on water resources, of course raises enormous problems, but also offers a unique possibility of reshaping parts of the earth for more optimal utilization. To study the systems aspects of such a perspective is the aim of the WELMM approach.

Two papers in this volume illustrate the WELMM method: this paper on coal mining, and Klitz's paper on WELMM Analysis of Coal Processing, Transporting, and Conversion.*

THE WELMM APPROACH TO COAL MINING

Contrary to many energy conversion facilities where most of the WELMM data are process (and size) specific, most of the WELMM impacts of coal mining are site specific. However, some interesting aggregated data have been developed recently by Hittman Associates [4], the Council for Environmental Quality [5], the Stanford Research Institute [6], Bechtel Corporation [7], and others, on a national and/or regional basis (mainly for the USA).

In order to afford a better understanding and illustration of this method, this report analyzes and compares the WELMM aspects of three coal mines: the Selby underground mine being developed in the UK [8], the Garsdorf surface mine in operation in the FRG [9], and the planned Burnham surface mine in the USA [10]. Table 1 gives the main characteristics of these mines. The detailed Resource Data sheet for the Burnham mine (Figure 2) and similar sheets for the Selby and Garsdorf mines are summarized in Table 2.

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*In addition to Ken Klitz, I am indebted to Bruno Lapillone, Martin Cellerier, and Arnulf Grubler for their help in developing the WELMM approach, and to R. Levien and W. Häfele for their continuous support and interest.

Table 1. Main mine characteristics.

Location	Selby, N. Yorkshire, UK	Garsdorf, Rhine area, FRG	Burnham, NW New Mexico, USA
Coal Characteristics		lignite	sub-bituminous
Calorific value [kcal/kg]		1900-2100	2300
Sulfur content [%]		low	0.72
Ash content [%]	$\leq$ 20	8 to 8	22
Moisture content [%]		50-60	17
Deposit Characteristics			
Estimated resources [Mt]	600+	1000	615
Seam thickness [m]	2.75-3.35	45-60	3.50 (in 4 seams)
Depth [m]	~ 750	up to 300	up to 50
Type of Mining	Underground	Open pit	Stripping
Main equipment	Long wall	Bucket wheel excavator	Dragline and power shovel
Annual Production [Mt/year]	max. 10 around 1987-1988	42 in 1974 50 forecasted	max. 17 in 1982+
Status	Start in 1980-1981	Started mid-1960s	Planned (~ 1980)

Table 2. Some environmental characteristics of the Selby, Garsdorf, and Burnham Mines.

	Selby	Garsdorf	Burnham
Total area [km^2]	390		162
Area mined [km^2]	290	25-26	89
Type	Very rich farmland	Very rich farmland	Poor grazeland
	Rural	High population density	Scarce population
		Large cities nearby	Indian reservation
Main problems	Disturbs traditional rural area	Deepest open pit water table	Uncertainty of reclamation potential
	Subsidence of agricultural and historical land	Resettlement of communities	

SHORT DESCRIPTION OF THE MINES

Selby

Although sporadic mining began in Roman times, the North Yorkshire coal field became particularly active in the nineteenth century, proceeding eastwards as depths increased and mining became more difficult. In the 1950s came evidence of a considerable extension of the Barnsley seam under the Selby area; this new coal field, confirmed in 1972, has "clean" coal, good enough to send straight to the power stations without washing.

On the western edge of the proposed mining area, good-class coal found at a shallower level will allow access to the main coal by a sloping drift connected to an underground road system that will lead to the five prime mining areas. Shafts are still necessary for ventilation and carrying men and materials, but the handling facilities for the coal, traditionally associated with spoil, huge areas of unsightly buildings, and industrial mess, will be concentrated in Gascoigne Wood, a set of disused sidings 0.22 km^2 in area.

The mining area will be divided into five blocks, each with its own deep shafts, the sites of which can be kept to about 8 ha each in each block. There will be two shafts per block, each about 7.3 m in diameter--one shaft for normal winding operations for men and materials and for taking fresh air to those working underground, and the second for air to return to the surface and for standby winding capacity. Each shaft site will work an area roughly 8 km in diameter, using the "retreat" method, with subsequent collapse after the powered supports have been moved, and will produce around 2 Mt per year (10 Mt per year maximum in total). The coal will be extracted in panels, pillars of untouched coal being left between each two panels to match detailed calculations on surface subsidence.

The Selby project has been described as possibly the biggest single (underground) coal-mining operation in the world.

Garsdorf

The Rhineland brown coal area (between Cologne and Aachen) covers about 2500 km^2 with coal seams up to 100 m thick at some points, although the average thickness is 50 m split up into as many as five seams in some regions. The heat content of the raw coal ranges from 1600 to 2900 kcal/kg, increasing by about 200 to 250 kcal/kg per 100 m increase in depth; the water content is 45% to 63%, decreasing by about 3% per 100 m increase in depth. This coal has been exploited since the beginning of the century; the manufacturing of briquettes (with about 18% moisture content) has largely given way to power production in mine-mouth plants.

Total reserves have been estimated at 55 × 10^9 t (18 × 10^9 t of coal equivalent at 7000 kcal/kg), of which 35 × 10^9 t (11 × 10^9 tce) are economically recoverable under 1974 conditions and with known or foreseeable technology.

The shallowest deposits have already been exploited through surface mines. The large Garsdorf deposit (10^9 t of brown coal reserves) was studied initially for underground mining. Too high wages and high drainage costs led to the conclusion in the 1950s that there was no alternative to deep opencast mining. The coal seam (45 to 60 m thick, divided into strata by several faults) is located near the surface in the eastern part of the field but sinks to nearly 300 m in the western region. To maintain the stability of the open-cut escarpments, efficient drainage is required.

With its 10^9 t coal reserves and its associated 2 × 10^9 m^3 of overburden of gravel, sand, and clay, and with its 45 to 50 Mt annual production, Garsdorf appears to be the largest material-handling operation on earth, nearly twice as large as its closest competitor, the Kennecott Copper Bingha pit in Utah in the USA.

Burnham

The Burnham coal mine project of the El Paso Natural Gas Company and Consolidation Coal Company is associated with a proposed coal gasification plant of 2.9 × 10^9 m^3/year initially, and ultimately 4.1 × 10^9 m^3/yr of synthetic pipeline gas to be developed in the Navajo Indian Reservation 56 km southwest of Farmington, New Mexico. The total coal reserves under the 161 km^2 of leased land are estimated at about 750 Mt, 615 Mt of which are recoverable by stripping. The coal has a heat value of 2300 kcal/kg. The average stripping ratio is about 4.9 m^3/t (overburden to coal). There are four major coal seams of a minimum thickness of 0.90 m each, outcropping in the lease, dipping to 50 m, and continuing to dip beyond the lease boundary.

Coal production, supposed to start around 1980, will initially be 11.7 Mt per year, rising to 17 Mt possibly in 1982 (including 25% fines not at present gasifiable) to feed the coal gasification plant and nearby coal power plants (San Juan and Four Corners).

The three mines selected, which may be counted among the most modern in coal exploitation, thus differ widely in the characteristics of their coal and deposits and in their environment. Their various WELMM aspects are no less different and provide useful information for further aggregation at higher levels.

THE WATER ASPECTS

The Rivers Ouse and Wharf flow along the eastern edge of the Selby area, much of which is low-lying. The Ouse sometimes floods; the surrounding fields of the Vale of York are criss-crossed by drains and dykes to try to dry them in the spring. The water table is very close to the surface, and the major problem--and the biggest fear of the Selby community--is subsidence and the threat of fine fields turning into marshes.

The water problem was crucial for the Garsdorf project. Since brown coal seams are interbedded in unconsolidated water-bearing formations, opencast mines had to be kept completely free of underground water and protected against flooding by means of submersible pumps. In order to lower the ground water levels, about 12 m^3 of water have to be pumped for every ton of usable coal, and 32% of the environmental costs (which themselves represent about 9% of production costs) are for the withdrawal of water.

In the Garsdorf open pit, the west escarpment also had to be protected against the ground water of the Erft river basin. The Erft had to be diverted toward the west in a new sealed river bed. Subsoil water pumps (15 m^3/min, lifting head 300 m) are suspended in wells and run continuously to lower the subsoil water level to below the deepest open-cut level (maximum well depth 360 m). Moreover, the Erft--an obvious natural drainage channel for subsoil water--did not suffice for all the open-cut work in the Rhine area, and a 17.6 km long canal was built leading to the Rhine. At present, 1100 wells are in continuous operation for the six surface mines in the Erft region. For Garsdorf alone, 4.56×10^9 m^3 of water have been pumped in 13 years.

The future successor to Garsdorf, the recently approved Hambach mine (up to 600 m deep), has been proposed for use after mining as a possible storage space for water (residual hole of 2.51×10^9 m^3). This is an interesting example of landscape remodeling through water and mining co-management.

The water problem for the Burnham project is of a different nature, and closer to scarcity than to surplus (see Table 2). The allocation of water in the San Juan River Basin is made through the Colorado River Compact of 1922 and the Upper Colorado River Basin Compact of 1948. In fact, of the 18.3×10^6 m^3 required for the project (2% annual diversion of the River San Juan, and 7% diversion at the period of minimum flow), only a small part is for the mining operation itself: about 1.5×10^6 m^3/year at full production for sprinkling roads, dust abatement in crushing and screening operations, potable water supply, irrigation for reclamation, etc. Some of this water can also come from a deep well (Morrison formation) or from the Navajo Reservoir.

Although the gasification plant is planned to be a "zero liquid effluent", the groundwater quality could be affected in the long term by the disposal of ash and solid wastes buried in the mined-out area.

THE ENERGY ASPECTS

Contrary to extraction operations requiring a measurable amount of the energy content of the fuel produced (oil or uranium shale or steam-enhanced recovery), coal mining needs only a small percentage of the energy extracted, generally in the order of 1% or 2%, including reclamation of the disturbed land. These operations thus appear to be among the most energy efficient in the whole energy industry.

THE LAND ASPECTS

Coal mining has caused major disturbance to the land. In fact, its effects can be direct or indirect: they can result from mine development (access roads, new housing settlements), occur during the mining itself, or be delayed by as much as several decades (subsidence in old mined areas). Impressive progress has been made in understanding the land subsidence associated with underground coal mining, as well as in reclamation, rehabilitation, and restoration techniques* for surface mining, to the point that temporary land disturbance can become a positive factor allowing beneficial reshaping and landscaping. And the potential for progress is still considerable, mainly in arid or semi-arid areas where many fuel or mineral deposits occur.

The main land problems for the Selby project were associated with subsidence of agricultural land, as was mentioned above, and of the community of Selby, especially the historically valuable Selby Abbey. A limit of 0.9 m has been set for subsidence with plans to extract a maximum of 2.4 m of the coal in most parts of the field, and pillars of unworked coal have been left at intervals (notably, the Selby Abbey pillar). Possibly, trenches around buildings such as old churches will be either left open or filled with compressible material so that ground pressure--the push and pull--will be reduced.

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*According to the Energy Policy Project of the Ford Foundation, "restoration" implies that the site conditions before disturbance will be replicated after the action; "reclamation" implies that the site is habitable to organisms that were originally present or to others that approximate them (in fact, reclamation is the term normally used); "rehabilitation" implies that the land will be returned to a state and productivity conforming to a prior land use plan, including a stable ecological state that does not contribute substantially to environmental deterioration and is consistent with surrounding esthetic values.

Among the other problems related to land, it is worth mentioning that British Railways will have to reroute the line because of the coal field, so that Selby will no longer be on the London-Edinburgh line--a serious consequence for the community.

The Rhine brown coal area, which includes Garsdorf, covers 2500 km^2 and has a population density of about 410 inhabitants per square kilometer, one of the highest in the world. It consists mainly of farmland of very fertile loess soil (wheat and sugar beet are the principal crops). As a result there is mandatory land reclamation and total resettling of communities (including rerouting railways, highways, and rivers across the mining area). Since coal mining first started, 43 villages with a total population of 19,500 have been resettled in the region, and the number is expected to reach 30,000 by the end of the century.

While resettlement measures change the landscape before mining, reclamation measures restore it after mining. As a rule, reclamation is done in two stages--mining and biological reclamation. The former creates the conditions needed for the latter, i.e. plant cultivation, town planning, etc. Biological reclamation calls for the creation of agricultural areas and forests (on 3 to 5 m of so-called forest gravel). Immediately after mining, overburden is dumped into the pit, thus building up the raw spoil bank. On top of this bank, the loess (considered as a valuable mineral) or forest gravel is immediately spread, and finally reclamation is carried out. Initial agricultural reclamation is followed by five years of intermediate farming. By cultivating certain plants and using fertilizers, the humus content is raised to 1.5% during this period. In the southern mining district a forest-lake area for recreational purposes has been created.

To put such a task into perspective, note that before reclamation techniques were introduced in 1960, the restoration costs were far higher than the worth of the reclaimed land. While the "economic benefit", even today, is still very minor, the social impact is of much greater importance. But although the brown coal mining industry "consumes" about 240 ha of farmland annually, some 120 ha of farmland are lost *each week* to city growth, highway construction, and industrial expansion [12].

In the Burnham project on the Navajo reservation, on the other hand, population density is very low and the soil is poor, with sparse vegetation. On the existing lease, land use is limited to livestock grazing* and the land value is relatively low.

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*Generally speaking, in the semi-arid areas of the western USA about 12 ha are needed to support a cow. Assuming a 15 m coal seam, this area lies over almost 2 Mt of coal.

However, since a number of Indian families live on the lease area, its value is also influenced by family tradition, esthetics, and family ties. (48 families will be displaced over 25 years.) The land disturbance would, at least temporarily, also destroy wildlife habitat and grazing; if the planned mining reclamation is not successful, this could be permanent. Restoration will aim to bring the area back to as close to its undisturbed condition as practicable (which means to rangeland use), although overall elevation of the affected area will be increased from 3 to 10 m because of the swell factor resulting from disturbing the overburden during mining.

MATERIALS ASPECTS

Two main aspects of the materials problem are linked to coal mining: materials requirements and materials handling. The second generally tends to dwarf the first, especially with the new giant surface mines requiring super-giant handling equipment for the overburden and for the coal itself. The handling problem is somewhat less spectacular for underground mining but because of the limited space available, it is no easier. A few figures for Selby illustrate this:

> At any of the five sites, there will be four coal faces. The total weight of equipment on any such face is about 1000 tons. This equipment includes 200 powered supports weighing at least four tons each. In addition to these four working faces there will be probably another three faces in the process of being equipped. Besides this, there will be a large number of conveyor drives each weighing up to 10-15 tons. Heading machines weighing up to 25 tons each will be used to drive the tunnels. Each mine will operate four mining locomotives and standby locomotives will be available. Each locomotive will weight 21 tons..... Besides this, about 80 tons daily of materials such as girders, bricks, cement, rail, timber, etc., will need to be transported underground.....[8].

During the building of the mine, about 500 t/day will have to be taken out of each shaft by truck for between 18 months and three years.

Incidentally, underground transportation of materials is one of the difficulties of managing such an enterprise. The related surface handling and transportation--most of it by truck--creates another difficulty because it is one of the visible interfaces between the developing mine and the surrounding community, especially in a previously quiet and rural area like Selby.

The Garsdorf mine has already been mentioned as probably the biggest material handling enterprise in the world because of the amount of coal produced annually *and* the associated overburden and topsoil. The dramatic increase with time is illustrated for the whole Rhine area and for Garsdorf by the following figures.

- In 1950, lignite production was 60 Mt (Rhine area); and 45×10^6 m^3 of overburden were handled--an overburden to coal ratio of 0.75:1.
- In 1974, 110 Mt of lignite was produced. But 226×10^6 m^3 of overburden was handled, and the overburden to coal ratio had increased to more than 2:1 (incidentally, the number of mines has decreased from 19 to 5, which also illustrates higher concentration and unit size).
- Of these amounts, Garsdorf accounted for 42 Mt of lignite and 77×10^6 m^3 of overburden, a total output of 196 Mt of material.
- The Hambach open-pit mine now being developed will surpass these figures, with 45 to 50 Mt of brown coal plus 270 to 300×10^6 m^3 of overburden per year (overburden to coal ratio about 6:1).

This output is due to the continuous and spectacular development of materials handling equipment*, which includes some of the biggest mobile pieces of equipment on land ever built. Some experts claim that an upper limit has been reached as with the biggest prehistoric animals of the secondary era.

By Garsdorf or Hambach standards, Burnham is a relatively small operation; but because of its isolation and environment, most of the operations have to be self-sufficient. For illustration, Table 3 lists the equipment necessary for development and operation of the mine for 25 years (together with some financial indications).

MANPOWER ASPECTS

The total ultimate labor force for Selby has been estimated at 4000; starting with 2000, presumably with about 200 miners per shift at each mine. The resulting fear of "depopulation" of the West Yorkshire mining area and of "overpopulation" of the Selby area led to the decision to scatter the miners around the villages and Selby itself (no "mining suburb").

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*Details are given in the papers of N.V. Melnikov and K.J. Benecke, in this volume.

Table 3. Burnham I gasification mine--mine equipment capital requirements.

Number		Depreciation period [years]
7	70 to 85 m^3 Dragline	25
5	Overburden Drill	25
3	Parting Drill	25
3	Shop-Office-Warehouse Complex	25
-	Shop Equipment	25
-	Electrical Distribution System	25
1	Haul and Access Roads (20 km each)	25
4	Coal Loading Shovel	25
-	Training Facilities	25
2	100 t Crane	25
2	90 t Lowboy Trailer	25
23	135 t Haulage Truck	10
	76 yd^3 Truck	10
4	Front-End Loader	10
3	Water Truck	10
4	Rubber-Tired Dozer	10
2	Road Grader	10
4	Coal Drill (twin mast)	10
2	Ambulance	10
-	Miscellaneous Pit Equipment	10
4	Bulk Anfo Trucks	10
5	Spare Dragline Buckets	10
4	D-4 Bulldozer	5
30	D-9 Bulldozer	5
4	Welding Truck	5
4	Electrician Truck	5
4	Fuel Truck	5
4	Lube Truck	5
7	Wheel Scraper	5

Year	-3	-2	-1	1	2
Annual Total Direct Cost:	$24,008	$55,238	72,236	37,776	3,426

(thousands of 1975 dollars)

The problems are completely different in the Rhine area because of the density of population and the proximity of large cities, and also becuase of the skill required for open-pit mining. A giant excavator can be operated by two men only: the driver, who raises and lowers the bucket wheel, pivots to and fro, and drives the caterpillars, and the man who guides the flow of mass to the conveyor and drives his loading device. Continuous operation, however, requires additional greasers, fitters, and electricians.

For Burnham, the problems are also related to its isolation and the environment of the mine. Table 4 gives the personnel requirements for the Burnham project as an example of such mining operations.

CONCLUSIONS

The above examples illustrate the WELMM approach to coal mining. They provide a basis for better understanding of the systems aspects of water, energy, land, materials, and manpower resources. As more data are collected, detailed statistics are progressively being applied to the energy strategies of the IIASA Energy Program.

Table 4. Burnham I gasification mine--mining personnel requirements.

Year	Quarter	Supervisory	Clerical & Secretarial	Technical	Security	Other*	Equip. Operators	Maint. Mechanics	Construction	
									Skilled	Unskilled
-2	1									
	2	2	1	4			15	7	6	6
	3	2	1	4			15	7	39	31
	4	2	1	4			15	7	45	25
-1	1	11	4	6	7	4	27	14	201	62
	2	26	6	10	7	7	54	24	402	132
	3	41	17	14	7	22	138	59	558	207
	4	57	23	18	7	41	221	98	273	128
1	1	57	23	18	7	41	246	106	121	46
	2	57	23	18	7	41	246	106	102	38
	3	57	23	18	7	41	246	106	102	38
	4	57	23	18	7	41	246	106	102	38
2	1	75	23	18	7	41	344	148	88	32
	2	75	23	18	7	41	344	148	88	32
	3	75	23	18	7	41	344	148	88	32
	4	75	23	18	7	41	344	148	88	32
3	1	75	23	18	7	41	442	190	5	
	2	75	23	18	7	41	442	190		
	3	75	23	18	7	41	442	190		
	4	75	23	18	7	41	442	190		

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WELMM ANALYSIS OF COAL PROCESSING, TRANSPORTING, AND CONVERSION SYSTEMS

J.K. Klitz

Introduction

An energy supply chain consists of a network of facilities that extract, process, transport, and convert energy for final end use. The chain begins with the basic fuel resource and terminates with various desirable energy products. Each energy chain is complex, has varying degrees of efficiency, and is capable of being altered as technologies change or as resources are depleted or developed.

The energy chain system of the world has always been dynamic, but is presently undergoing changes as the efficiencies of some of the links are being scrutinized, some being stressed or unstressed, and new links are being added or proposed.

WELMM

It is within this context that the WELMM approach has been developed as a means of analyzing such complex energy supply chains. The WELMM approach is an impact matrix concept and mainly focuses on five limited resources: Water, Energy, Land, Materials, and Manpower. The basic objective is to assess the natural resource requirements of various energy production strategies. The WELMM requirements are those items necessary to construct and operate a particular facility found within the energy chain system. For a more detailed description of the WELMM approach one should refer to Professor Grenon's paper also presented at this conference.

Coal Energy Chain

The coal-to-electricity chain is a well established and employed fuel chain. It is the major foreseeable outlet for coal in the next and coming decades. It is also one of the most complex chains due to events that have transpired in the last decade. Compexities in the coal fuel chain have been added with the increased amount of environmental controls of conventional power plants and the advent of mine mouth power plants and gasification plants.

Potentially, the chain could continue to be expanded as coal liquid refining facilities are added along with combined cycle and fluidized-bed power plants. In addition, as the potential reliance on coal increases, the transportation of coal is being altered as larger quantities of coal are to be transported via unitized train or possible new slurry pipelines.

Hence, it is within this framework that this paper attempts to show the results of applying the WELMM approach to evaluating a portion of the coal-to-electricity chain. A comparison has been made of nine such chains by alteration of the various transportation and conversion systems. Figure 1 illustrates a portion of the coal-to-electricity chain system and those chains evaluated.

Processing and Transportation

The process for producing steam coal acceptable for power plants consists of preparing run-of-the-mine coal by crushing, screening and gravimetric beneficiation. This process is assumed to be a mine-mouth facility.

Being a solid, coal has always been transported in relatively small batch quantities. The size of those quantities continues to be expanded as more unitized coal trains are employed. The advent of the coal slurry pipeline allows for an efficient method of transfer of a solid and a continuous supply method. Consequently, three modes of coal transportation have been considered for comparison: slurry pipeline, unitized trains of 105 hopper cars each, and the same unitized train system but including the expenditure of a single-use, single-track rail line. The distance selected for transfer of coal from processing to the coal-fired power plants is 965 km (600 miles). Tables 1 and 2 give the WELMM resources requirements to construct and operate the processing and transportation systems respectively.*

Conversion to Electricity

For comparison, the following three types of coal-fired power plants were evaluated within the coal-to-electricity chain: conventional-uncontrolled, conventional-controlled, and fluidized-bed.

Environmental constraints continue to be a limiting factor on the use of coal to generate electricity, especially in the USA. Where low sulfur coals (less than or equal to 0.7% sulfur for bituminous coal) are utilized to fire steam boilers, conventional power plants equipped with particulate-removal equipment will continue in use.

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*A majority of the data in these and subsequent tables have their origins in WELMM summary analysis sheets for coal production facilities researched and prepared by Arnulf Grubler of the IIASA staff. This earlier work provided the data necessary for this study.

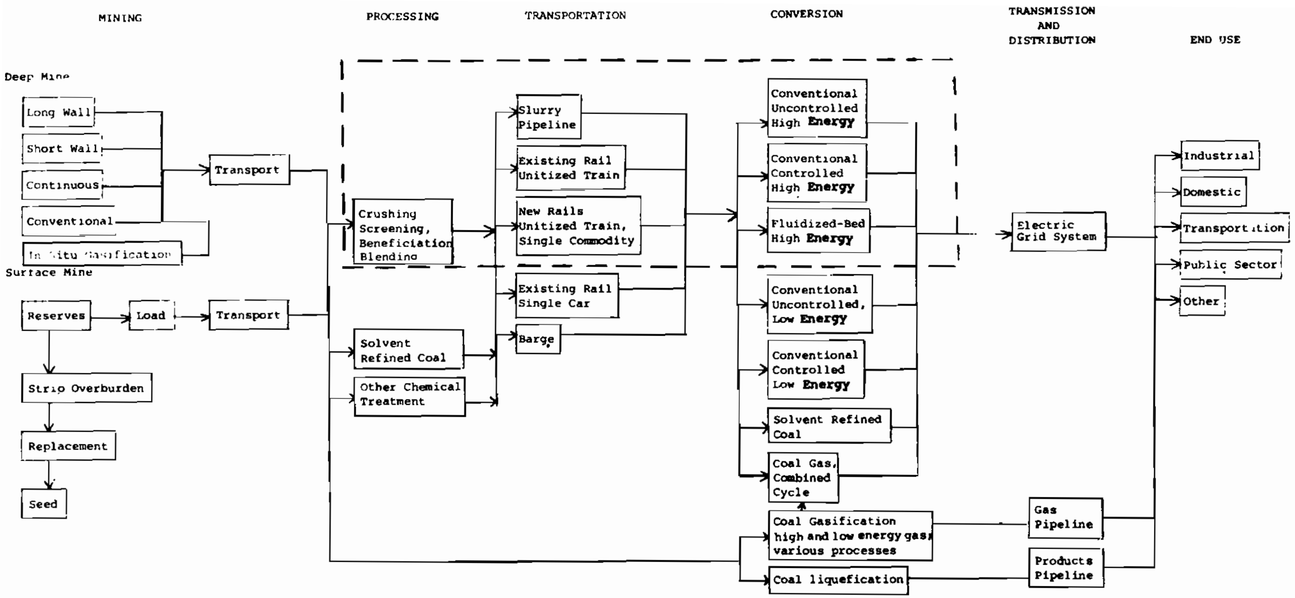

Figure 1. Coal to fuel conversion cycle. The dashed lines define those portions of the energy chains evaluated within this study.

Table 1. Direct resource requirements to construct coal processing and transportation facilities.

Resource	Coal Processing	Transportation System--965 km		
		Slurry Pipeline	Unitized Train	Single Purpose Rail Bed
Water [m^3]	3,916	78,728		
Energy				
Electricity [GJ]		33.86×10^5		
Motor Fuels [GJ]	5.84×10^4	6.21×10^5		
Land [km^2]	0.04	.64		9.15
Exclusive				
Nonexclusive		35.50		
Man Power (Man-years)	138	3,809	30	2,421
Materials [t]				
Concrete	15,807	65,766		
Pipe Tubing < 61 cm Dia	263	3,894		
Pipe Tubing > 61 cm Dia	5	222,650		
Structural Steel	749	5,367		
Reinforcing Steel	789	7,209		
Carbon Steel			3,864	114,217
Alloy Steel			64	
Wood				95,268
Crushed Stone				1,388,000

The environmentally controlled power plant selected for comparison is of the type of technology available in 1985, employing a lime/limestone scrubber process to remove sulfur dioxide from the stack gas. The disposal of the sludge via a settling pond continues to present a major "solid" waste problem.

The coal-fired, fluidized-bed boiler allows for sulfur to be removed in the combustion process itself. Combustion is accomplished in an inert bed of coal ash or lime that rests on a plate of nozzles. Combustion air passes through the nozzles and into the bed causing it to move much as a liquid. The air serves as a combustion source for the finely ground coal that is injected near the base of the fluidized bed. Low operating temperatures between 870 and 980 °C (1600 and 1800 °F) allow for reduced nitrogen oxide emission as compared to conventional boilers. The burning of coal in the presence of limestone is an effective method of removing the sulfur.

Tables 3 and 4 give the direct WELMM resource requirements to construct and operate the above described types of coal-fired power plants respectively.

Table 2. Annual direct resource requirements to operate coal processing and transportation facilities.

Resources	Processing	Transportation System--965 km		
		Slurry Pipeline	Unitized Train	Single Purpose Rail Bed
Water[1] [m^3]	9.05×10^5	2.43×10^7		
Energy [GJ]				
Electricity	1.47×10^5	3.34×10^6		
Motor Fuels	1.85×10^3	0.22×10^4	3.75×10^5	
Land [km^2]				
Exclusive	0.04	0.64		9.05
Nonexclusive		35.50	16.0	
Man Power [Man-years]	237	214	124	271
Materials (US $ 1975)[2]				Negligible
Metal Products	63,115	2,9,105	54,360	
Equipment	228,510	1,546,290	2,385,800	
Chemicals	10,037	1,072,036	--	
Misc.	15,384	79,704	116,874	

[1] Water intake; not necessarily consumption.

[2] Cost data were provided here and in some of the subsequent tables because the actual quantities of material and equipment to operate the transportation facilities were not available. The cost data are later used in Table 8 to gain some insight in the comparison of chains over a thirty year operating period.

Comparison of Chains--Construction/Operating

For comparison purposes, each chain contained only one coal-fired power plant of a normalized size of 800 MW(e). Hence the demand for coal from the mine for each chain is dependent upon the operating efficiency of each facility of the chain (see Table 5) and the resources recovered from each stage. As a result, the number of facilities for each chain (excluding the power plant) was adjusted to provide the necessary coal demand of one power plant.

Table 5 also indicates the weaker links of the coal-to-electricity chains, relative to the efficiencies of each stage. If significant improvements of efficiencies of the chain are to be made they must come in the areas of deep mining processing, and conversion. Already there are examples of improvements being seen in the area of mining and not specifically reflected in Table 5.

Table 3. Direct resource requirements to *construct* different types of coal-fired power plants.

Resource	Coal-fired Power Plant (800 MW(e)) Type		
	Conventional; Uncontrolled, High Energy	Conventional; Controlled, High Energy	Fluidized-Bed
Water [m^3]	56,421	66,813	45,800
Energy [GJ]			
Electricity	2.32×10^5	2.96×10^5	1.00×10^4
Motor Fuels	7.39×10^5	8.18×10^5	6.57×10^5
Land [km^2]			
(Exclusive)	0.8	3.44	1.32
Man Power [Man-years]	2499	3047	2500
Materials [t]			
Concrete	103,401	100,954	87,500
Finished Steel	7,561	9,992	8,660
Reinforcing Steel	13,055	26,308	16,990
Nonferrous Metals	48	800	783

Table 4. Annual direct resources to *operate* different types of coal-fired plants.

Resources	Coal-fired Power Plant (800 MW(e)) Type		
	Conventional; Uncontrolled High Energy	Conventional; Controlled High Energy	Fluidized-Bed Atmospheric, High Energy, 1981
Water [m^3]			
Intake	14.6×10^6	9.35×10^6	11.82×10^6
Consumed	7.0×10^6	7.8×10^6	7.39×10^6
Energy [GJ]			
Electricity			
Motor Fuels	8.44×10^3	2.80×10^5	1.82×10^5
Process Heating		5.82×10^5	
Land [km^2]			
(Exclusive)	0.8	3.44	1.32
Man Power [Man-years]	109	120	119
Materials			
Limestone [t]		333,000	506,142
Metal Products [US $ 1975]	1,201,300	1,799,547	962,845
Equipment [US $ 1975]	750,710	1,124,563	942,407
Chemicals [US $ 1975]	--	--	324,733
Misc. Materials [US $ 1975]	65,190	95,654	40,875

Table 5. Operating efficiencies of coal-fired electrical systems, USA, as given in percentages

	Extraction		Processing	Transportation		Conversion			Trans-mission[4]
	Deep	Surface		Slurry	Rail	Conventional Uncontrolled	Conventional Controlled	Fluidized Bed	
Resource Efficiency[1]	57	80	75.0[5]	98	99	37.8	38.3	35.7	91.2
Processing Energy[2]	0.8	0.8	0.09	0.49	1.17	0	0	0	0
Resource Energy Efficiency[3]	56.2	79.2	74.91	97.51	97.83	37.8	38.3	35.7	91.2

Source: Council on Environmental Quality, A.E. Uhl, Bechtel Inc., and IIASA.

[1] Percentage energy value entering that remains after that phase of the chain.

[2] Percentage energy content entering each stage of chain.

[3] Percentage resource recovered minus percentage energy input.

[4] Power sold divided by power produced.

[5] Low efficiency percentage represents only that quantity of coal acceptable for coal-fired power plant. An additional quantity of coal is available for other processes.

Using Table 5 and the data provided in the previous tables, one can now determine the total adjusted resources required to construct and operate the various coal chains. Such results follow in Tables 6 and 7. It must be emphasized that these two tables provide the *total* direct resources to construct or operate the entire quantities of facilities or partial facilities represented in each chain and necessary for coal processing, transportation, and conversion.

Total WELMM Systems Analysis

Again, from the data developed in the previous tables one can make a comparison of the various chains over the operating lifetimes of the facilities--assumed to be 30 years. Table 8 gives such results with the replacement of facilities being taken into account where necessary, such as the replacement of hopper cars of the unitized trains. Hence, Table 8 includes not only the resources operating requirements but also the initial and subsequent facility construction requirements. Several significant conclusions may be developed from the WELMM analysis summarized in Table 8, including:

Transportation:

- The slurry pipeline is the lowest consumer of resources over the total thirty year period except for water intake. The water intake for a chain utilizing a slurry pipeline is 1.2 times greater than a chain using a rail system.

- Chains that employ a unitized train system for transporting coal consume twice as much energy, 1.6 times more labor, and incur higher operating expenses for materials than comparable chains that use slurry pipelines.

Conversion to Electricity:

- Chains that employ the conventional controlled power plants with scrubbers consume more than twice as much nonelectrical energy and 4.1 times as much exclusive use land than comparable chains using conventional uncontrolled plants.

- Operating expenses for equipment, materials, and consumables for a conventional controlled power plant employing a unitized train is 1.2 times greater than a noncontrolled chain, and 1.4 times greater for a similar comparison but using a slurry pipeline.

General:

- The total quantity of construction materials is approximately the same when one compares chains of similar power plants or of similar transportation systems, if one excludes the wooden railroad ties and crushed stone to build the single-use rail line.

Table 6. Summary comparison of total resource requirements for *construction* of facilities for alternative coal energy chains (processing, transportation, and convenience).

Resources	Coal-fired Power Plant (800 MW(e)) Type								
	Conventional; Uncontrolled High Energy			Conventional; Controlled High Energy 1985			Fluidized-Bed, Atmospheric, 1981		
	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Rail-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Rail-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Rail-lines
Water [m^3]	63,406	57,897	57,897	73,708	68,292	68,292	53,119	47,389	47,389
Energy [GJ]									
Electricity	4.67×10^5	2.32×10^5	2.32×10^5	5.28×10^5	2.96×10^5	2.96×10^5	2.46×10^5	10	10
Motor Fuels	8.05×10^5	7.61×10^5	7.61×10^5	8.83×10^5	8.40×10^5	8.40×10^5	11.31×10^5	6.81×10^5	6.81×10^5
Land									
(Exclusive)	0.86	0.81	1.45	3.50	3.46	4.08	1.38	1.34	2.01
(Nonexclusive)	2.47			2.44			2.58		
Man Power [Man-years]	2,817	2,597	2,763	3,361	3,144	3,309	2,836	2,605	2,781
Materials [t]									
Concrete	114,078	109,356	109,356	111,494	106,923	106,923	98,810	100,267	100,267
Finished Steel	24,073	13,954	21,807	26,289	16,319	24,086	26,149	9,072	17,388
Reinforcing Steel	13,861	13,352	13,352	27,103	26,606	26,606	17,843	17,310	17,402
Nonferrous Metals	48	48	48	800	800	800	783	783	783
Wood			6,550			6,478			6,936
Crushed Stone			95,439			94,384			101,060

Table 7. Summary comparison of total resource requirements for *operating* the facilities for alternative coal energy chains (processing, transportation, and conversion).

Resource	Coal-fired Power Plants (800 MW(e)) Type								
	Conventional; Uncontrolled High Energy			Conventional; Controlled High Energy 1985			Fluidized-Bed; Atmospheric, 1981		
	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Pipe-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Pipe-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines	Unit Train, Plus Single Use Pipe-lines
Water[1] $[m^3]$	166.4×10^5	149.4×10^5	149.4×10^5	113.6×10^5	96.9×10^5	96.9×10^5	139.8×10^5	121.9×10^5	121.9×10^5
Energy [GJ]									
Electricity	2.89×10^5	0.55×10^5	0.55×10^5	2.85×10^5	0.56×10^5	0.56×10^5	3.06×10^5	0.6×10^5	0.6×10^5
Motor Fuels	0.01×10^5	5.83×10^5	5.83×10^5	2.81×10^5	8.48×10^5	8.48×10^5	1.83×10^5	7.91×10^5	7.91×10^5
Process Heating				5.82×10^5	5.82×10^5	5.82×10^5			
Land $[km^2]$									
(Exclusive)	0.86	0.81	1.45	3.50	3.46	4.08	1.38	1.34	2.01
(Nonexclusive)	2.47			2.44			2.58		
Man Power [Man-years]	216	388	407	225	397	416	232	416	436
Materials									
Limestone [t]				333,000	333,000	333,000	506,142	506,142	506,142
Metal Products [US $ 1975]	1,240,918	1,308,252	1,308,252	1,838,649	1,911,626	1,911,626	1,004,802	1,076,479	1,076,479
Equipment [US $ 1975]	946,488	4,487,087	4,487,087	1,317,792	4,820,563	4,820,563	1,149,751	4,899,984	4,899,984
Chemicals [US $ 1975]	78,395	3,782	3,782	77,369	3,790	3,790	407,763	328,799	328,799
Misc. Material [US $ 1975]	76,674	249,804	249,804	106,989	278,293	278,293	53,035	236,444	236,444

[1] Water intake, not necessarily the consumption.

Table 8. Summary comparison of resources required to *construct* and operate and facilities of alternative coal energy chains (processing, transportation and conversion) for thirty years.

Resources	Coal-fired Power Plant (800 MW(e)) Type								
	Conventional; Uncontrolled High Energy			Conventional; Controlled High Energy, 1985			Fluidized-Bed Atmospheric, 1981		
	Slurry Pipe-lines	Unit Train, Existing Rail-lines[1]	Unit Trains Plus Single Use Rail-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines[1]	Unit Trains Plus Single Use Rail-lines	Slurry Pipe-lines	Unit Train, Existing Rail-lines[1]	Unit Trains Plus Single Use Rail-lines
Water [m^3]	4.99×10^8	4.48×10^8	4.48×10^8	3.41×10^8	2.91×10^8	2.91×10^8	4.19×10^8	3.66×10^8	3.66×10^8
Energy [GJ]									
Electricity	9.14×10^6	1.88×10^6	1.88×10^6	9.08×10^6	1.98×10^6	1.98×10^6	9.43×10^6	1.8×10^6	1.8×10^6
Motor Fuels	0.84×10^6	18.25×10^6	18.25×10^6	9.31×10^6	26.28×10^6	26.28×10^6	6.62×10^6	24.41×10^6	24.41×10^6
Process Heat				17.46×10^6	17.46×10^6	17.46×10^6			
Land [km^3]									
(Exclusive)	0.86	0.81	1.45	3.50	3.46	4.08	1.38	1.34	2.01
(Nonexclusive)	2.46			2.44			2.58		
Man Power [Man-years]	9,297	14,253	14,989	10,111	15,070	15,805	9,796	15,101	15,877
Materials {10^3 t}									
Concrete [10^3 t]	114	109	109	111	107	107	99	100	100
Finished Steel [10^3 t]	24	16	24	26	18	26	26	11	19
Reinforcing Steel [10^3 t]	14	13	13	27	27	27	18	17	17
Nonferrous Metals [10^3 t]				1	1	1	1	1	1
Wood [10^3 t]			7			6			7
Crushed Stone [10^3 t]			95			94			101
Limestone [10^3 t]				9,990	9,990	9,990	5,184	15,184	15,184
Total Operating Material [10^6 US $ 1975] Equipment Expenses	69	181	181	100	210	210	78	196	196

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[1] Assumes 52% of cars and locomotives require replacement during 30 year per Project Independence Study.

[2] These dollar values represent operating expenses only and do not include the above metric tons of construction materials, excluding limestone.

Summary and Conclusions

Summarizing the above, one can generally state that the transfer of coal via slurry pipeline is the least costly method in terms of resource requirements, with the exception of water intake. In addition, as is obvious, the conventional power plant with environmental controls is a greater consumer of resources than a comparable noncontrolled conventional plant. The advanced technology of the fluidized bed plants would provide the benefits of environmental control at a reduced resource cost.

No attempt was made in this paper to differentiate between the quality of water or land nor was any consideration given to the scarcity of water, land, or materials. For our initial purposes this is adequate in providing the necessary data for IIASA's global/regional energy models for the reference case evaluation. But it is continually recognized that as we complete studies of a regional or local nature we must differentiate between the quality and scarcities of such resources. Consequently, in such regional studies, one or more of the general conclusions and summary statements from above could be invalidated. But, in regional as well as global studies the WELMM approach provides an opportunity to evaluate the specific advantages of various processes that are not always self-evident and to quantify those advantages or disadvantages.

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COAL DEVELOPMENT IN DIFFERENT COUNTRIES

FUTURE ASPECTS OF COAL IN AUSTRIA

I. Schmoranz

INTRODUCTION

Energy has achieved a prominent status in today's political and economic discussions. The oil embargo of 1973 did not create this discussion but it helped to focus public and scientific opinion on the field. Today, energy policy and energy modeling is a subject with one of the highest priorities, of which the conferences and seminars dealing with the subject give ample evidence.

What are the specific characteristics of energy that have given it such vital importance?

- Energy is not only an essential factor in the production sector, it is also directly connected with the standard of living. In other words, a cut in energy supply would at least in the short run hinder economic activity with all the problems connected with it, plus have a lowering effect on the standard of living.

- The accelerated development and the changing pattern of the economies in the industrialized countries has had very strong consequences on the development of energy demand. With fixed resources of some energy components it is not difficult to compute how long these reserves will last.

- From the medium and long term point of view we observe a scientific and technological revolution resulting in a transition process. More and more traditional energy is being replaced by nuclear fuel and other new energy sources. Exploring this transition process, we are entering a new area and cannot refer to conclusions drawn from earlier experiences.

- Although the energy sector has some independent features, it is very strongly connected with the other sectors of the economy. The most important link is through supply and demand of energy, the constraints on capital and manpower, and on trade balances.

- The individual consumer or producer does not demand energy as such, but demands the services or characteristics delivered by the energy.

The last point mentioned is important for understanding the transition process in the energy sector, especially the substitution of coal by other energy sources. The services delivered by coal, e.g. heating, are not the only factors influencing its demand. Another is what we call an "index of comfort". Since in an industrialized society with a high standard of living the latter is of increasing importance, the demand for coal, which has in relation to other energy sources such as electricity or heating oil a low index of comfort, will be very strongly affected by it.

INTERNATIONAL ASPECTS

Estimates of world coal reserves vary widely. The Organisation for Economic Co-operation and Development (OECD), estimates the resources at 8700 × 10^{12} toe [1], H. Kahn at 4250 × 10^{12} toe [2].

The absolute level of estimated stock reserves is, however, of secondary importance, since only a small fraction of the estimated resources are interesting from an economic point of view. Though these reserves amount only to 690 × 10^{12} toe, this stock is generally considered to be large enough to meet the coal demand for the next century [3]. The local distribution of coal reserves, which is given in Table 1, shows that about 90% of total reserves are to be found in three countries, namely the USSR, the USA, and China. The important conclusion for the Austrian energy sector is that it is highly unlikely to expect a recessive effect on the economy as a result of shortages of coal.

Table 1. Distribution of world reserves of coal (bituminous and brown coal).

Source: [1]

Region	Proven		Potential		Total	
	[10^{12} tce]	[%]	[10^{12} tce]	[%]	[10^{12} tce]	[%]
America	1175	38	1158	17	2333	24
USA	1062	35	1140	-	2202	23
Africa	55	2	9	-	64	-
Australia/Oceania	260	9	-	-	260	3
Asia	416	14	1200	18	1616	17
Peoples Republic of China	300	10	1200	18	1500	15
Europe	542	18	60	1	602	6
USSR	577	19	4328	64	4905	50
World Total	3025	100	6755	100	9780	100

ENERGY PROJECTIONS FOR AUSTRIA

General Economic Development

General economic development strongly influences energy demand. Naturally the overall growth rate of the economy, the changing structure of the economy, and the development in personal disposable income with the induced changing of consumer habits have considerable consequences on energy demand. It is beyond the scope of this paper, to analyze all these effects. We therefore concentrate on the energy coefficient (i.e. the energy input per unit of output of the different sectors) and the energy demand per capita for the private household sector. These coefficients are a function of all the developments mentioned above and can thus be regarded as a good proxy for them.

The Austrian Economy in the Next Decade

Official estimates for the Austrian economy, which form the basis for the energy projections, give an optimistic picture. Annual growth rates for the next decade (i.e. from 1975 to 1985) of 4% and 3.5% for the following five years are estimated. The economic development of the last half year in Austria and the changing prospects of the economic situation in the world as a whole has had a dampening effect on this optimism. However, growth rates of 3% are still expected to be possible in the long run.

The growth of industrial production, which largely determines the general economic development, will be 5% for the next decade and a little more than 4% for the following half decade. The energy intensive industries will, with the exception of the aluminum industry, grow with a higher rate than the average for industry. This will result in a relatively higher energy demand than would be the case with an unchanged industrial structure.

Projections for Energy Demand

The results of the energy projections are given in Table 2. Total energy input will increase by about 4%, the energy demand of industry by about 2%. These results reflect a declining energy coefficient, since the growth rates for industry will be about 5%.

The increase of demand of the transportation sector is less than the average, whereas households, services, agriculture, and administrations account for increasing shares in energy demand.

The high growth rates in energy demand by the household sector is because the standard of living in Austria has risen substantially in the last decade. At the 4% expected annual increase in GNP, household demand for energy intensive goods--larger flats, better heating, household equipment, more and larger private cars, etc.--will expand thus leading to a more than proportional rate compared with aggregate energy demand.

Table 2. Energy demand projections.

Source: [4,5,6]

	Average annual increase [%]		
	1974-1980	1980-1985	1985-1990
Gross domestic demand	+3.8	+4.1	+3.9
Net domestic demand	+3.2	4.1	3.4
Transformation process	4.5	3.0	3.9
Industry	1.3	2.2	2.1
Transportation sector	3.9	3.6	2.7
Others*	4.8	4.7	5.1

*Households, manufacturing, agriculture, administration, and services.

The increase in industrial demand for energy is unexpectedly low. The latter tendency can partly be attributed to current energy saving measures, which would result in a declining energy coefficient. It is hoped that special effort will be made to introduce such measures in the energy intensive industries.

Energy demand in the transportation sector has been revised slightly in the last years. Two developments make it difficult to estimate the exact future demand. On the one hand, the tendency to larger cars with a higher fuel demand, which is the result of larger incomes per capita, is observed. On the other hand, there exists a tendency to cut down the fuel demand of larger cars. This, in connection with the lower distances traveled per capita, which is certainly the effect of the higher oil prices, works in the opposite direction. Both tendencies together result in an increase in energy demand that is only slightly lower than the increase in total demand.

The structure of the future energy input is given in Table 3. This table shows the declining importance of bituminous coal and lignite as well as that of oil. Water power and natural gas will account for a slightly bigger share, whereas nuclear energy's share will increase from its present 0% to 12.6%. However, these figures were published in September 1976 and since that time a strong antinuclear movement has been formed in Austria, whose activities have led the government to reconsider their projections.

Table 3. Structure of future energy demand in Austria.

	Percentage of total demand				
	Results		Projections		
	1973	1974	1980	1985	1990
Bituminous coal	12.7	13.7	10.6	9.2	7.8
Lignite	6.5	7.0	5.1	3.6	2.7
Oil	56.1	51.1	53.3	48.2	48.3
Natural gas	15.5	17.4	15.9	19.2	18.6
Water power	9.0	10.5	10.6	10.3	9.6
Nuclear energy	0	0	4.2	9.2	12.6
Other	0.2	0.3	0.3	0.3	0.4

To avoid the sharp increase of nuclear energy, considerations are made in two directions. First, to dampen energy demand and to promote energy saving measures, especially in the household sector. Second, to look for alternative energy sources, especially in the direction of new and renewable energy sources.

The Demand for Coal

The projected demand for coal is shown in Tables 4, 5, and 6. They indicate an overall decreasing importance of all sorts of coal with one exception. Coke input into the transformation process shows an increase which means that the demand for pit coal will only decrease by about 10%. The demand of industry and households will decrease substantially, and the demand of the transportation sector will be reduced to almost nothing.

Table 4. Demand for pit coal [10^9 kcal].

	Results		Projections		
	1973	1974	1980	1985	1990
Industry	308	546	245	175	105
Transportation	1,043	763	175	98	91
Rest	2,562	2,121	1,200	1,750	1,750
Transformation					
Coke production	16,051	16,268	16,100	16,100	16,100
Electricity production	161	560	70	70	70
Total	20,125	20,258	18,690	18,193	18,116

Table 5. Demand for brown coal [10^9 kcal].

	Results		Projections		
	1973	1974	1980	1985	1990
Industry	777	1,295	1,085	630	350
Transportation	70	70	35	28	21
Rest	4,410	4,312	3,500	2,800	2,100
Energy	189	161	105	70	70
Transformation					
Gas production	203	182	0	0	0
Electricity production	8,204	8,666	8,666	7,910	7,910
Total	13,853	14,686	13,391	11,438	10,451

Table 6. Demand for coke [10^9 kcal].

	Results		Projections		
	1973	1974	1980	1985	1990
Industry	8,645	10,122	10,500	10,150	9,975
Transportation	98	84	84	70	35
Rest	5,453	4,914	4,200	3,500	3,500
Transformation	4,851	5,285	6,160	9,310	10,500
Total	19,047	20,405	20,944	23,030	24,010

The same development is projected for brown coal, where the input of brown coal for electricity production accounts for nearly 80% of the total.

Estimated Coal Reserves in Austria

The estimated coal reserves for Austria are given in Table 7. Only half of the indicated reserves, however, are economically interesting, since the extraction costs of most of the known reserves are too high. Fettweis [7] suggests only 51×10^9 t with a resultant average extraction lifetime of 13.5 years. The future extraction of coal is therefore going to decline according to the planning figures of the mining enterprises. These are, however, questionable especially because of the uncertain future prospects of nuclear energy. Coal is one possible substitute and thus, the development of nuclear energy also affects the development of coal.

Table 7. Estimated coal reserves for Austria [10^9 t].

	Identified and inferred	Hypothetical	Prospective
Bituminous	1	3	6
Brown coal	152	58	159

Imports of Coal

The projected import of coal is given in Table 8. Pit coal must be imported completely, since no domestic production exists. The import of brown coal and coke will rise, the latter by about 50%.

Table 8. Imports of coal [10^3 t].

	1976	1980	1985
Bituminous	2800	2670	2599
Coke	1000	1292	2590
Brown coal	650	828	718

SUMMARY

The projections for global energy demand of Austria, covering the period 1975 to 1990, show an annual increase of 4%, which is about the same as the expected growth rate of the GNP.

This average figure is the result of diverse tendencies exhibited by the different sectors in the economy. A more than average increasing demand for energy is expected in the private household and service industry sector, and a less than average increasing demand is expected in industry. The latter tendency can partly be attributed to current energy saving measures in the industrial sector, which would result in a declining energy coefficient (i.e. energy input per unit output of industry). At the 4% expected annual increase in GNP households demand for energy intensive goods--larger flats, better heating, household equipment, more and larger private cars, etc.--will expand thus a leading to a more than proportional rate than the rise in aggregate energy demand.

The projected structure of energy supply shows a decreasing importance of coal. The percentage of coal in total energy demand which at present is about 10%, will fall to about 5% in 1990. This 5% figure is, however, slightly misleading, since 4% out of the 5% will be required as an input into the transformation process, especially in electricity generation. Only 1% of total energy demand by the final users will be covered by coal.

In addition, the progressively decreasing importance of coal as an energy source reflects the fact that coal seen from a purely economic point of view is certainly an inferior good. That means that with rising national income, both industry and the private sector will tend to substitute coal by superior energy sources. However, existing coal resources should be considered as a strategic reserve good, important in cases of supply shortages in other energy sources or retardations in the development and utilization of new energy sources, e.g. nuclear and solar energy.

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OUTLINE OF A MATHEMATICAL-LOGICAL MODEL OF THE FUEL-ENERGY SYSTEM

V. Ehrenberger, A. Fajkoš, and L. Petráš

INTRODUCTION

A system-theoretic analysis of problems, characteristic for the designing of energy resources development models, provides several important requirements to be satisfied by any applicable modeling approach. Two aspects of this fact will be introduced, of both practical and theoretical importance. Further, some conclusions will be drawn in terms of requirements to be imposed on the modeling techniques. Finally, a few examples of handling conditions and relations are given, rather typical for the existing energy system and its development.

Mining Technologies

A major portion of the country's primary energy resources is provided by the coal mining industry and this will be true for the foreseeable future. The modeling of reasonable ways and possibilities of coal output development is characterized by the existence of specific conditions which are due to current mining technologies. Such conditions are sometimes called "mining-logic" [2,3,4,5]. This term stands for clear-cut qualitative (logical) conditions and relations--usually very important--that if neglected would cause (and, in fact, often do cause) an unacceptably large distortion of the situation to be modeled and would thus lead to inapplicability of the resulting model. Naturally, quantitative conditions and restrictions are also present so that conditions of both types must be incorporated into our mathematical model.

Modeling Complex Economic Systems

The development of energy resources represents a complex economic system. A systematic and effective application of both modeling techniques and computers to the control of vast economic systems requires the solution of many problems. These problems could not be completely solved in the past and relatively short time period but their solution was then not as urgently needed as may be the case now. Some work in this direction has been done by J. Bouška and interesting results can be found in [1]. It is evident that designing a large single model to describe an extensive economic system is impracticable, extensive as the model may be, for various reasons:

- The excessively laborious and hard to survey design of an extremely extensive model entails difficulties not easy to overcome, connected with the debugging of a defective model with many faults.

- There are difficulties in the numerical specification of very extensive models.

- The numerical work with the model is not detailed enough.

- It is difficult to interpret the computated results.

- There is a hierarchical structure of economic problems necessitating several organizational levels to be incorporated in the model.

A natural approach to this situation is the design of a system of models, i.e. a set of both models and relations between them defining the interdependence between the inputs and outputs of individual models. The system of models reduces the natural incompatibility of practical managerial requirements with the capabilities of modeling techniques and computers [1].

PROPERTIES OF MODELING METHODS

We are not going to consider in any detail the interesting and complex questions involved in calculating a system of models, but will confine ourselves to some characteristic requirements for the design of the top level (pilot) submodel of the system. The realization of these requirements should (as a consequence of the hierarchical structure of the modeled system) also facilitate substantially both the design of the system of models and its operational application.

Any useful modeling technique should:

- Enable a ready and lucid formalization of a very wide area of real-life situations, conditions and relations of diverse nature; the logical conditions and relations should be stressed (universally);

- Promote an active and systematic collaboration between the professional system analysts, etc., and the responsible manager of his staff (proper distribution of work, interpretation of results, even partial ones, and/or preliminary formulation of substantial circumstances);

- Be sufficiently uniform to facilitate the transition between individual submodels, above all those of different hierarchical (organizational) levels and to promote the necessary aggregation (uniformity).

METHOD OF MATHEMATIC-LOGICAL MODELING (MLM METHOD)

The above requirements are well satisfied by the MLM method described in more detail in [2,3,4,5]. It consists of a set of algorithms and computer programs and its frame is produced by a system of logically related procedures based on a suitable combination of mathematical-logic and Boolean algebra.

The basic steps of the entire procedure can be formulated as follows:

Step 1

Analyze the whole problem and formulate verbally (as precisely as possible) all substantial circumstances, requirements, conditions, and relations.

Step 2

State and define "partial variants", i.e. alternative possibilities of the partial links (in our case the partial links of the resource side and of the consumption side are taken separately).

Step 3

Formalize the verbally stated conditions etc. from Steps 1 and 2, i.e. write them in one of the following forms:

- logical (PL),
- Boolean (B),
- combined (C),
- pseudo-Boolean (PB), see [6].

The particular form is chosen from among the four possibilities in such a way that the respective formalization is as simple and easy as possible. The rewriting, if necessary at all, is left for the next step.

Step 4

If there are conditions of the PL, B, or C form, they are all rewritten in the PB form.

Step 5

Solve the system of pseudo-Boolean equations and/or inequalities obtained in Step 4, with the use of a set of computer programs described in [7]. This results in the set of all feasible variants that appear in a very convenient form from the viewpoint of the subsequent economic interpretation of results, namely, the form of "disjoint families of solutions" [6]. The term "feasible variant" stands for every combination of the partial variants from Step 2 that satisfy the system of conditions of Steps 1 and 2, formalized in Step 3.

Step 6

Interpret the set of feasible variants that can be substantially facilitated by the convenient form of solution set of Step 5.

Step 7

If the analysis of feasible variants brings about the need to revise the conditions originally assumed (such as adding new conditions or changing some of the conditions of the original system, or canceling some restrictions, etc.), go back to Step 1.

Step 8

If the analysis of Step 6 proves the adequacy or even necessity of optimizing calculations (preceding the interpretation of variants), appropriate criteria are defined in order to facilitate a comparison of the variants of Step 5.

Step 9

Formalize the criteria of Step 8 analogously with the conditions and relations formalized in Step 3. This procedure produces a pseudo-Boolean function (generally nonlinear).

Step 10

Perform optimization calculations by using the above mentioned set of programs [7].

Step 11

Interpret the results obtained, etc.--see Figure 1. This concise description should be supplemented by a few remarks.

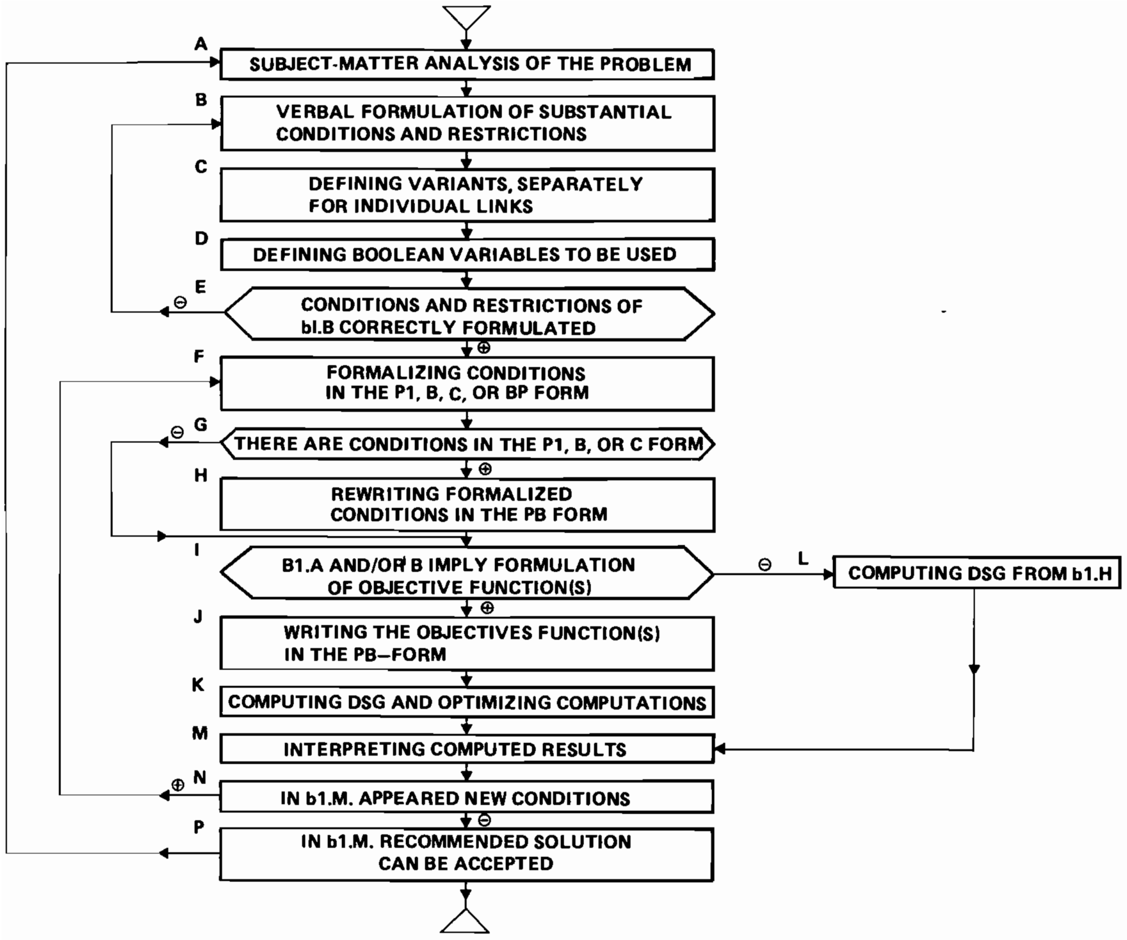

Figure 1. Outline of the MLM method procedure.

It can easily be proved that every function $f:\{0,1\}^n \rightarrow \{0,1\}$ can be given an equivalent PB form [6,8]. This fact is of extreme importance because it ensures applicability of Steps 4 and 6.

Much more difficult is the problem presented by Step 5. Here systems of pseudo-Boolean equations and/or inequalities are computed by using programs based on the Hammer-Rudeanu algorithm [6]. This is still a disputed point among specialists [9], but unsettled as it may be, the programs have proved reliable and given faultless results whenever applied [7,9]. The set of programs is capable of further development. Such development must be very effective being promoted by the rapid progress in computers.

The third point relates to Steps 3 and 5 jointly. Speaking about a system of equations and/or inequalities, we usually have in mind a system of *simultaneous* relations. If there are n such relations with M_i, the solution set of the i-th, then the solution set of the system is

$$M = \bigcap_{i=1}^{n} M_i \qquad \text{(see Figure 2a)}.$$

Real situations connected with the development of a fuel-energy system often lead to a system of conditions (and thus also of PB relations) with another, more complicated logical structure.

Using a quite simple illustration, we can take a system as shown in Figure 2b. In this case one gets

$$M = \bigcap_{i=1}^{8} M_i \cap \Big(\bigcap_{i=9}^{10} M_i \cup M_{11}\Big) \cap \Big(\bigcup_{i=12}^{13} M_i\Big) \cap \bigcap_{i=14}^{18} M_i \quad .$$

The system of programs described in [7], however, enables the solution of even more general systems of equations and/or inequalities. Numbering the individual relations in a corresponding manner is all that is needed in this case (see Figure 2b):

(P1) - (1)

(P2) - (2)

.
.
.

(P8) - (8)

(P9) - (9.1.1)

(P10) - (9.1.2)

(P11) - (9.2)

(P12) - (10.1)

(P13) - (10.2)

(P14) - (11)

(P15) - (12)

(P16) - (13)

(P17) - (14)

(P18) - (15)

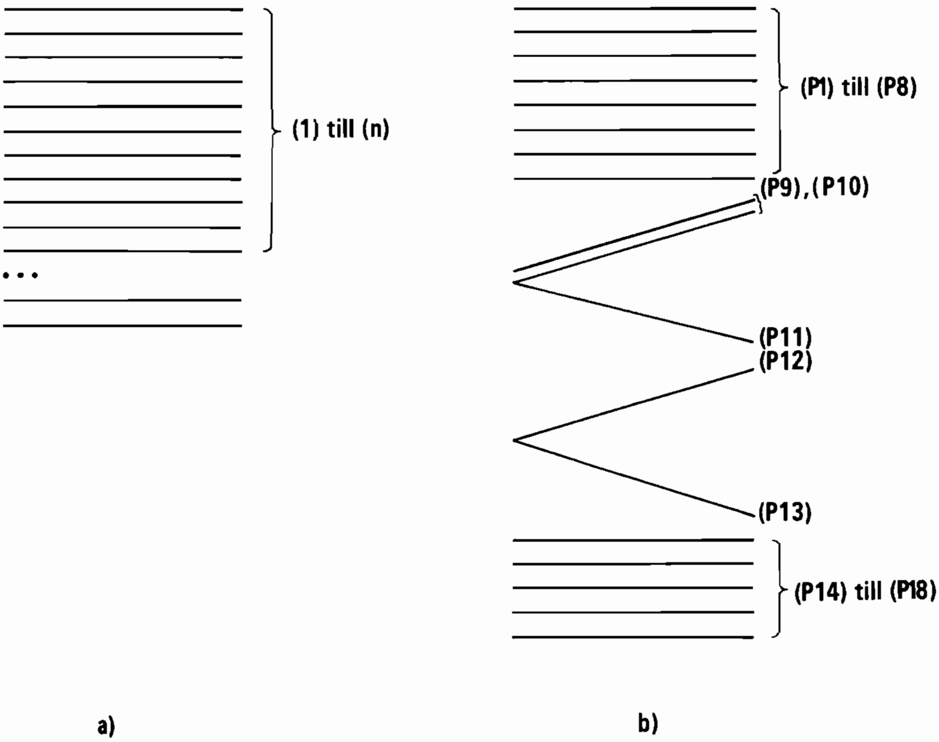

Figure 2. Structure of the PB relations system;

(a) Simultaneous system, $M = \bigcap_{i=1}^{n} M_i$;

(b) System of a more general logical structure,

$$M = \bigcap_{i=1}^{8} M_i \cap (\bigcap_{i=9}^{10} M_i \cup M_{11}) \cap (\bigcup_{i=12}^{13} M_i) \cap \bigcap_{i=14}^{18} M_i \ .$$

Now the given system can be immediately punched for the computer. The relations have to be written in a way ensuring the pair-wise disjointness of corresponding branches. The following is an example for the case shown in Figure 2b:

$$M_9 \cap M_{10} \cap M_{11} = \emptyset \quad , \qquad M_{12} \cap M_{13} = \emptyset \quad .$$

One can see from the expression for M and from Figure 2b that designing the feasible solution set M consists in our case in the solution of four pair-wise disjoint PB equations and inequality systems and in taking unions of these four sets (possibly empty).

The typical features of the MLM method significant for the structure and numerical solution of the model can now be summarized:

- Requirements for the incorporation of various conditions and relations into the model (logical and quantitative conditions) can be properly satisfied;
- Conditions leading to nonlinearity of resulting relations need not be avoided, nor do constraints on the form and outputs of the submodels used have to be prohibitively strict (linearity, continuity);
- The system of restrictions need not be logically decomposed with the aim of obtaining an admissible type of resulting models;
- The numerical solution can be considerably demanding (computer time, capacity, computer reliability, etc.) and the scope (volume) of the results increases according to the model extent. For this reason it is vital to choose and to define the variables and partial variants as well as the aggregation degree most carefully.

EXAMPLE

The form of the model and the way it is compiled can be best shown by an example. Anyhow, it is evident that the definition of the single partial variants and relations must be preceded by a detailed subject analysis (see Steps 1 and 2).

Changes accepted during the analysis of Steps 1 and 2 and entailing a revised definition of partial variants, another aggregation degree, a change of conditions imposed on feasible variants, perhaps some additional conditions (which essentially leads just to a change in the form and numerical values of matrices A and B^k in Tables 1 and 2) should cause no particular difficulties.

The form of the model, the way it is compiled, and its numerical solution, and the form of the results and the way they are interpreted will remain unchanged.

A reliable basis for specifying research tasks to correspond with the model conception will be given. (Contents and form of the outputs of the individual submodels are derived directly from the requirements of the top level (pilot) submodel.)

The symbols used in the formalization of conditions and relaions are defined in Tables 1 and 2. The symbols x_i $(i = 1,2,\ldots,n)$ represent the Boolean variables (n is the number of development variants at the source side - Federal Ministry of Fuel and Energy (FMPE)) defined as follows:

$$x_i = \begin{cases} 1 & \text{for variant } i \\ 0 & \text{for any other case} \end{cases} .$$

Quite analogous are the variables y_i^k introduced where k gives the number of the sector (consumer). The system of 1 + r equations follows directly from the definitions

$$\sum_{i=1}^{n} x_i = 1 \quad ,$$

$$\sum_{i=1}^{m_k} y_i^k = 1 \qquad (k = 1,2,\ldots,r) \quad , \tag{s_1}$$

where r is the number of consumers (sectors) with the exception of FMPE, and m_k is the number of variants of the consumer k. The feasible variants are, generally speaking, defined by various limits such as:

The limit of the total investments involved is L_1. This condition has the following form:

$$\sum_{i=1}^{n} b_i^{x,12} x_i + \sum_{i=1}^{m_k} \sum_{k=1}^{r} b_i^{k,12} y_i \le L_1 \quad . \tag{1}$$

Table 1. Resources - Federal Ministry of Fuel and Power Matrix A ≡ (a_i^j).

Variant	Symbol of the Variable		Bituminous coal				Brown coal		Nuclear	Import			Elec. energy	Heat
			Total Mt	Coking Mt	Other Mt	Other 10^6 MJ	Mt	10^6 MJ	10^9 kWh	Crude oil Mt	Gas 10^9 m^3	Elec. energy 10^9 kWh	10^9 kWh	10^6 MJ
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	x_1	Constraints	a_1^1	a_1^2	a_1^3	a_1^4	a_1^5	a_1^6	a_1^7	a_1^8	a_1^9	a_1^{10}	a_1^{11}	a_1^{12}
2	x_2		a_2^1	a_2^2	a_2^3	a_2^4	a_2^5	a_2^6	a_2^7	a_2^8	a_2^9	a_2^{10}	a_2^{11}	a_2^{12}
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i	x_i		a_i^1	a_i^2	a_i^3	a_i^4	a_i^5	a_i^6	a_i^7	a_i^8	a_i^9	a_i^{10}	a_i^{11}	a_i^{12}
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n	x_n^1		a_n^1	a_n^2	a_n^3	a_n^4	a_n^5	a_n^6	a_n^7	a_n^8	a_n^9	a_n^{10}	a_n^{11}	a_n^{12}

Table 2. Consumers - Branch k Matrix $B^k \equiv (b_i^{k,j})$.

Variant	Symbol of the Variable		Bituminous coal				Brown coal		Import		Elec. energy	Heat	Man-power	Invest-ment	Other imports	
			Total Mt	Coking Mt	Energy Mt	Energy 10^6 MJ	Mt	10^6 MJ	Crude oil Mt	Gas 10^9 m^3	10^9 kWh	10^6 MJ	-	10^6 Kčs	10^6 Rub.	10^6 $
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	y_1^k	Constraints	$b_1^{k,1}$	$b_1^{k,2}$	$b_1^{k,3}$	$b_1^{k,4}$	$b_1^{k,5}$	$b_1^{k,6}$	$b_1^{k,7}$	$b_1^{k,8}$	$b_1^{k,9}$	$b_1^{k,10}$	$b_1^{k,11}$	$b_1^{k,12}$	$b_1^{k,13}$	$b_1^{k,14}$
2	y_2^k		$b_2^{k,1}$	$b_2^{k,2}$	$b_2^{k,3}$	$b_2^{k,4}$	$b_2^{k,5}$	$b_2^{k,6}$	$b_2^{k,7}$	$b_2^{k,8}$	$b_2^{k,9}$	$b_2^{k,10}$	$b_2^{k,11}$	$b_2^{k,12}$	$b_2^{k,13}$	$b_2^{k,14}$
. . .																
i	y_i^k		$b_i^{k,1}$	$b_i^{k,2}$	$b_i^{k,3}$	$b_i^{k,4}$	$b_i^{k,5}$	$b_i^{k,6}$	$b_i^{k,7}$	$b_i^{k,8}$	$b_i^{k,9}$	$b_i^{k,10}$	$b_i^{k,11}$	$b_i^{k,12}$	$b_i^{k,13}$	$b_i^{k,14}$
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m_k	$y_{m_k}^k$		$b_{m_k}^{k,1}$	$b_{m_k}^{k,2}$	$b_{m_k}^{k,3}$	$b_{m_k}^{k,4}$	$b_{m_k}^{k,5}$	$b_{m_k}^{k,6}$	$b_{m_k}^{k,7}$	$b_{m_k}^{k,8}$	$b_{m_k}^{k,9}$	$b_{m_k}^{k,10}$	$b_{m_k}^{k,11}$	$b_{m_k}^{k,12}$	$b_{m_k}^{k,13}$	$b_{m_k}^{k,14}$

Similarly, let the number of workers in the sum for all sectors be limited by L_2. Then

$$\sum_{i=1}^{n} b_i^{x,11} x_i + \sum_{i=1}^{m_k} \sum_{k=1}^{r} b_i^{k,11} y_i \le L_2 \quad . \tag{2}$$

The overall limits for imports--see columns 16 and 17 of Table 2--are written in the same way.

The next series of conditions must ensure that consumer requirements do not exceed the availability of resources. Let us take the following situations as an example: sectors k_1, k_2, and k_3 require brown coal. The following inequalities must hold; for the tonnage:

$$\begin{aligned} &\sum_{i=1}^{m_{k_1}} b_i^{k_1,5} y_i^{k_1} + \sum_{i=1}^{m_{k_2}} b_i^{k_2,5} y_i^{k_2} + \sum_{i=1}^{m_{k_3}} b_i^{k_3,5} y_i^{k_3} \\ &+ \sum_{i=1}^{n} b_i^{x,5} x_i - \sum_{i=1}^{n} a_i^{5} x_i \le 0 \quad , \end{aligned} \tag{3}$$

and for the quantity of heat:

$$\begin{aligned} &\sum_{i=1}^{m_{k_1}} b_i^{k_1,5} y_i^{k_1} + \sum_{i=1}^{m_{k_2}} b_i^{k_2,5} y_i^{k_2} + \sum_{i=1}^{m_{k_3}} b_i^{k_3,5} y_i^{k_3} \\ &+ \sum_{i=1}^{n} b_i^{x,5} x_i - \sum_{i=1}^{n} a_i^{x,6} x_i \le 0 \quad . \end{aligned} \tag{4}$$

The relations between the variants of individual sectors, however, may differ substantially from those mentioned here as typical examples and written in the form of PB relations (S_1), (1), (2), (3), and (4). They can be "deeper" and need only have the character of quantitative constraints and conditions. Nevertheless, they can well be equally important in relation to a suitable representation of reality.

Let us give an example for such a "logical" or "qualitative" relation: variant 3 of sector 1 and variants 1 and 2 of sector 2 are based on an extensive and expansive development of production technologies. Such development requires both high investments and import means. On the other hand, these variants entail a reduction of specific fuel-energy consumption and an increase in labor productivity. To be reasonably utilized, such new progressive technologies must be applied also in other suitable sectors, say in sector 3, i.e. in sector 3 variant 1 cannot be applied with a less progressive production process.

This condition can be written in PL form (Step 3)

$$\left(Y_3^1 \vee Y_1^2 \vee Y_2^2\right) \Rightarrow \neg Y_1^3 \quad ,$$

and rewritten (Step 4) into equivalent PB form

$$y_3^1 + \bar{y}_3^1 y_1^2 + \bar{y}_3^1 \bar{y}_1^2 y_2^2 - \bar{y}_1^3 \leq 0 \quad , \tag{5}$$

where by definition

$$\bar{y} \equiv 1 - y \quad . \tag{6}$$

Based on Steps 1 and 2, all other conditions and relations considered essential for the model (Step 4) can be written in a similar way and one obtains the model in the form of a system of PB equations and/or inequalities, i.e. a system of relations each of which has the form:

$$\sum_i a_i \tilde{x}_{i_1} \tilde{x}_{i_2} \ldots \tilde{x}_{i_{n(i)}} \overset{<}{\underset{>}{=}} \alpha_i \quad , \tag{7}$$

where a_i, α_i are real numbers,

$\tilde{x} = x$ or $\bar{x}$ (see also (6)), and

x is a Boolean variable.

If we denote the system of remaining PB relations by (S_2), the resulting model receives the form of the PB relation system

$$\{(S_1),\ (1),\ (2),\ (3),\ (4),\ (5),\ (S_2)\}$$

with the total number of variables

$$n + m_1 + m_2 + \cdots + m_r \quad .$$

CONCLUSION

The MLM method leading to a system of BP relation of type (7) seems to be an adequate technique for the modeling efforts in question. It appreciably facilitates the incorporation of diverse types of real system conditions into the model to be built.

A system of computer programs has been worked out that makes the use of the compiled model possible in practice [7,9], although opinion is not yet uniform on the efficiency of the numerical solutions of more extensive systems [6,7,9]. However, one can expect that the ongoing development of computer programs coupled to rapid computer development should bring a positive answer to this question.

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EVALUATION OF MODELING EFFORTS IN THE DEVELOPMENT OF CZECHOSLOVAKIA'S FUEL-ENERGY SYSTEM

V. Ehrenberger, A. Fajkoš, and A. Roček

INTRODUCTION

The Sixth Five-Year Plan of Czechoslovakia's national economy has already included the first stage of the solution to the problem connected with the changed external conditions of the fuel-energy system development. But the solution as a whole, covering a time period of 15 to 20 years, represents a most complex problem and the related work has to be intensified and deepened substantially. The fuel-energy system of the country has always been considered one of the most complex facets of economic development [3,4,5,6,7,8].

The past development of the fuel-energy system has some outstanding features of great significance to its future direction. During the first 10 to 15 postwar years the development of the fuel-energy system was secured solely by increments of the domestic fuel and energy sources by the enormous extent of construction of deep and opencast coal mines. In the 15 year period ending in 1975, the role of external relations increased considerably. During 1965 to 1970 the increment of imported fuel-energy sources (realized mostly in hydrocarbons) was higher than the overall increase in the consumption of fuels and energy of the national economy.

Let I be the initial import of fuel-energy sources,

ΔI, the import increment,

D, the initial domestic fuel-energy sources,

ΔD, the domestic sources increment,

S, the initial overall consumption of fuel and energy in the national economy, and

ΔS, the overall increase of fuel and energy consumption in the national economy.

Then for the time period mentioned

$$\Delta I > \Delta S \quad .$$

Since

$$S + \Delta S = D + \Delta D + I + \Delta I \quad ,$$

and since also

$$S = D + I \quad ,$$

we get

$$\Delta S = \Delta I + \Delta D \quad ,$$

and thus also

$$\Delta D = \Delta S - \Delta T < 0 \quad .$$

As can be seen the volume of the domestic fuel-energy sources in the national economy decreased during the time period in absolute terms.

This relation did not continue in the next time period. On the contrary, in 1976 to 1980 the following situation is supposed:

$$\Delta S' \doteq 2\Delta S \quad ,$$

whereas

$$\Delta D' \doteq \frac{1}{3}\Delta S' \quad .$$

The individual components of the fuel-energy system development are interrelated. These relations have some generally valid features as well as some specific qualities due to local conditions. Some of these relations will be dealt with in the next section. There it will be evident that any chosen system-theoretical or modeling approach will be generally acceptable only if it enables the principal relations and conditions to be expressed sufficiently accurately.

PRINCIPAL RELATIONS IN CZECHOSLOVAKIA'S FUEL-ENERGY SYSTEM

The development shown in Table 1 may provide the preliminary basic orientation.

Table 1.

Year	1960	1965	1970	1975	1980
100 I/S	10.9	18.7	25.7	34.0	39.7

Even for the forseeable future a decisive role is to be maintained by coal production which has its specific trend given by

- the present state of coal output development at individual coal deposits,
- the exhaustion rate of coal reserves (the method of evaluating coal reserves in the Czechoslovak region of the Upper Silesian Basin is described in [2]),
- technical progress in coal production, and
- dependence on the whole national economy.

The increase of resources is concentrated in brown coal, the total output of which should approach 100 Mt as early as 1980. This increase is all by opencast mining. At the same time coal output will decline at some expiring deposits. The opencast mines' output of brown coal is further characterized by the growth of the overburden coal ratio (m^3/t) which will be about 50% between 1970 and 1990.

To achieve the required coal output it is necessary to extend the mechanization of mining; in system-theoretical and modeling efforts the real relation between the mining subsystems and the subsystem represented by the production of machine equipment for opencast mining must be respected. An analogous relation concerns underground coal mining too. This implies that the model has to be built in a way ensuring that the resulting variants include only possible combinations of variants of all relevant subsystems.

We are not going to deal systematically with the definition of all essential relations of this kind--it would require too much space. However, some significant relations are worth mentioning.

Let us adhere to coal production for the moment. At present, the following problem is being studied: a reevaluation of exploitation of black coal reserves under more difficult conditions and from seams of lesser thickness is being carried out. As a result new variants arise characterized by different output volumes in the fixed years and associated with other subsystems variants.

Similarly, system relations connected with problems of a radical increase in the utilization of oil as a chemical raw material are being studied. Outstanding and broad interrelations occur in the field of rationalization of electric energy production with the aim of reducing the specific consumption of primary energy sources.

It is evident that even the above mentioned interrelations could not be completely realized in models constructed up till now. We come back to this question later in the paper where the cooperation of individual links of the Czechoslovak scientific research basis acting, to some extent, in the field of modeling the development of the fuel-energy system will be discussed. Before doing so, we shall characterize briefly some model solutions.

CHARACTERISTICS OF SOME MODELS

Mathematical Model of the Power Economy as a Whole and of its Main Components [1]

The task was to find a model that gave the optimum structure of the energy balance, i.e. a balance that would cover the given fuel and energy demand of the national economy at minimum cost without violating the constraints on individual energy sources.

Here, the existence of variants is to be understood as follows:

- Deriving some energy forms and carriers from various technological processes or with different parameters (electricity, heat, gas).

- Possible substitution of fuel bases for gaining some energy forms and carriers (electricity, heat, the raw material basis for pyrolysis, coke oven heating, coal gas production).

- Possible substitution of some energy forms and carriers in the final consumption in some processes and services (pig iron, rolling mills, forges, cast iron, cement, ammonia, road transportation, etc.).

- Different possible patterns of the yield of some energy processes (hard and brown coal preparation).

- Possibility of various proportions between domestic and imported energy sources, etc.

The above problem was formalized as a minimization problem of linear programming. The constraints used were of two types, the requirement vector, determined by the final effective consumption of energy forms and carriers, and the vector of limiting energy sources. The objective function was set up as the sum of social expenses. The optimization model consists of 89 equations (energy forms and nonenergy products) and 176 variables. The number of technical coefficients in the matrix amounts to 676. The model variables describe the energy and nonenergy processes as well as variants defined within these processes.

By using this model, computations of the optimal variant, according to several scenarios were carried out. This work represents the first attempt at applying an optimization model to the energy economy of Czechoslovakia as a whole.

Mathematical Model for the Future Development of a Coal District [12]

This model is representative of models for the development of coal production subsystems. It was designed for application to the north Bohemian brown coal district, i.e. the country's largest coal district where at present 65 Mt of brown coal yearly are being produced mainly by opencast mining.

The model consists of 5 submodels covering the decisive areas for future coal district development up to the year 2000. It was designed as a linear programming model with mixed variables (continuous and Boolean ones). The Boolean variables apply to every supplying sector. Three types of constraints were set: production capacity, consumers' requirements, and the volume of investments and labor. The objective function is the sum of investment, production, and transportation expenditures.

Basic input data:

- suppliers of solid fuels and variants of their development in time series,
- consumers of solid fuels and their consumption in time series,
- technical coefficients dependent on possible new production of solid fuels,
- labor volume pertaining to the given time interval,
- fixed expenditure for the construction of new coal mines,
- variable costs (depending on the output) of new mines,
- transportation costs for each path connecting producer with consumer, and
- effective investment volume for the specific time interval.

Output data:

- chosen way of development,
- considered volume and pattern of the production and transportation of solid fuels, and
- minimum expenditure applied to the proposed solution.

Evaluation of Expert Estimates [9]

In [9], the problem of an optimal evaluation of a family of expert estimates has been solved with the aim of ordering the given families of the development variants according to the usefulness of individual variants.

The required evaluation method should objectively, i.e. based on reasonable, stated, and unchangeable principles, process several orderings proposed by individual experts. The expert evaluations (orderings) usually contain sensible subjective elements. The required optimal ordering, however, has

- to make full use of the results of the expert evaluations presented,
- to result exclusively from the reasonably chosen, stated, and unchangeable general principles, without any ad hoc additional "rules", and
- to be immediately realizable in practical cases; this is to say that the search for the optimum ordering must be precisely algorithmized and, if necessary, capable of being carried out by the computer.

In [14], a definition of optimal ordering has been given that meets the first two requirements very well. However, the authors do not treat the practical realization problem of the defined optimal evaluation, i.e. the third requirement. Our attention concentrated therefore in [4] just on compiling a suitable algorithm. For this purpose a distance was defined on the set of all orderings and the required algorithms were compiled for two optimal criteria: the median and the mean value [14].

The derived algorithms described in [9] are based on designing the set of all evaluations given in the form of a pseudo-Boolean equation, as well as the criteria i.e. median or mean value in the form of a linear or nonlinear pseudo-Boolean function [13]. Thus the problem was transformed into a pseudo-Boolean programming problem [13]. Hence advantage can be taken of the apparatus expanded in [10] and [11] which includes the relevant computer programs of J. Linhartová [15].

It can be proved [9,14] that the above distance between two expert evaluations A, B is

$$d(A,B) = \sum_{i,j} (a_{ij} + b_{ij} - 2a_{ij}b_{ij}) \quad ,$$

where (a_{ij}), (b_{ij}) are incidence matrices of evaluations A, B.

Under the same assumptions, it can be shown that finding the median of an evaluations family $A^{(1)},\ldots,A^{(s)}$ is equivalent to the following pseudo-Boolean programming problem:

To find the minimal points of the function

$$\sum_{i,j} \alpha_{ij}x_{ij} \qquad (x_{ik} \in B_2;\ i,j = 1,\ldots,n)$$

with the restriction

$$\sum_{i<j} x_{ij}x_{ji} + \sum_{\substack{k\neq i\\ k\neq j}} \sum_{j\neq i} \sum_{i} x_{ij}x_{jk}\overline{x}_{ik} + \sum_{\substack{k\neq i\\ k\neq j}} \sum_{j\neq i} \sum_{i} x_{ij}\overline{x}_{jk}\overline{x}_{kj}\overline{x}_{ik} = 0 \quad ,$$

where n is the number of variants (orderings) to be evaluated and

$$\alpha_{ij} = s - 2 \sum_{k=1}^{s} a_{ij}^{(k)} \quad .$$

Other Submodels

An additional series of submodels has been worked out. They are focused on

- the structure of the fuel and power economy,
- the development of the electric power system,
- the prediction of sulfur dioxide and fly ash emission,
- the development of the electrification system,
- the development of transmission systems,
- the influence of mine-technical and geological parameters on the costs of coal production, and
- the preliminary development of Czechoslovakia's gas supply system.

OBJECTIVES OF THE SCIENTIFIC RESEARCH BASIS IN THE FIELD OF MODELING THE FUEL-ENERGY SYSTEM

The organizations that participated in modeling the development of Czechoslovakia's fuel-energy system are listed in Table 2.

Table 2.

Organization	Central Organ	Set corresponding to work within the fuel-energy system modeling
Power Research Institute	FMPE*	A
Research Institute of Fuel and Power Economics	FMPE*	B
Institute for Fuel Research	FMPE*	C
Institute for Development of the Fuel-Energy Basis	FMTIR**	D
Research Institute for Planning and Management	SPK***	E

*Federal Ministry of Fuel and Power
**Federal Ministry for Technology and Investment
***State Planning Commission

Considering the systems approach [16] as a basis, we can see that many essential requirements within the modeling of the fuel-energy system development has not yet been met. As a measure of fulfillment of these requirements, the function (measure) f subjoining values to the corresponding work volumes is defined in Table 3.

Table 3.

Area	Set of work:	
	required from the view-point of systems-theory	realized
Coal as a whole	H_1	G_1
Traditional resources	H_2	G_2
Nuclear energy	H_3	G_3
Other nontraditional resources	H_4	G_4
Top-level model	H_5	G_5

Let

$$M = A \cup B \cup C \cup D \cup E$$

and N be other efforts.

Some significant facts resulted from the analysis and must be respected in future work. These facts are primarily consequences of the following (see also Tables 2 and 3):

$$f(G_1 \cap M) = f(G_1 \cap (A \cup B \cup C)) < f(H_1) \quad ,$$

$$f(G_2 \cap M) < f(H_2) \quad ,$$

$$f(G_5 \cap (M \cup N)) < f(H_5) \quad .$$

CONCLUSION

The above brief survey provides a picture of the present state of modeling the development of the fuel-energy system and, furthermore, it indicates an orientation of the work to be done with regard to the proper subject matter, to the mathematical and organizational aspect, and to the necessary collaboration and cooperation.

It is fairly obvious that most attention must be paid to interconnections of individual activities performed by the various organizations. In this context the role of IIASA and its Energy Program comes to the fore and it is remarkable that the Institute has succeeded in developing broadly its intended activity in such a very short time.

As far as modeling efforts are concerned, necessary measures are under way to strengthen the system ties in the fuel-energy system models. We should like to follow at an early stage (possibly together with IIASA) with model studies of the coal production development related to the whole fuel-energy system.

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STATUS AND PERSPECTIVES OF THE HARD COAL MINING INDUSTRY IN THE FRG

E.E. Anderheggen

In four mining districts, Ruhr, Saar, Aachen, and Ibbenbüren, the FRG has deposits of bituminous coal and anthracite totaling 230,000 Mt, of which about 24,000 Mt are economically workable. This is the result of investigations on world coal resources for the World Energy Conference 1977 in Istanbul, about which Dr. Schilling reported here.

At present an annual output of about 90 Mt is produced in underground mines from these deposits. The case study on coal for the FRG comes to the conclusion that the primary energy demand for hard coal can be covered up to about 1990 from this production capacity but it will then have to increase rapidly and reach about 200 Mt by the year 2000. The economically workable coal deposits of about 24,000 Mt would cover the annual demand of 200 Mt from 1990 for more than 100 years.

Before I discuss whether and how this increased demand can be met technically, I will describe further developments of the conventional mining technique. The predominant coal winning method in the FRG coal industry is longwall mining. Technical and machine features and the prospects for this method under FRG conditions have been described by Ostermann. Daily coal outputs of 3000 t and more from one longwall face are regularly attained in several FRG workings. Although above the high average daily coal output of all working districts of 1207 in 1976, longwall mining can still permit further increases in coal output. Indeed a double coal face in Ensdorf colliery in the Saar had a maximum daily output of 11,000 t in August 1977.

For the working of steeply dipping or very disturbed coal seams, an efficient mining method is available with the hydromechanical coal winning system in use in the USSR and in Canada. In November this year, the first colliery in the Ruhr--Hansa Colliery in Dortmund--took up hydromechanical production with a daily output of 3500 t.

The high outputs already achieved in several peak faces will become the targets for many similar mines. The present peak performances have been reached by comprehensive mechanization. But they can be reached permanently only when the efficiency of the operating sectors before and after the coal faces is similarly high.

As the result of the development of mining technique during the last 20 years, hard coal production in the FRG has been concentrated in a small number of efficient mines. In the period 1957 to 1976, the number of collieries diminished from 173 to 43 while daily output per colliery increased from 2978 to 8137 tons. As for the output per manshift underground, often considered a yardstick for the state of mechanization and rationalization, there has been a leveling off in recent years in the FRG as in other West European countries and the USA to 4068 kg/manshift in 1973, despite steady efforts for further development of mining technique in all operational sectors. The Saar coal mines with an annual coal output of about 9 Mt show what modern methods of coal getting achieve under generally favourable conditions: the five Saar collieries had a monthly average in 1976 of 4521 kg/manshift, and this was increased to 5536 kg in August 1977; the Ensdorf colliery reached an underground output of 12.3 t/manshift and a daily coal output of more than 11,000 tons in August 1977 and the Göttelborn colliery more than 10 t/manshift in June 1977. These clearly show the prospects for existing coal getting technology in the German hard coal mining industry. Just by application of already available methods and processes, together with common efforts to solve the still outstanding technical problems, it will be possible to become even more efficient.

By such a further development of conventional mining technique, the demand of the FRG for coal can be covered without a reduction in its competitiveness until 1990. From 1990 on, it is necessary that new production capacities of at least 100 Mt per annum must be established to cover the FRG's projected coal demand of 200 Mt of hard coal equivalents in the year 2000, because an increase of coal imports cannot be reckoned with. In order to reach this new coal capacity, new mines are to be constructed. These will have to work coal from the few good coal deposits left, but also achieve an increase in productivity of 40% per worker; novel processes for a utilization of coal deposits must be developed and applied. These include, in particular, processes for extraction of coal deposits that do not involve men working underground.

Reports have been presented at this Conference about coal gasification in situ in the USSR, the USA and in Belgium. The FRG's Federal Ministry for Research and Technology has a project for gasification at great depth. It is characterized by:

- Coal gasification under pressure that is variable from 20 to 60 bar,

- Testing coal gasification with different gasification agents including hydrogen,

- Coal gasification at greater depths than 800 m, and

- Long-term coal gasification by means of filtration gasification.

Methods of microbial leaching have obtained technical importance recently for the extraction of poor ores, for example copper ores. A first study of microbial coal extraction has been carried out by the Bergbau-Forschung GmbH in Essen. A large technical application of microbial coal extraction is not altogether out of the question, but not to be expected in the near future.

I would like to summarize the results of my paper:

The primary energy demand for hard coal in the FRG can be covered with the present production capacity of 95 to 100 Mt until about 1990. The systematic further development of conventional mining technique gives reason to expect an increase in productivity, by which the competitiveness of coal against other energy sources can be maintained and possibly even improved.

New production capacities must be established, in case the demand for hard coal increases suddenly from 1990 to about 200 Mt in the year 2000, as the FRG case study shows, and if this additional demand cannot be met by coal imports.

The economically workable coal deposits in the FRG, amounting to about 24,000 Mt, would be sufficient to cover such a demand. The coal deposits to be extracted in future will probably have a less favorable formation.

Increased production even with such less favorable coal deposits, and maintainance of competitiveness of the additionally produced in view of the high capital cost for new collieries, can be achieved presumably only by application of novel coal winning processes. Wide difficulties will have to be overcome to make such new coal winning processes--especially coal gasification in situ--economical in practice.

A SCENARIO FOR A MEDIUM-TERM REVIVAL OF COAL IN THE FRG: RESULTS OF A CASE STUDY*

W. Sassin

INTRODUCTION

Global coal resources are very large and will have to be exploited more extensively in order to satisfy future energy needs of mankind. Yet the coal industry in many countries faces severe economic difficulties despite the fact that the main competitor of coal, crude oil, experienced a fourfold price increase in 1973/74.

IIASA's Energy Program is analyzing the various alternative sources of energy that can contribute significantly to a long-term global energy supply. In this perspective past trends of coal deployment and future necessities clearly diverge. Such a historic situation does not exist for the other two principal options, nuclear and solar energy. Concentrating on coal as the closest option at hand, we decided on some medium-term studies first. Detailed investigations on a regional level were considered necessary to clarify the possibilities of reversing the trend of a declining or stagnating coal consumption. As a second step we planned to integrate the results of the specific analyses into a more long-term and globally consistent coal option. This approach led to the methodology finally adopted for our national case studies. Two studies were performed, one for the UK and one for the FRG.

The FRG was selected mainly for the following reasons:

- It has a significant coal mining industry.
- Because of the high import rates of crude oil and natural gas, a need exists to substitute alternative sources of energy as early as possible.
- A fairly advanced economy exists that requires modern forms of secondary energy; these must be derived from any primary energy input, including coal.
- Access to the main indigenous coal resources is quite difficult. It necessitates a high degree of mechanization in mining and has led to a high output per manshift; still the cost of coal is fairly high, compared internationally.

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*The case study was performed in collaboration with Dr. F. Hoffmann, Gesamtverband des Deutschen Steinkohlenbergbaues, Essen, and Dr. R. Hildebrandt, Steinkohlenbergbauverein, Essen, FRG.

- Because of the high population density, environmental constraints play a major role, influencing both conversion processes and siting decisions.

The FRG therefore represents a crucial case for an early revival of coal under conditions that can be expected to develop in other regions with some time delay.

The study was performed in close collaboration with the Gesamtverband des Deutschen Steinkohlenbergbaues and the Steinkohlenbergbauverein, Essen, FRG. The results summarized here are published in more detail in [1].

PRESENT ENERGY SUPPLY SITUATION AND PROSPECTS THROUGH THE YEAR 2000

In 1974 the FRG had a primary energy consumption of 366 × 10^6 tce. More than half of this was accounted for by crude oil, 95% of which had to be imported, mainly from OPEC countries. Nearly one third of the primary energy demand was met by coal, which came almost exclusively from domestic production. Moreover, 35 × 10^6 tce was exported, the predominant share to EC countries.

The share of natural gas in primary energy consumption was about 13%. Since domestic supply is limited, more than half had to be imported. Nuclear energy, with a share of approximately 1%, played only a minor role in meeting primary energy demand. Altogether, about 60% of the primary energy consumed was imported.

Before the oil crisis, primary energy demand was estimated to rise to approximately 600 × 10^6 tce by 1985. The effects of the oil crisis and a reassessment of economic growth prospects have led to reduced estimates: now only 480 to 500 × 10^6 tce is expected by 1985. This would constitute a rise of 120 to 140 × 10^6 tce above the 1974 level.

It is still unclear how this additional demand can be satisfied. Nuclear energy is expected to experience the highest growth rate. However, it will not be possible to achieve by 1985 the amount of 45 to 50 GW that was projected in the first revision of the energy program of the Federal Government (erste Fortschreibung des Energieprogramms). Estimates in 1977 foresaw an installed nuclear capacity of 30 to 35 GW(el); present forecasts are even lower. In view of the results of studies on the international energy supply [2,3], a difficult oil supply situation around 1985 cannot be ruled out. Consequently the earlier estimates are used in this study so as not to overestimate the need for coal. 30 to 35 GW(el) nuclear power plants would produce 200 TWh of electricity, which translates into an equivalent of 60 × 10^6 tce primary energy supply.

The supply of lignite is expected to rise only slightly because its production is constrained by geological conditions. The potential for producing energy from water power has been almost fully realized. It seems then that at least half of the expected additional demand for primary energy must be met by fossil energy sources, such as natural gas, crude oil, and hard coal. Because of existing contracts, natural gas supply is expected to increase by almost 40 × 10^6 tce to 85 × 10^6 tce. This rise is guaranteed by increased imports from the Netherlands and the USSR and by new imports from Norway (North Sea) and Iran. The remaining additional demand of 20 to 40 × 10^6 tce must be met by crude oil and hard coal.

The original projections for the year 2000 centered around an energy demand of 1 × 10^9 tce. After a significant downward revision of the economic growth rates and allowing for effective conservation measures, a demand of 700 × 10^6 tce for the year 2000 appears more likely. In this case 200 × 10^6 tce over and above the 1985 figure will be needed, a major part of which could again come from nuclear energy if the optimistic estimates of an installed nuclear capacity of 130 GW(el) in 2000 can be realized. Environmental concerns and a growing opposition to nuclear energy might lead to a significant reduction of this estimate; but it is used here in order to arrive at a conservative potential coal demand. This leaves a gap of another 70 × 10^6 tce that must be added from natural gas, crude oil, or hard coal between 1985 and 2000. Most existing contracts for natural gas expire after 1990. Since from that time on, domestic production must also be expected to drop, new contracts for the import of 60 × 10^9 m^3 are required if the level reached in 1985 is to be maintained. Possible suppliers are the North Sea countries, but above all the USSR and the OPEC countries. Even if the necessary gas quantities could be supplied, serious problems are foreseeable:

- The dependence on imports would continue to increase.

- The dependence on OPEC countries would then extend to natural gas, a substantial part of which these countries would have to provide in spite of continued supplies from the North Sea.

- Due to the distances to be covered, much more liquid natural gas (LNG) would have to be imported at costs considerably higher than those of pipeline gas.

- Transportation costs, combined with the generally strong increase in natural gas demand, would likely cause considerable price increases for this energy source.

The supply risks of crude oil, which are the result of the great amounts imported from OPEC countries, are not likely to be eliminated. The petroleum discoveries in the North Sea, which might bring temporary relief, are of only minor importance for the FRG. Thus a further extension of oil and gas imports seems an undesirable but unavoidable consequence, unless more coal can be absorbed by the market.

ASSUMPTIONS AND RESULTS OF MARKET ANALYSIS FOR COAL

Since 1960, coal in the FRG lost a significant share in primary energy consumption. The absolute production of coal went down from 180 × 10^6 tce in 1956 to 125 × 10^6 tce and has nearly stabilized now. The technical potential to produce significantly more coal exists; the real bottleneck obviously derives from the difficulties in coal use at the consumer end. The study thus started from consumer needs and proceeded backward to the possible coal input that could be absorbed by the economy. The following steps will be briefly summarized:

- Projection of volume and structure of final energy demand;
- Determination of substitution possibilities by coal and selection of the necessary conversion processes;
- Time requirement for the introduction of these new technologies and determination of possible growth rates for new coal products;
- Effects on primary energy demand.

Projection of Final Energy Demand

From 1960 to 1973, final energy consumption rose by an average of 4.4% p.a. According to recent studies [4,5,6], significantly lower growth rates are projected for the period until the year 2000. Starting with an average of 2.5% p.a. between 1974 and 1980, the growth rate is assumed to fall to 1.4% p.a. around 2000--due partly to saturation tendencies, partly to an anticipated decrease of overall economic growth, and partly to conservation efforts, resulting in more efficient use of energy.

Final energy demand is an aggregate of the demands of various consumer groups requesting a spectrum of special forms of final energy. Specific estimates were derived for:

- Fuels in the transportation sector,
- Coke in the steel industry,
- Coke-oven and blast furnace gas.

A significant substitution of these energy carriers within the time horizon of this study is either impossible or very unlikely. The remaining energy carriers in other markets are in principle interchangeable and compete at least to a certain extent. These are:

- Liquid fuels (for heat production);
- Solid fuels;
- Gaseous fuels;
- Electricity;
- District heat.

Gaseous fuels, electricity, and district heat form the group of energy carriers supplied by grids. In the past there were distinct and regular changes in the market shares of these interchangeable final energy forms. Figure 1 contains past data and projections made by accounting for potential tendency changes. Straight lines in the logarithmic plot of Figure 1 represent logistic (S shaped) curves, a functional relationship that holds extremely well for many commodities including energy products [7,8].

The steady growth of final energy supplied through grids reflects the long-term consumer preference for clean and comfort-

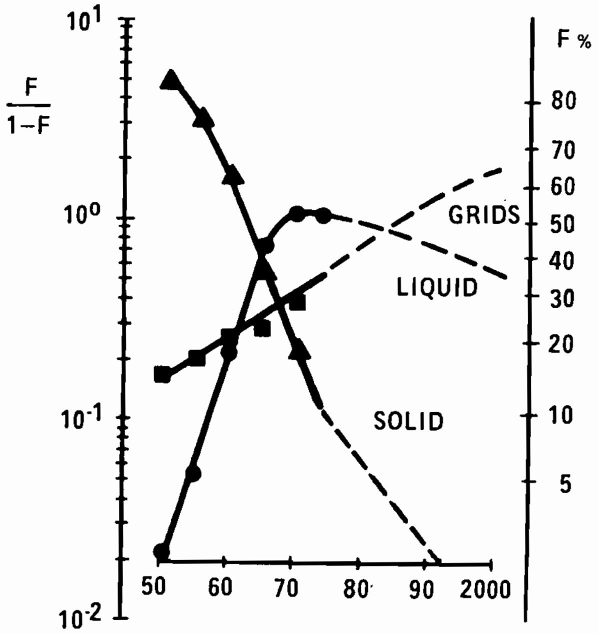

Figure 1. Market shares (F) of final energy forms (substitutable fraction, FRG).

able energy forms, a trend that will probably continue. By 2000 gaseous fuels, electricity, and district heat could have reached more than 60% of the interchangeable forms of final energy. This is still less than is found in some large conurbations today, where 50% of the total population lives [6]. It is worth mentioning that this projection by and large coincides with detailed investigations carried out elsewhere for electricity, gas, and district heat. It implies, for example, that the growth rates of electricity consumption will fall from the average 7% p.a. between 1960 and 1970 to an average of 4.6% p.a. between 1974 and 2000.

Figure 1 shows a remarkably fast decline of solid fuels, compensated by an equally remarkable growth of liquid fuels. Already in 1970 this switch from solid to liquid experienced a kind of saturation effect. It is not due to the oil crisis, but simply to the fact that solid fuels have practically left this submarket. In view of the anticipated difficulties in maintaining an adequate crude oil supply, the inherent trend toward a further increase in the share of energy supply via grids is likely to continue.

Figure 2 summarizes the various projections defining final energy demand. Apart from the shaded areas, submarkets with distinctive requirements are thus established that can in principle absorb final energy forms to be derived from coal.

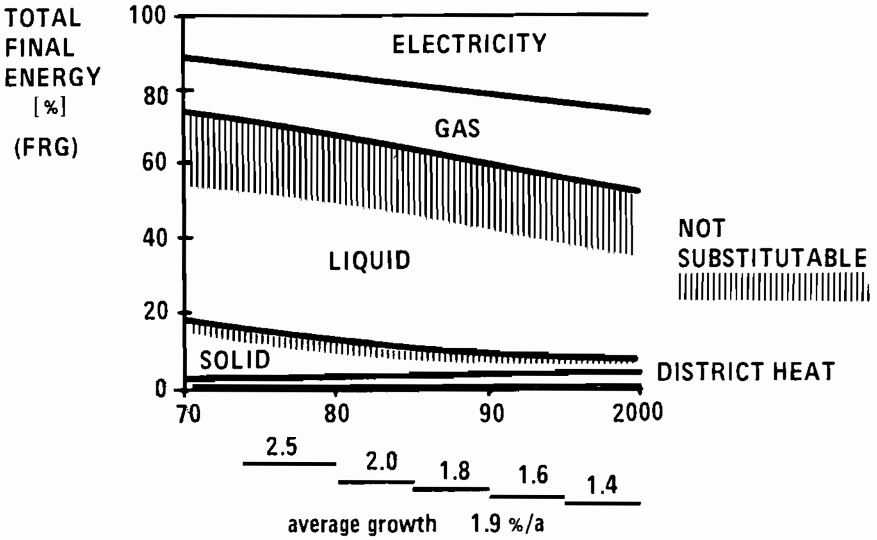

Figure 2. Projection of final energy demand--structure and growth rates.

Possible Substitutions and Selection of Coal Conversion Technologies

We will briefly consider the three submarkets for:

- Liquid fuels, except for transportation purposes;
- Gaseous fuels;
- Electricity, including co-generation of district heat.

Of the numerous possibilities to convert coal into suitable products that could penetrate these submarkets, we have screened out those where early availability, cost calculations, and environmental acceptability appear most promising with respect to present conditions in the submarkets.

Liquid Fuels

At present, final energy demand for liquid fuels is exclusively met by crude oil products. Although the chemical composition of coal would make it possible to produce syncrudes, an indirect substitution appears more promising. It is certainly easier to shift heavy distillates from crude by hydration to light fractions than to liquefy coal. For an indirect substitution, heat is derived from "fluidized coal" instead of heavy fuel oil. Two processes remained, the fluidized bed process and solvent refined coal.

As the fluidized bed process may be used for all forms of heat production above a certain minimum unit size and as it can accept a broad spectrum of coal qualities, it was chosen as the reference technology for the liquid fuels sector.

Gaseous Fuels

For the production of a substitute natural gas (SNG) there are a number of gasification processes. In addition to conventional processes (Lurgi, Koppers-Totzek, and Winkler), which are being improved, new processes are being developed whose main goal is to obtain more favorable product gas composition and greater efficiency (e.g. synthans, hygas, bigas, Rummel-Otto). The most recent projects concern third generation processes where the process heat is held in from the outside (e.g. from a high-temperature nuclear reactor).

In this case study we took only the conventional processes into account, and an adjustment to the most recent state of technology is taken for granted. The reasons are the following:

- Only the conventional processes mentioned can be put into operation within a very short time without a major additional R&D input.

- The economically promising third generation processes depend on the development of the high temperature reactor (HTR). Here, numerous problems still have to be solved. Moreover, the gasification process itself also requires comprehensive research efforts; we therefore assume that an important contribution of the process to the replacement of natural gas cannot be expected before the year 2000.

- For the other processes, only demonstration plants are in existence and it is uncertain when industrial exploitation can be expected.

The conventional processes can be used for the gasification of hard coal or lignite. Because of the product gas composition (relatively high content of methane), the Lurgi process offers the most favorable conditions for the production of SNG. In the following, we therefore assume that this process will be the one most used.

Electricity, Including Co-Generation of District Heat

From our present point of view, there are essentially two new technologies suitable for electricity production from coal:

- *Pressurized coal gasification* (PCG) with combined gas/steam turbine process. This process is being tested at a demonstration plant with a capacity of 170 MW. It is best suited for power stations with medium to high capacities (800 to 1000 MW blocks).

- *Fluidized bed process* under pressure with combined exhaust gas and steam turbine. While fluidization will be ready for operation within the short term, the process under pressure still requires development work. This technology is suitable for medium-sized to big plants as well as for small plants (50 to 100 MW) and serves for the decentralized supply to consumers with electricity and district heat (co-generation of electric power and heat).

Both processes can be developed to such a degree that they are ready for industrial use within the period considered, whereby pressurized coal gasification has a time advantage.

We finally chose the following reference technologies for the introduction of "new coal" to feel into the three submarkets described above:

- Fluidization (pressurized and nonpressurized) for industrial heat;

- Coal gasification by conventional methods (Lurgi) for the production of SNG from lignite and from hard coal;

- Electricity production by means of pressurized coal gasification and, at a later stage, fluidization under pressure for central stations;

- Co-generation of electricity and heat in small fluidization units under pressure for decentralized supply.

Figure 3 illustrates the cost situation of "new coal" with respect to the present final energy forms with which it has to compete in the different submarkets. The cost of the hard coal input is given as a parameter.

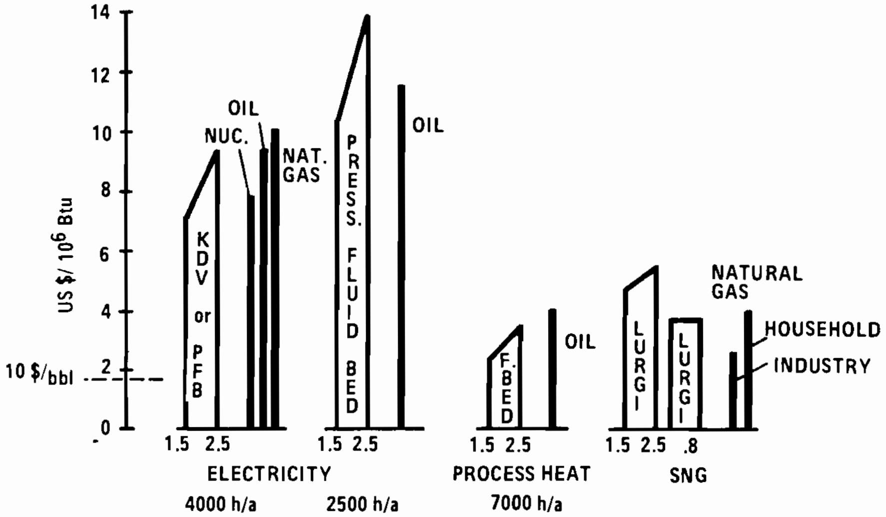

Figure 3. New coal conversion technologies--costs.

Estimates of product costs for the individual technologies depend on assumptions on plant size and possible load factor. Both were chosen to be consistent with the situation in the specific submarkets and in line with the supply possibilities of other primary energy sources, especially with nuclear base load preferences. The estimates contain some uncertainties, mainly because such plants are not in operation yet. This uncertainty is overshadowed by the large price variations in the necessary coal input. Present prices for indigenous steam coal are at 21 DM/Gcal*; imported coal is available at lower prices.

In general it is clear that the technologies selected can lead to competitive products; in the case of SNG produced from

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*10 DM/Gcal ≈ 1 US $\$/10^6$ Btu

lignite, a competitive situation can be expected at least toward the end of the time period considered here.

Time Requirement for Introducing New Coal

Figure 4 lists the four reference technologies selected as prime candidates to feed into the submarkets shown in Figure 2.

COAL SUBSTITUTES FOR	PENETRATION		NEW TECHNOLOGY
NUCLEAR	1985 850 MW	23 [a]	POWERPLANT 4000 h/a KDV, PRESS. FLUID. BED
OIL (HEAVY AND LIGHT NATURAL GAS	1990 1 GW	50 [a]	POWERPLANT 2500 h/a PRESS. FLUID. BED
HEAVY FUEL OIL	1985 200 MW	18 [a]	INDUSTR. BOILERS FLUID. BED 7000 h/a
NATURAL GAS	1990 4 GW	18 [a]	SNG PLANT LURGI 7500 h/a

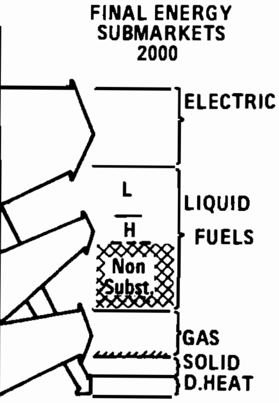

Figure 4. Channels for new coal (FRG).

The volumes of the submarkets will change over time. Figure 4 indicates the width of the expected channels through which coal-derived products could be fed into the final energy market of the year 2000. The main forms of primary energy that would predominantly be replaced by coal are also given. Crucial points are the availability and possible rates of commercial introduction of the new coal conversion technologies. The earliest commercial availability of each reference technology was estimated from the present state of development, the R & D still required, and the time necessary to design, plan, license, and construct plants of suitable unit size.

There are good reasons to assume that the commercialization of the new coal conversion technologies will follow the same functional relationship as was observed in the past 25 years in the respective submarkets. Taking similar penetration mechanisms in the past as an indication of the readiness of a particular submarket to adopt a technological change, estimates of possible penetration speeds for new coal were derived. Natural gas, for example, required a time span of 18 years (equivalent) to take over 50% of the market of town gas. Such short introduction times depend on the availability of the distribution and consumer infrastructure. We projected a similar development for the introduction of synthetic pipeline gas from coal, as can be seen from Figure 4. Characteristic time constants for the other three technologies in Figure 4 were estimated in a similar way.

Effects on Primary Energy Demand

On the basis of the projected introduction of new coal conversion technologies, coal requirements can be calculated as a function of time. Taking into account the probable conversion losses of coal, and including the traditional uses of coal for steel and electricity production in existing power plants, Figure 5 gives the total coal demand that can be expected in the FRG up to the year 2000. Because of the limited availability of lignite, its present use for base load electricity generation would gradually shift to gasification.

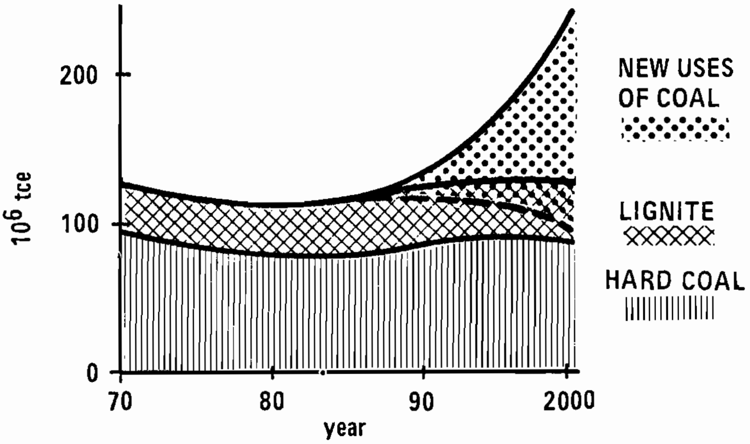

Figure 5. Coal option scenario: total coal demand (FRG).

The results of the market penetration projections were carefully checked against the anticipated supply situation for alternative primary energy sources. No inconsistencies appeared. The maximum possible growth for nuclear power is not constant. The necessary extension of the park of conventional coal-fired power plants between now and 1990 does not restrict the later addition of new coal conversion technologies.

Figure 6 puts the increase of coal in perspective with the development of other primary energy inputs. The primary energy balance in this figure was calculated backwards from the final energy demand projection with the appropriate entries for non-energetic uses of oil, gas, and coal and likely improvements in the efficiencies of noncoal conversion processes.

The resulting 720 × 10^6 tce primary energy demand is in fair agreement with projections derived by other groups [9] using different approaches.

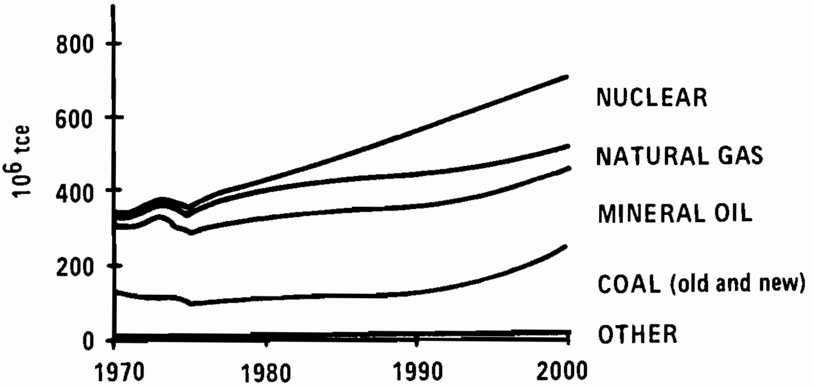

Figure 6. Coal option scenario: primary energy consumption (FRG).

Figures 5 and 6 indicate that under realistic conditions coal consumption could be revived significantly from 1990 onward. The projection for 2000 is 240 × 10^6 tce, twice the present figure. In parallel with this marked growth of coal, an ambitious nuclear program will have to be implemented if oil and gas imports are to remain roughly at the present level.

Extrapolation of the results of our analysis beyond the year 2000 shows that coal could further increase its market share. The channels to the consumer are not fully used in 2000. Additional coal conversion technologies, e.g. the production of methanol, would open additional channels.

IMPLICATIONS OF A COAL REVIVAL

The positive outlook for reintroducing large amounts of coal into the market immediately raises the question whether sufficient coal can be supplied in time. The capital requirements for production and conversion and the related infrastructure were estimated. Together with consideration of the manpower problem, they make it possible to judge the coal-related difficulties of an energy policy heading for the scenario quantified in Figures 5 and 6. Detailed environmental considerations had to be put aside at this level of investigation. Pollution problems are strongly related to local conditions and would raise questions of local siting policies. As the reference technologies have the inherent potential to reduce the level of chemical emissions below that of present technologies based on coal, the environmental impacts will be limited. Two problems of the conversion step remain open, however: increased production of waste heat and availability of new sites close to consumer centers.

If we assume that the future coal supply would have to rely exclusively on indigenous resources, the additional 100 × 10^6 tce must come from deep mines. The present capacity of hard coal mines is approximately 100 × 10^6 tce per year; 90 × 10^6 tce is actually produced. 20 new pits, each with a capacity of 5 × 10^6 tce per year, would have to be in operation between 1990 and 2000. On the basis of present costs this amounts to DM 40 to 45 × 10^9, including financing costs. In view of the lead times of 10 to 15 years, planning of new pits would have to start immediately. The average investment per year for the 20-year period between 1980 and 2000 is DM 1.3 × 10^9 above the normal investments of approximately DM 1.0 × 10^9 to maintain present output of the existing mines.

Without investments for coal transportation, conversion facilities would require an aggregate investment of roughly DM 80 × 10^9. The total capital required to introduce an additional 100 × 10^6 tce of new coal per year significantly exceeds DM 100 × 10^9.

Equally impressive are the manpower requirements of the coal scenario. At present about 200,000 people are employed in hard coal mining; 60% work underground. Assuming a 40% increase in coal output per manshift, 300,000 employees were needed by the year 2000 to produce an annual 2 × 10^9t of hard coal. This implies new mining technologies with a consequent need for highly skilled labor. Because of the opening of new pits, manpower requirements would increase from the mid-eighties, so that new training programs would have to start soon.

CONCLUSIONS

The results of the analysis of final energy demand and the supply situation for crude oil, natural gas, and nuclear energy indicate that a revival of coal must be considered a real possibility for the FRG. The assumptions used to quantify a coal scenario were consistently chosen to give a low estimate for the market potential of new coal. Possible lower growth rates for nuclear energy or a further increase in crude oil prices would increase the calculated total coal demand of 240 × 10^6 tce by the year 2000. The estimated capital and manpower requirements indicate the sizeable economic problem of providing another 100×10^6 tce from indigenous hard coal converted into final energy forms suitable for the consumer. In view of the anticipated oil supply gap--which might develop in the eighties--it would be difficult for coal to act as the main substitute for oil that early. The far-reaching commitments of a coal option stem from the large capital investments needed and the special requirements on the labor force. Imports could possibly improve the chances of a coal option. The main reason for a revival of coal clearly is to prepare for future global energy supply shortages. Within the time horizon of this study, the decision to count on imports of coal would certainly depend on stable and reliable political relations between potential coal exporters and the FRG.

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SYSTEMATIC ANALYSIS OF HOME PRODUCED COAL IN HUNGARY

L. Kapolyi, G. Réczey, and G. Szentgyörgyi

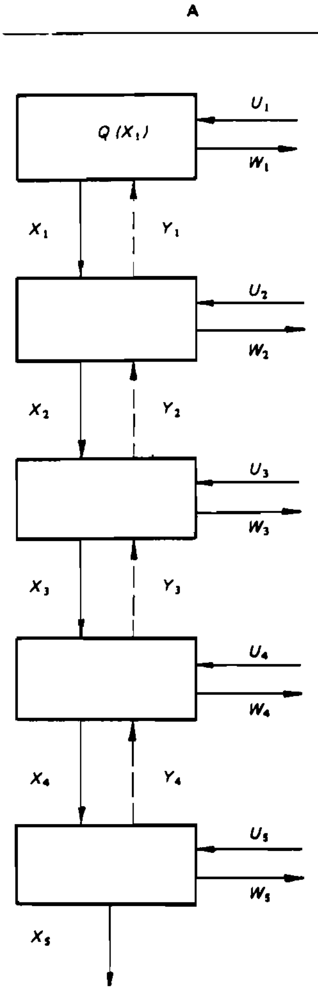
VERTICAL PRODUCTION FLOWS AS ELEMENTS OF THE SYSTEMS ANALYSIS METHOD

National production flows as a result of production growth in all directions become ever more complex. For this reason a larger share of the limited material resources available--here the accent is on mineral resources--are drawn into production. Parallel to this, the technical basis of mineral raw material processing and utilization is also enlarging. Hence an economically effective technique is generated to fulfill the dynamically growing needs in a complex way. In studying this process systems theory is indispensable especially in view of the complex sophisticated activities.

Based on systems analysis the vertical flows of processing mineral raw materials are discussed according to Figure 1. Column A of Figure 1 shows the vertical flowchart of mineral raw material processing (see also the notes underneath the Figure); column B is the general scope of these activities; columns C and D contain examples. The procedure that is being followed employs functions to set the elements of the system against each other for the purpose of dynamically representing the technical level and economic efficiency of vertical production flows [1,2,3].

With the use of appropriate mathematics it is possible for all the elements of the flowchart to have horizontal relations in the national economy. In this way an optimum efficiency can be attained at the national economy level. The use of complex systems analysis in this case--in view of the home production of coal in Hungary--is warranted by the fact that the use of coal for power and industrial production purposes has changed considerably compared with other imported alternatives. Its role may be a determining factor in the development of the national economy. Its significance cannot be accentuated enough in the light of present and future growth of energy needs.

The decision making method chosen takes into consideration the change of the techniques of raw material exploration, production, and utilization processes and follows them through technical and economical parameters in a complex way. The energy technology activity to be based on mineral resources--one of these being coal--is developed on a variable base. The production and processing activity already available in the energy technology is also taken into account. Thus the unified logical system of the energy industry is formed on the basis of proven and future mineral raw material resources and the kind of energy industry that is or may be at our disposal: this is the basis for the systems analysis. The parameters of system models may be varied



B	C	D
Exploration of mineral resources	Coal-bauxite	Copper ore
Production of primary mineral raw material in the mining	Coal and bauxite, as twin-products of the mining	Copper ore
Preparation for delivery of intermediate mineral raw material	Coal for energy production coal Enriched bauxite, alumina	Enriched copper ore
Processing for delivery of ultimate mineral raw material	Electrical energy Steam for heating supply Aluminium ingot	Anode and cathode copper
Production of semi-endproduct and endproduct	Mechanical labour, illumination, technological heating supply, municipal heating supply, Aluminium rod	Copper rod, wire, sheet, cable etc.

Signs and Abbreviations: Each symbol represents a vector and vector function. The components of the vectors are qualitative and quantitative parameters. Q, mineral resource; X_1, X_2, X_3, X_4, X_5, vectors of the main products; Y_1, Y_2, Y_3, Y_4, feedback along the main process; U_1, U_2, U_3, U_4, U_5, expenditure of the processing phases, in natural units; W_1, W_2, W_3, W_4, W_5, emission of the processing phases in natural unit; P_x, P_y, P_u, P_w, prices; K_x, K_y, K_u, K_w, costs; and $Z(x,y,u,w,p,k) \rightarrow$ Extr., final function optimization.

Figure 1. The block scheme of the vertical processing of mineral resources.

according to functional aspects and by utilizing the possibilities of mathematics they can be optimized by taking into account the known limiting factors. This way the decision making can be forced in between two asymptotes: the nearly exponentially growing mineral raw material demand and the geological reserves being limited in the long run.

RELATIONSHIPS BETWEEN VERTICAL ENERGY FLOWS

The basis for the relationships between energy flows is the technical replaceability of energy carriers [4]. Figure 2 shows an easy and characteristic example of the classical technologies of electric power production. For the purpose of numerical expression of technological relationships an "interpretation" is made about the future of electric power production on the basis of all mineral raw material resources. At different times--e.g. in 1990, 2000, etc.--on the basis of proved and future resources the profiles of different energy strategies must be sketched based on the technical and economical parameters of the vertical flows. Then operators ensuring the optimum conditions at the national level must be accepted.

Figure 3 illustrates two specific questions. One of them is the incorporation of vertical flows into the national economy. First a view was taken about the actual balances (e.g. capacity utilization of various branches, unit investment coefficients of increment, capacities, etc.). Then future profiles were drafted including "adequate" plan balances. It can easily be realized that by viewing the various energy sources in electric power production flows there is a difference in utilization and these differences may be a determining factor in decision making at the national level. The other question is the utilization of home produced energy sources or imported energy sources in general [5].

The Hungarian government and the competent authorities of COMECON have accepted the idea of development of home raw material and energy production sources. The available systems analysis makes it possible to determine the limits of "self supply" and its changes over time in view of the national interest. The balance of intersectoral relations clearly illustrates what branches of the open Hungarian economy are producing export goods for meeting the cost of imports--naturally, this statement is valid for all open economies. The computations must be done in the areas of marginal relations. If the prospective efficiency of the foreign economy and the technical and economic parameters of utilization of foreign energy sources are known as well as the trend of energy demand, then, and only then, can decision making be realized concerning the ratio of home and imported energy source utilization.

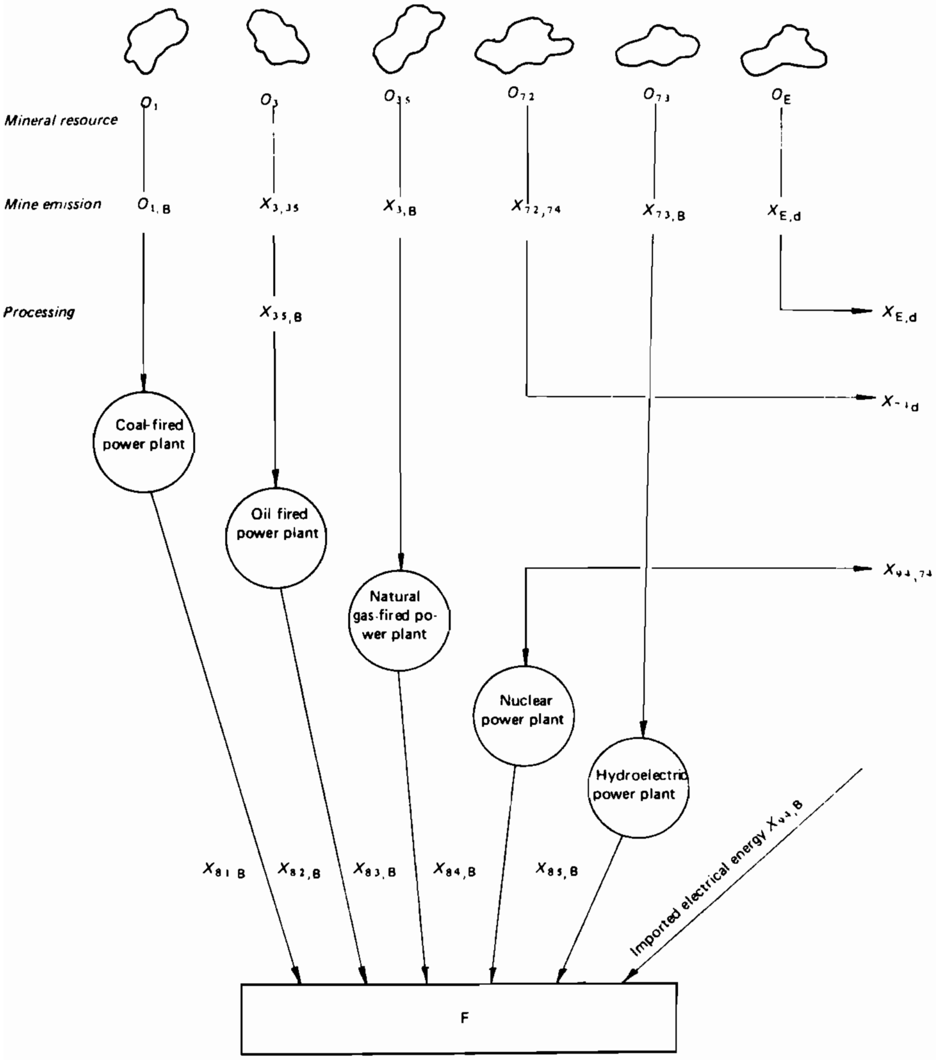


Figure 2. Power generating systems with different energy carriers.

j	Denomination of branches		Columns of the technological matrix								Inhabitants	Public institutions	Installation	Export	Change in stockpile	Total resources
i			1	3	35	72	73	8	E	N	a	b	c	d	e	95
1	Coal mining	sources of power						$X_{1,8}$								
2	Crude oil and natural gas production			$X_{3,35}$				$X_{3,8}$								
35	Oil refining							$X_{35,8}$						$X_{EF,d}$		
72	Uranium ore mining							$X_{72,8}$								
73	Water management							$X_{73,8}$								
74	Processing of uranium ore													$X_{74,d}$		
8	Production of electrical energy		$X_{8\,1}$	$X_{8,3}$	$X_{8\,35}$	$X_{8,72}$	$X_{8,73}$	$X_{8\,8}$	$X_{8.E}$	$X_{8.N}$	$X_{8\,a}$	$X_{8,b}$	$X_{8,c}$	$X_{8,d}$	–	$F_{8\,95}$
81	on the base of coal	Factoring on the vertical sheme out of i/o model														
82	oil															
83	natural gas															
84	nuclear power plant															
85	hydroelectric power plant															
E	Exporting branches							$X_{E,8}$						$X_{E,d}$		
N	Other branches of the national economy							$X_{N,8}$								
A	Material and nonmaterial branches, total							$X_{A,8}$								
90	Amortization							$X_{90\,8}$								
91	Wages and incomes							$X_{91,8}$								
92	Accumulation							$X_{92,8}$								
93	Total domestic production							$X_{93,8}$								
94	Additional import (see vertical scheme)							$X_{94,8}$								
95	Total sources:							$F_{95,8}$								

Figure 3. The elements of the vertical systems in the balance of intersectoral relations.

ENERGY AS A SUBSYSTEM OF THE NATIONAL ECONOMY

The description of the complete vertical flow on the basis of systems analysis from the exploration phase to the utilization of mineral resources examines the material, cost, and value flow as one unit. In the interaction of the national economy and energy this means that the consumers are a fixed limiting condition to all developments. For them energy utilization is something of a "necessary evil" since their primary interest is in some utility or production object and quite often energy utilization is rated after other national needs with their totally variable conditions at a time given and future. The accent is on the time and variability factors.

The major aim of the national economy is the rapid increase in national income for which the present state of the complex branch system and infrastructure provides the starting base. Hence systems analysis detects among other things that several energy supply systems may belong to all possible alternatives of increasing the national income. The right decision making requires that the analysis should not stop at the optimization of the energy system but always with the change in national income as a whole. In this respect the energy industry will be a subsystem of the national economy that covers large volumes and is basically significant.

THE ROLE OF MODERN TECHNOLOGY FOR COAL PRODUCTION IN THE FUTURE ENERGY SUPPLY

Within the framework of systems analysis, the flow of coal from the in situ state to the consumer is set in one vertical flow and all processes that are involved in the exploration, production, and utilization phase of coal are analyzed and made suitable for development from the point of view of up-to-dateness, i.e. all technical and economic parameters are improved. This process cannot be represented with a "smooth curve": innovations may create steep sections both in the technical and economic parameters.

Moreover, the question must be viewed for the long run: international reserves of coal are two orders of magnitude higher than the known reserves of hydrocarbons that are used at present as energy carriers. Although the prospective reserves of hydrocarbons do not yet show the end of the "economic" hydrocarbon recovery period--this phrase has a special meaning since 1973--a statement like it has a much lesser meaning in the case of coal. For a number of reasons energy experts do not think of a specialization to any one of the energy sources in the next 50 to 100 years and do not make strategies for the realization of one but think rather of a balance of all energy sources. "Development" will be achieved by the continuous technical progress. In competition to local potentialities a major role will be played by the up-to-dateness of the energy sources in the total vertical flow or in certain parts of the vertical flow. The final decision can only be made by taking into consideration all phases simultaneously.

The technical improvement itself without any economic background is not a solution. In this respect too the many sided dynamic development process must be followed. At a given time and place for a given consumer the use of coal-based synthetic natural gas may be economic. Yet, at other places its economic use may be attained at a later date or never. The rate of development may be decisive in choosing between the different energy branches and it may be influenced to a certain extent by development strategy. The "most likely" consequences of various development strategies must be foreseen to prepare for the correct decision making.

THE COAL AS VIEWED FROM THE WELMM ASPECT IN HUNGARY

The wide ranging research program that IIASA carries out within the framework of the WELMM project makes it reasonable to express certain qualitative statements about coal utilization since the analysis of coordinated work has just begun in Hungary.

The maximum coal consumption was reached in 1964 in Hungary (about 100 Pcal/year). At present the coal production is under 70 Pcal/year. But, as a result of the reconstruction process that is underway in the coal production industry it may reach or even exceed the previous maximum by the turn of the century. The composition of production will be changed, nearly 50% of the previous underground mining will be changed to opencast mining. Most underground mining in Hungary is below the karstic water level. As a result coal mining--as a necessity--is supplemented by "water mining" which is significant for the public water supply system.

As far as the base energy source production and self consumption are concerned, the following changes may be expected:

- in the coal production process the extent of mechanization will increase and decrease the amount of human labor;
- secondary and tertiary production methods will be implemented in hydrocarbon production since it could be economic; and
- natural gas stored underground within the natural gas system will be utilized for balancing the load.

Figure 4 illustrates the occurrences according to geographical areas. It can clearly be seen that there is a wide distribution of major coal and hydrocarbon occurrences in the country. This also means that the temporary utilization of valuable agricultural area in the country never creates a problem. Coal mining mechanization has not fully utilized the possibilities given by modern technology. There is no doubt that in the future a strong equalization process is going to take place between coal

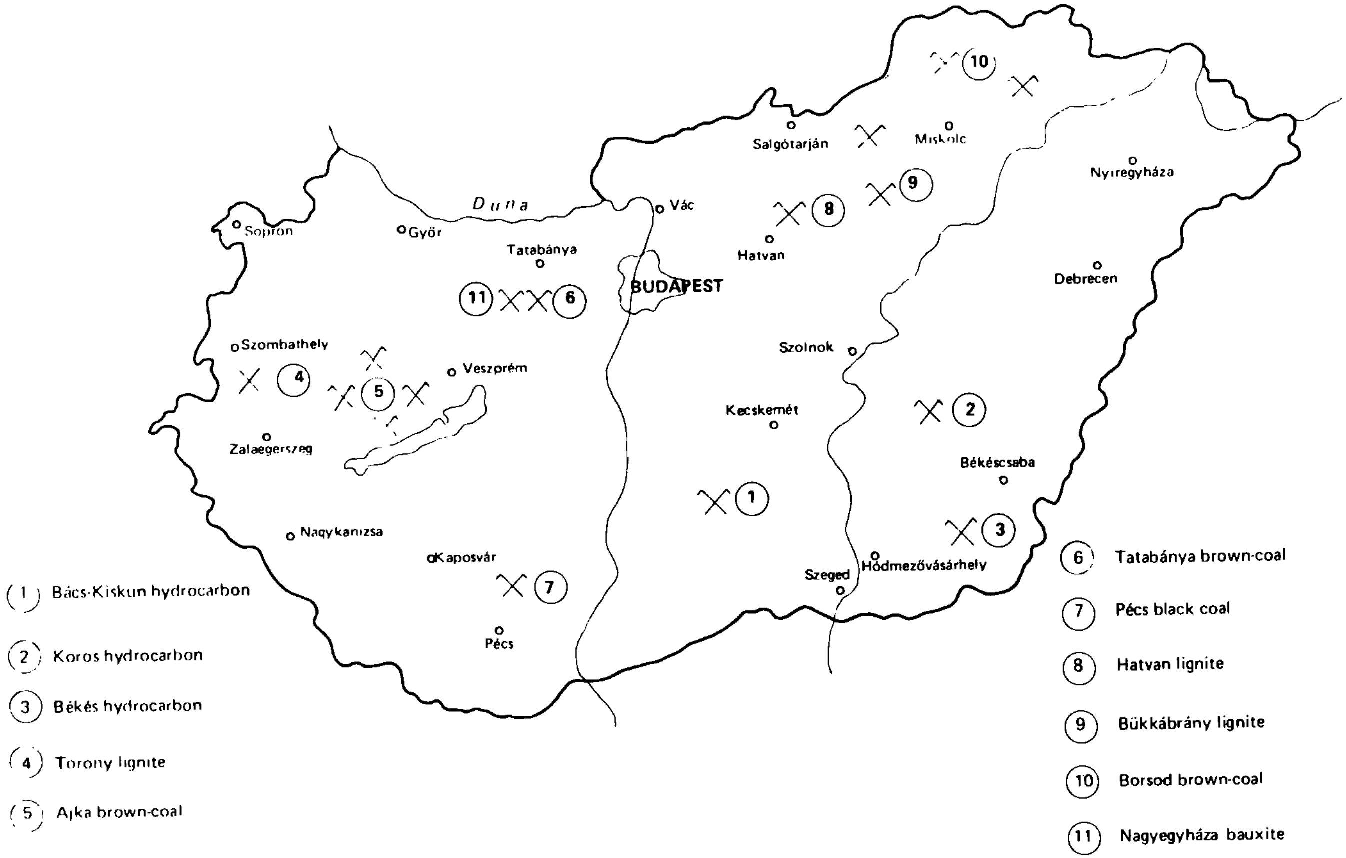


Figure 4. Siting of mineral power resources in Hungary.

and hydrocarbons and in the field of base material processing and transformation where at present there is no doubt the hydrocarbons have the advantage. New technologies in coal utilization have to overcome this advantage.

CONCLUSION

In the last 10 years a change of attitude has taken place in the world economy on the management of raw materials. This change of attitude was especially pronounced in the recent past in the most important raw materials: the energy carriers. The concept that favored production and thus processing of mineral raw materials with the largest economic efficiency due to the "favorable" raw material supply was succeeded by the apparently similar "economy principle" but with a much longer time scale. With the present economy principle the raw material producing states and raw material importing states take the view that raw material and energy sources in the world--including all "conventional" raw materials and "new" raw materials that will be produced in great quantity in the next 30 to 40 years--are limited. For this reason special care must be taken in the utilization of existing reserves.

The harmony between the proved mineral raw material reserves and the requirement for raw materials is to be achieved through good management of raw material resources. The theoretical and methodological bases for these are set by the economic environment and the time horizon considered. The economic environment includes major economic policy aspects, foreign trade policy, the level of development of the national economy, etc. The effect of the time horizon shows itself in the need for structural changes and the time limit for the realization of technical development. Results of the present technical-scientific revolution also significantly influence the management of raw material resources. Thus the technologies of some industries are basically changed and preliminary conditions for the improvement of the economic efficiency of the complete vertical flow are created. Moreover, the number of new types and kinds of end products replacing materials that are in use now are being increased.

Thus the static concept of raw material economy management cannot be accepted. The supply and the optimization of this has to be analyzed dynamically as a function of time.

The use of mineral raw materials and end products made from them or from other outside products is always in relation to the technical, technological, and economic environments that affect production, processing, and utilization.

Relations may be revealed between the mineral raw material resources which are classified according to geological age, the industry to be assigned to them, and their partial and unified development possibilities. These relations essentially have a dynamic character and can be characterized by the economic effectivity attributable to the basic mineral resources and to the production technology.

It is evident that this effectivity is influenced by numerous factors like: the time factor in general, quantitative and qualitative changes in mineral resources, technical standards of production and processing, quality standards of intermediate and end products, related trends of demand and supply, etc. These factors are also characterized by a dynamism in their inner relations, e.g. the general effect of the time factor, the economic environment of development processes related to the method of utilization, and economic trends influencing the environment. For this reason the prevailing economic efficiency of mineral resources depending on this complex dynamism has a potential character.

Concrete analysis is always carried out in geographical areas selected according to administrative, economic-geographical or geoeconomic aspects and it is based on the complex raw material resource base aggregated in respect to the operating production systems, and industrial development possibilities. For this reason engineering, geological, physical, mineralogical, chemical, physicochemical, geochemical, and material structural analysis of raw material resources and basic technical, economical, technological, and international aspects of new production processes necessary for the industrial development are investigated. Based on the above, a unified and closed production system can be developed from the production of raw materials up to the production of end products taking into account the operating base product production and processing activity. These independent systems may be regarded as subsystems and at the end they can be aggregated into a comprehensive system.

It may be concluded from the above that for the discussion of an industrial activity system based on given complex mineral resources and of its functional analysis, some formal basis must be developed for the dynamic description of the utilization of mineral raw material resources. The systems model of the utilization of mineral resources creates a dynamic relation of functions between the quantitative and qualitative parameters of the mineral resources, the technical and economic characteristics of their extraction system, the variable possibilities of their utilization under the conditions of the technical and economic environments. As a result it can be integrated into the national economy and comparisons made with other activities.

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COAL RESOURCES AND EXTRACTION TECHNOLOGY IN INDIA

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INTRODUCTION

The major workable coal deposits occur in two stratigraphic horizons--the Lower Gondwanas of Permian age and the coal and lignite deposits of Tertiary age. The bulk of the coal and lignite resources are located in peninsular India with relatively minor occurrences of Tertiary coal in either extremities of extra-peninsular India (Figure 1).

Permian coals are largely confined to the peninsular area and constitute about 99% of the total coal resources of the country. They are located within the "golden triangle" in the southeastern quadrant bounded by 78° E longitude and 24° N latitude, leaving three quarters of the country practically devoid of any major source of energy. Of the lignite deposits, the most important one is located in south India (in the State of Tamil Nadu). Of the Tertiary coal deposits, those in the northeastern region, covering the States of Assam, Arunachal, Nagaland and Meghalaya, are more important.

The differences in geological age are attended by differences in chemical composition--the Gondwana coals being largely bituminous and the Tertiary coals largely lignitic and lignite.

DISTRIBUTION AND OCCURRENCE

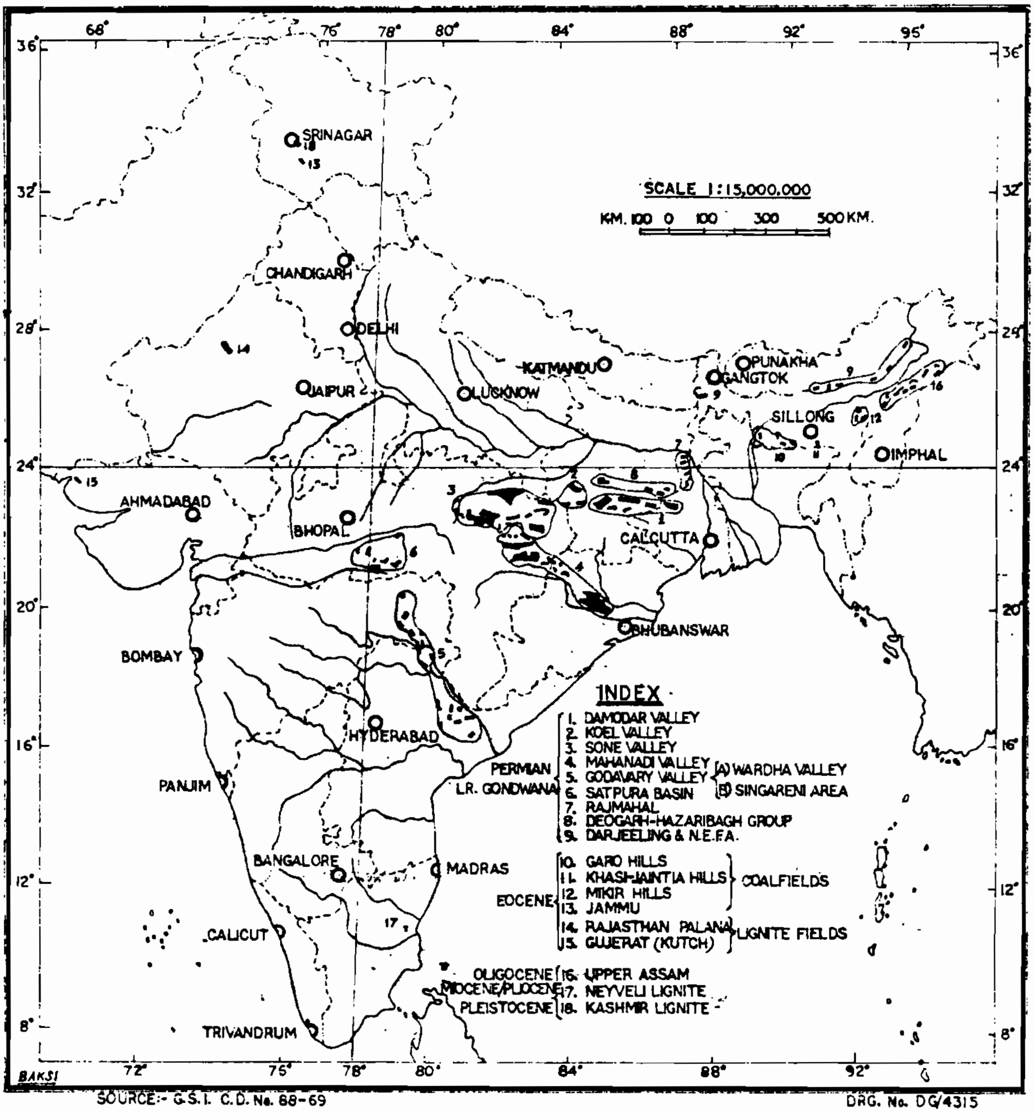
The distribution of coal and lignite in the various stratigraphic horizons is given in Table 1.

GONDWANA COALS

Geological Setting

The Gondwana coalfields occupy basin-shaped depressions in the older formations and are aligned along four prominent river valleys, Damodar-Koel, Sone-Mahanadi, Pranhita-Godavari, and Satpura. Outside these alignments occur the coalfields of Rajmahal Hills and the Deoghar group (Figure 2).

It can be seen from Table 1 that the workable coal deposits of the Gondwanas occur in three distinct formations, the



SOURCE:- G.S.I. C.D. No. 88-69

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Figure 1. Map of India showing coal and lignite fields.

Table 1.

	Age	Geological Formation	Occurrence
TERTIARY	Pleistocene	Karewas	Kashmir lignite
	Upper Micene to Pliocene	Cuddalore bed	South Arcot lignite (Tamil Nadu)
	Oligocene	Tikak Parbat Formation of Barail Group	Coals of Upper Assam, Arunachal and Nagaland
	Eocene	Laki and Jaintia Group	Lignites of Rajasthan and Gujrat and coals of Jammu, Lower Assam, and Meghalaya
GONDWANA	Lr. Cretaceous	Umia stage, Jabalpur	Thin coal seams in Gujarat
	Lr. Jurassic	Kota and Chikiala Formation	Thin coal seams in Satpura and Godavari
	Upper Permian	Raniganj Formation and the equivalents (Upper Coal Measures)	Lower Gondwana coalfields of peninsular India and foothill region of the eastern Himalayas
	Middle Permian	Barren Measures	
	Lr. Permian	Barakar Formation (Lower Coal Measures)	
	Basal Permian	Karharbari Formation (Basal Coal Measures)	

Karharbaris (Basal Coal Measures), the Barakars (Lower Coal Measures) and the Raniganj (Upper Coal Measures). The Karharbaris and the Barakars are more extensively developed wherever the Lower Gondwana rocks are exposed. The Barakars exhibit prolific coal seams, which are at the height of their development in the Damodar Valley but considerably reduced in thickness elsewhere. The Raniganj Formation is well developed in the Damodar Valley from the point of view of workable coal deposits. Sandwiched between the Upper and the Lower Coal Measures are the Barren Measures, a formation largely composed of shales and fine-grained micaceous sandstones and devoid of any workable coal deposits. This formation, too, has restricted development but is well developed in the Damodar Valley.

Lithological Characters

Basal Coal Measures (Karharbari)

The Karharbaris are extensively developed based on studies [1,2] carried out on the quality and characteristics of the coals

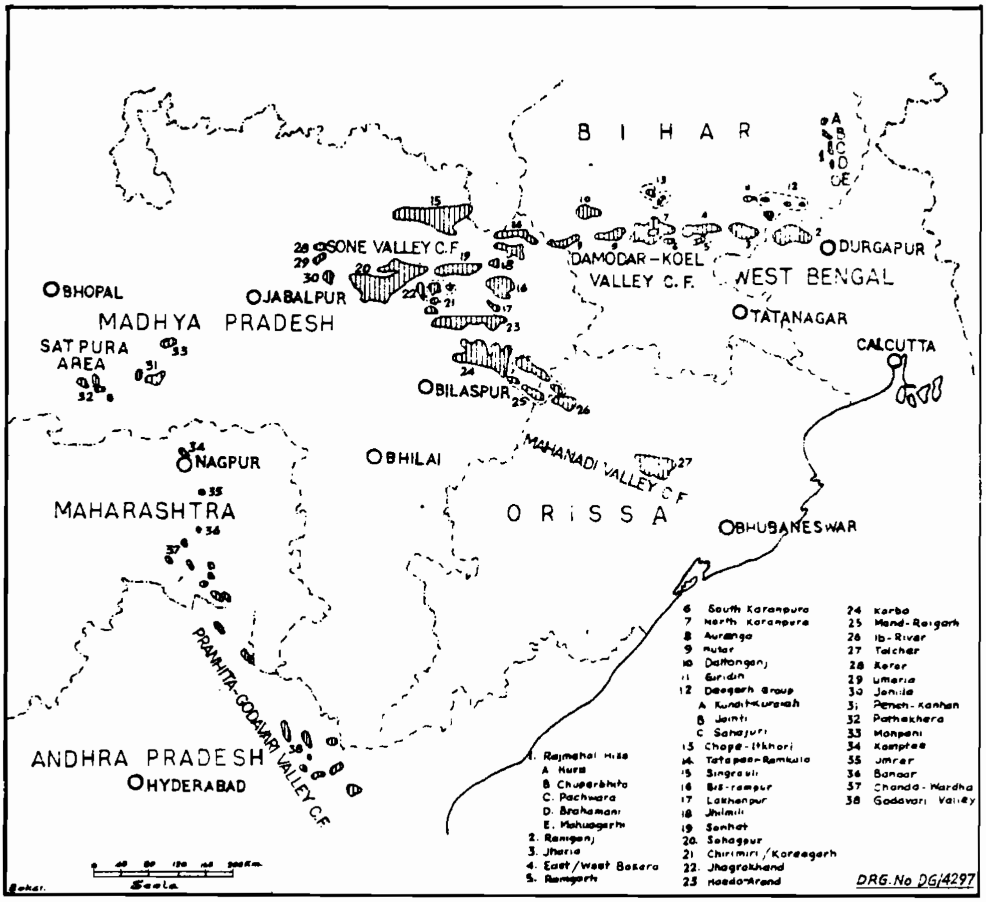

Figure 2. Gondwana coalfields of India.

occurring therein. They are composed mainly of coarse sandstones, grits, and conglomerates and generally a few thin to moderately thick coal seams. The thickness of the formation varies from about 65 to 290 m and the coal to noncoal ratio from about 1:4 to 1:59.

The coals, which are dull-looking with a very faintly developed laminated structure, are normally of better quality (as measured by ash) and have low phosphorus content. The bulk of the coals occurring in this formation are noncaking but those occurring in many of the coalfields of the Damodar Valley are of the caking variety.

Lower Coal Measures (Barakars)

Based on the quality and the characteristics of the coals contained therein, a subdivision was first proposed into the Lower, the Middle and the Upper Barakars [1,2]. While the Lower Barakars are extensively developed, the occurrence of the Middle and the Upper Barakars is mostly confined to the Damodar Valley Coalfields.

Lower Barakars

The Lower Barakars are mainly composed of coarse-grained sandstones with subordinate shales/carbonaceous shales and a number of coal seams. The sandstones are mostly light in color with brownish red, yellow, and other tints varying to pure white and are highly current bedded.

The thickness of the formation varies from about 60 to 470 m and the coal to noncoal ratio from 1:2 to 1:21.

The coal seams are mainly moderately thick to thick, the maximum thickness of an individual seam being as much as 42 m in the Sone-Mahanadi Valley. The seams are generally interbanded with dirt bands of shales and carbonaceous shales. The coals have high ash content and the mineral matter associated with the coal is very much intergrown, as a result of which the coals have difficult washing characteristics [1,2]. The quality of the coals deteriorates further on inclusion of the dirt bands. The coals show well developed laminated structure.

While most of the coal is of Lower rank and noncaking, that occurring in many of the coalfields of the Damodar Valley is of higher rank and of the caking variety.

Middle Barakars

The Middle Barakars of the Damodar Valley are composed of sandstones that are largely medium to coarse grained with increasing proportions of finer clastics compared to those of the Lower Barakars and a number of other coal seams.

The thickness varies from about 96 to 371 m, and contains moderately thick to thick coal seams varying from about 2 to 24 m. The seams, however, contain coals generally of better quality and have better washing characteristics. The coals have well developed laminated structure. The coal to noncoal ratio varies from 1:2 to 1:7.

Upper Barakars

The Upper Barakars are composed of sandstones that are largely medium to fine grained with increasing proportions of finer clastics compared to that of the Middle Barakars. The thickness varies from about 136 to 406 m. The coal to rock ratio ranges from 1:3 to 1:35.

The associated coal seams are generally thick or moderately thick--in the Singrauli Coalfield the Jhingurdah Top Seam, about 134 m thick, is the second thickest seam in the world.

The coals exhibit quality and cleaning characteristics somewhat similar to those of the Middle Barakars. This holds good for the eastern coalfields of the Damodar Valley, namely Raniganj and Jharia, but there is a tendency for the coals to deteriorate in quality westwards of Jharia.

Upper Coal Measures (Raniganj Formation)

The Raniganj Formation is composed mainly of fine-grained sandstones and shales and thin to moderately thick seams. The clastic sediments are definitely finer than those of the Barakars and the felspar content is also considerably reduced. The thickness of this formation is 642 m and 454 m in the Raniganj and the Jharia coalfields respectively of the Damodar Valley where this is mainly developed. The coal to noncoal ratio is 1:27 and 1:21 in the Raniganj and the Jharia Coalfields respectively. The coal seams are mainly moderately thick and provide the major bulk of superior quality coals in the country. This formation also contains some excellent semicoking coals in the Raniganj Coalfield and medium coking coals in the Jharia Coalfield which are used by the steel industry in blends for the manufacture of metallurgical coke.

The broad quality data of the coals of the Karharbaris, the Barakars, and the Raniganj Formations are given in Table 2. The sulfur content of all the coals is generally low--of the order of 0.5 to 0.7%

TERTIARY COAL AND LIGNITE

Coal

The Tertiary coals are best developed in the northeastern region and there are a number of coal occurrences. The coals occur in two groups of formations--the Jaintia Group and the Barail Group, the former being of Eocene age and the latter of Oligocene age. The most important coalfields are Daranggiri and Langrin of Eocene age and Namchik-Namphuk, Makum, Dilli-Jaipur, and Nazira of Oligocene age.

Table 2. Quality characteristics of coals of different formations.

Formation	Analysis (Excluding Dirt)					
	M. [%] at 60% RH and 40 °C	Ash [%]	V.M. [%]	C.V. [kcal/kg]	S[%]**	P[%]**
Karharbari	0.4-11.0	10-26	20-39	4373-6923	0.2-1.6	0.002-0.173
Lower Barakars	0.3-10.0	21-40	22-36	3425-6875	0.2-1.6	0.002-0.248
Middle Barakars	0.8-11.0	12-36	25-40	4110-4800	0.2-0.7	0.010-0.440
Upper Barakars	1.0-8.0	13-31	22-30	3593-4680	0.33-0.76	0.010-0.546
Raniganj	1.0-10.0*	10-30	24-39	4450-7000	0.3-0.8	0.006-0.252

*Air dried basis
**The S and P contents are on air dried 60% RH and 40 °C.

In both groups, the number of coal seams is small and the majority of them are relatively thin, particularly in the coal measures of Eocene age. Of the seams that occur in the Barail Group, there are two that are fairly thick, the 6 m seam and the 18 m seam (Makum Coalfield).

The coals are characterized in general by high moisture, low ash and high sulfur content. The bulk of the sulfur is organic: the total sulfur content generally varies from 2 to 7%, of which 40 to 90% is organic. On account of this high organic sulfur content, the coals from some of the areas (Makum Coalfield) exhibit dual properties of high and low rank coals and have strongly caking properties. While the major part cannot be used in coking blends for the manufacture of metallurgical coke on account of their high sulfur content, some (having less than 3% sulfur) may be so used. Such coals are a "hybrid" between coal and oil and are eminently suitable for liquefaction to oil by hydrogenation.

The thickness of the formations varies from 66 to 600 m. The coal to noncoal ratio ranges from 1:14 to 1:44.

Lignites

The major deposit of lignite occurs in the South-Arcot District of Tamil Nadu. The other occurrences in Rajasthan and Gujrat are of minor economic significance. The chemical composition of the various lignites of the country is given in Table 3.

Table 3.

Lignite deposit	Thickness	Analysis (as received basis)				
		M. [%]	Ash [%]	V.M. [%]	F.C. [%]	C.V. [kcal/kg]
Neyveli (Tamil Nadu)	0.3-23.0	52.0	3.0	25.0	20.0	2500-3000
Kutch (Gujrat)	0.4-11.0	35.0	8.5	33.0	23.5	3600-4200
Broach (Gujrat)	2.0-3.0	32.5	12.5	33.1	21.8	3700
Palana	1.2-16.0	45.0	10.3	28.0	16.7	3000
Kashmir	0.03-1.7	4.0-17.0	30.4-55.0	11.7-20.5	-	1700-2200

PETROGRAPHIC COMPOSITION OF INDIAN COALS

The depositional history and the conditions of sedimentation leading to the formation of coals are reflected in the petrographic composition of the coals of the various formations. The coals of the various formations are characterized by a certain petrographic make-up (in terms of macerals) as summarized in Table 4 [3].

Table 4.

Formation	Petrographic composition % vol. (visible mineral-matter-free basis)		
	Vitrinite	Exinite	Inertinite
Karharbari	35-55	< 11	35-55
Barakar	60-75	< 11	20-35
Raniganj	70-84	< 11	12-20
Tertiary (Makum Coalfield, Assam)	81-88	< 11	< 10

The petrographic make-up is very revealing in as much as the Karharbari Formation is characterized by a high inertinite content of 35 to 55% (and higher), the Barakar Formation by 20 to 35%, the Raniganj Formation by 12 to 20% and the Tertiary coals of Assam by less than 10%. The high inertinite content of the Karharbaris lends support to the view that the coal was formed in shallow waters--a condition extremely favorable for oxidative dehydrogenation by aerobic microbial population leading to the concentration of subhydrous macerals. The low phosphorus content of the coals lends further support to the view.

The lower degree of concentration of inertinite in the Barakar and the Raniganj coal seems to suggest that the conditions of transformation of vegetable matter to coals of these formations were perhaps not as favorable for oxidative dehydrogenation as those of the Karharbari coals.

Unlike the fresh water Gondwana coals, the Tertiary coals were laid down in the shallow waters of the sea, probably in coastal lagoons. While it is clear that the immersion of vegetable matter in either salt or fresh water does not affect the process of coal formation, the marine waters appear to affect the nature and the characteristics of the resultant product. It would appear that the shallow waters of the sea (into which the inland vegetation drifted to form the coals of the Barail group of Upper Assam) were, perhaps, more preservative in character. This has resulted in the low inertinite content of the coals.

Rank and Kinds of Coal

Coals of practically all ranks occur in India except peat and anthracite. The classification as adopted by the Indian Standard Institution is shown in Table 5 and the composition of the coals in Table 6. The broad chemical characteristics of the various kinds of coal used for metallurgical purposes are shown in Table 7.

Noncoking coals

All coals that are either poorly or feebly caking or noncaking, whether of high or low volatile types, and that do not fall under the categories mentioned above have been grouped under this category.

Resources of Coal and Lignite

Classification and Category of Reserves

Category of Reserves:

With a view to having a uniform procedure for coal reserve estimation, a standard procedure was laid down by the Committee on Assessment of Resources* of the Coal Council in the late 1950s. By this procedure, reserves have to be classified under three categories--"proved", "indicated", and "inferred" depending on their reliability as shown below:

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*of which the senior author was a member.

Table 5. Classification of Indian coals as per Indian Standard Institution.

Type	Subdivision or Group		Range of Volatiles [%] at 900+15 °C (Unit Coal Basis)	Range of Gross Calorific Value[kcal/kg] (Btu/lb) (Unit Coal Basis)	Range of Moisture [%] (Mineral Free Coal Basis)		Chief Uses
	Name	Group Symbol			Near saturation at 96% RH at 40 °C	Air Dried at 60% RH and 40 °C	
1	2	3	4	5	6	7	8
Anthracite	Anthracite	A_1	3 to 10	8330-8670 (15000-15600)	2 to 4	1 to 3	Gasification,producers,domestic stoves, and where intense local heat and no smoke are required
	Semi-anthracite	A_2	10 to 15	8440-8780 (15200-15800)	1.5 - 3	1 to 2	
Bituminous Coals(caking strength increasing from B_5 to B_2	Low volatile (coking)	B_1	15 to 20	8670-8890 (15600-16000)	1.5 - 2.5	0.5 - 1.5	Carbonization for metallurgical coke; typical coking coals
	Medium volatile(coking)	B_2	20 - 32	8440-8780 (15200-15800)	1.5 - 2.5	0.5 - 2.0	
	High volatile (coking)	B_3	Over 32	8280-8610 (14900-15500)	2 to 5	1 to 3	Coking coals,gas coals,gasification
	High volatile (semi-coking)	B_4	Over 32	8060-8440 (14500-15200)	5 - 10	3 to 7	Gas coals,gasification,long flame heating
	High volatile (noncoking)	B_5	Over 32	7500-8060 (13500-14500)	10 - 20	7 to 14	Steam-raising,gasification,long flame heating
Subbituminous Coals	Noncaking slaking on weathering	B_6	Over 32	6940-7500 (12500-13500)	20 - 30	10 to 20	Steam raising and gasification
Lignites or brown coals	Normal lignite	L_1	45 to 55	6110-6940 (11000-12500)	30 - 70	10 - 25	Steam raising, briquetting,gasification,distillation
	Canneloid lignite	L_2	55 - 65	6940-7500 (12500-13500)	30 - 70	10 - 25	

Note: All coals may be used for combustion purposes, for example, steam raising. Minor plant adjustments may be required for good efficiency, especially with low volatile coals such as A_1, A_2, and B_1.

Table 6. Composition of Indian coals.

Type	Percentages in Unit Coal				
	Carbon	Hydrogen	Nitrogen	Sulfur (organic)*	Oxygen
Anthracite A_1	> 93	3 - 4	1	0.5	1 - 2
A_2	93 - 92	3 - 4	1	0.5	1 - 2
B_1	92 - 91	4.4 - 4.6	1.5	0.5	1 - 2
B_2	91 - 87	4.5 - 5.3	1.5	0.5	2 - 6
Bituminous B_3	87 - 84	5.0 - 5.8	2	0.5	5 - 8
B_4	84 - 82	5.0 - 5.5	2.5	0.5	8 - 11
B_5	82 - 80	4.5 - 5.5	2.5	0.5	10 - 15
Subbituminous B_6	80 - 76	4.5 - 5.0	2	0.5	15 - 17
Lignites (normal) L_1	75 - 65	4.5 - 5.5	1	1	20 - 30
(canneloid) L_2	75 - 65	5 - 6	1	1	20 - 30
Peat	60 - 50	5.5 - 6.5	1 to 3	0.5	30 - 40

*Some (Tertiary) coals from Assam contain up to 4% of organic sulfur. The carbon percentages of Assam coals that have developed caking properties are lower than those shown against the groups.

- Proved reserves are those estimated from dimensions revealed in outcrops, trenches, mine-workings, and boreholes and their extension for a reasonable distance not exceeding 200 m on geological evidence. Where little or no exploratory work has been done and where the outcrop exceeds 1 km in length, another line drawn roughly 200 m in from the outcrop will define a block of coal that may be regarded as "proved" geologically.

- Indicated reserves. For these the points of observations must be 1000 m apart but may be 2000 m for beds of geological continuity. Thus, a line drawn 1000 to 2000 m in from the outcrop will demarcate the block of coal to be regarded as indicated.

- Inferred reserves are those for which quantitative estimates are based largely on broad knowledge of the geological character of the bed but for which there are no measurements. The estimates are based on an assumed continuity for which there is geological evidence and more than 1000 to 2000 m in from the outcrop.

Table 7.

Type of Coal	Air Dry Basis m [%]	Coal properties on D.M.M.F. Basis				Remarks
		V.M.[%]	C[%]	H[%]	Calorific Value [kcal/kg]	
Prime coking	1	22 - 32	88 - 91	4.8 - 5.3	8700-8850	For best coking coals VM%-25-30%,C%-88-90%,H%-4.9-5.2%
Medium coking						
[a] High volatile coals	1 - 2	32 - 37	86 - 88	5.1 - 5.4	8500-8700	
[b] Low volatile	1 - 2	20- 22	90 - 91	4.7 - 4.9	8700-8800	
Semi-coking coals	2 - 3	37 - 44	83 - 85	5.4 - 5.8	8200-8500	
Weakly coking coals*	3 - 5	38 - 46	83 - 84	5.1 - 5.6	8200-8400	On the low volatile side the VM% would be 18-20% and M-1.0%

*Some of the Karharbari coals of Central India are, however, likely to have lower volatile matter and hydrogen contents and higher carbon and energy values than the limit specified above. In the case of the abnormally high sulfur Assam coals, the air-dry moisture and carbon content (unit coal) will be lower than stipulated above. The hydrogen content (unit coal), on the other hand, is likely to be higher.

Proved coal reserves of bituminous coals (for which reliable quality data become available) have to be classified according to the quality on the basis of the analysis of seam sample as shown below:

- Low to medium volatile coals or coking coal (air-dried moisture up to 2% and volatile matter on unit coal basis up to 35%): class I, ash not exceeding 17%; class II, ash between 17 and 24%; class III, ash between 24 and 35%; class IV, ash between 35 and 50%.

- High volatile and high moisture coal (moisture more than 2% and volatile matter exceeding 35% on unit coal basis): class I, ash + moisture not exceeding 19%; class II, ash + moisture between 19 and 28%; class III, ash + moisture between 28 and 40%; class IV, ash + moisture between 40 and 55%.

- High sulfur coal: no quality classification needed.

Classification of seams according to the thickness for the purpose of mineability:

The Indian Standard Procedure (ISP) lays down that the reserves are required to be estimated for the thickness groups 0.5-1.5 m, 1.5-3.5 m, 3.5-5.0 m, 5.0-10.0 m, and above 10.0 m.

The minimum thickness of a seam considered workable in India is 1.2 m in view of the fact that mining of thinner seams is costly and that moderately thick to thick seams do exist. Thinner seams have been worked in parts of the Tertiary coalfields of Northeastern India but their production is nominal. Under special circumstances, thinner seams could be worked depending on the quality and special properties, but development in general in seams thinner than 1.2 m would mean less production per cut, extra stone work, and difficulties in ventilation and transport of coal. The prevalent method of mining in India is board and pillar and this is likely to continue for a few decades more as the most popular method.

For this mining method the classification of seams is as shown below:

- A thin seam is 1.2 to 1.83 m thick,
- A moderately thick seam is 1.83 to 4.57 m thick, and
- A thick seam is more than 4.57 m thick.

The ideal thickness for longwall mining with caving is reckoned as 1.5 to 2.4 m. The following classification may be adopted in future for longwall mining:

- Thin, 1.2 to 1.5 m
- Moderately thick, 1.5 to 2.4 m
- Thick, more than 2.4 m.

Coal Resources:

The total reserves of coal in India have been recently estimated [5] for seams 1.2 m and above in thickness and generally down to a depth of 600 m to be of the order of 83,745 Mt. The reserves of lignite are of the order of 2099 Mt (see Table 8).

However, there are many coalfields and parts of developed coalfields that are still lying virgin and unexplored. The reserves are, therefore, likely to change when additional data become available. Additional resources are not only likely to be available from depths beyond 600 m, but also from seams of 0.5 m to 1.2 m thick. In fact, resources of coals from such thin seams from three coalfields of the Damodar Valley alone are of the order of about 1500 Mt down to a depth of 600 m.

Table 8. India's coal reserves (Mt).

Location	Proved	Indicated	Inferred	Total
GONDWANA COALS				
Damodar/Koel Valley	13,507.56	21,604.32	15,963.10	51,074.98
Outside Damodar Valley (Deoghar group Rajmahal)	119.76	989.78	2,157.78	3,267.32
Sone-Mahanadi Valley	4,839.20	6,471.71	9,203.71	20,514.62
Satpura Basin	391.98	403.35	1,643.47	2,438.80
Pranhita-Godavari Valley	1,718.53	2,413.35	1,344.06	5,475.94
Total	20,577.03	31,882.51	30,312.12	82,771.66
TERTIARY COALS				
Northeastern India	161.21	191.71	549.06	901.98
Northwestern India	-	-	71.00	71.00
Total	161.21	191.71	620.06	972.98
Grand Total	20,738.24	32,074.22	30,932.18	83,744.64
LIGNITE				
South India (Tamil Nadu)	1,717.00	202.00	-	1,919.00
Rest (western and north-western India)	141.56	-	28.70	180.26
Total	1,858.56	202.00	28.70	2,099.26
Type of Coal				
Prime coking	3,251.89	1,586.26	460.73	5,298.88
Medium coking (high and low volatile)	3,793.33	4,275.20	1,308.03	9,376.56
Semi- to weakly coking	1,206.16	2,600.98	914.79	4,721.93
Noncoking	12,486.86	23,611.78	28,248.63	64,347.27
Total	20,738.24	32,074.22	30,932.18	83,744.64

Of the lignite deposits in the country, the most important one, constituting about 91.4% of the reserves, occurs in one state only (Tamil Nadu) in fuel-starved south India.

COAL PRODUCTION IN INDIA

Production of coal in India has grown substantially in the last few years to about 102 Mt in 1976-1977 from a level of 72 Mt in 1971-1972. The average growth rate is about 8.2% per annum during this period.

India's First Five Year Plan started in 1950-1951 and continued up to 1955-1956 and, thereafter, the planned growth followed successively in the form of Second, Third, and Fourth Five Year Plans. The total built-up capacity of coal in India at the end of successive plan periods continued increasing, but the actual production had to be kept below the optimum levels due to the inability of other industries to consume this coal. The reasons are obvious and characteristic of a developing economy highly influenced by the interaction of general global economic pressures.

1973-1974 witnessed one of the world's worst periods of economic recession and inflation which even affected the developed countries.

Thus, though the built-up capacity may attain a level of about 125 Mt per annum in 1978-1979, production may necessarily have to be pegged down to a lower level commensurate with demand. It is expected that the demand may pick up by the end of 1978-1979 to 114-115 Mt and 213-215 Mt in 1987-1988.

Use of Coal in Different Industries

The country has substantial reserves of coal and occupies 8th position in the world with about 0.8% of the world's total reserves. The industries are more or less getting oriented toward using coal as a basic fuel.

Resources of the Good Quality Noncoking Coals

It is estimated that a total 3762 Mt of good quality noncoking coals (6100 ± 200 kcal/kg) will be available. Of this, a total of 1205 Mt are in the proved category and the rest in the indicated and inferred categories. Of the proved reserves again, 471 Mt of coal are likely to have a gross energy value of 6300 ± 200 kcal/kg. About 65% of the good quality coal estimated occurs only in the Raniganj Coalfield in the eastern part of the country. The sulfur content of the good quality coals is also low--0.5 to 0.7%.

Additional reserves of good quality noncoking coals are expected to occur in the Tatapani-Ramkola, Hasdo-Arand, and Mand-Raigarh coalfields in the Sone-Mahanadi Valley in the central part of the country. These coalfields are still lying virgin.

Table 9. Consumption of commercial and noncommercial energy from 1950-1951 to 1970-1971 and projected demand up to 1990-1991 (in million tonnes of coal equivalent).

Year	Commercial Energy				Noncommercial Energy				Grand Total Commercial and Noncommercial
	Coal*	Oil**	Hydel and Nuclear	Total	Firewood	Cow Dung (Dry)	Vegetable Waste	Total	
1950-1951	32.80	6.80 (3.40)	2.90 (2.90)	42.50	80.75 (85.00)	25.20 (45.00)	19.50 (25.00)	125.45	167.95
1955-1956	38.40	8.80 (4.40)	3.70 (3.70)	50.90	84.55 (89.00)	27.44 (49.00)	22.62 (29.00)	134.61	185.51
1960-1961	47.10	13.50 (6.75)	6.57 (6.57)	67.17	95.98 (101.04)	31.01 (55.38)	24.24 (31.08)	151.23	218.40
1965-1966	64.20	19.88 (9.94)	12.74 (12.74)	96.82	106.23 (111.82)	34.31 (61.28)	26.83 (34.41)	167.37	264.19
1968-1969	68.40	25.32 (12.66)	17.96 (17.96)	111.68	112.61 (118.54)	36.38 (64.98)	28.44 (36.46)	177.43	289.11
1970-1971	71.10	29.90 (14.95)	22.09 (22.09)	123.09	116.62 (122.76)	37.67 (67.28)	29.46 (37.77)	183.75	306.84
1978-1979	115.10***	49.0 (24.5)	55.0 (55.0)	219.10	125.40 (132.00)	36.40 (65.00)	35.88 (46.00)	197.68	416.78
1983-1984	170.36***	66.4 (33.2)	89.0 (89.0)	325.76	124.45 (131.0)	36.40 (65.0)	35.88 (46.00)	196.73	522.49
1990-1991	259.20***	105.0 (52.5)	164.0 (164.0)	528.20	115.90 (122.0)	29.68 (53.00)	35.88 (46.00)	181.46	709.66

*Including coal used for power generation.

**Exclusive of oil products used in nonenergy sector.

***Coal demand as per the assessment now being carried out by the working group.

Figures within brackets are in million tonnes except in column 4 where it is 10^9 kWh.

(cont'd)

Table 9 (cont'd)

The following conversion factors have been used to arrive at coal equivalent:

Fuel	Unit	Coal equivalent
Average Indian coal (5000 kcal/kg)	1 t	1 t
Oil	1 t	2 t
Electricity	10^9 kWh	-
Firewood	1 t	0.95 t
Cowdung (dry)	1 t	0.56 t
Vegetable Waste	1 t	0.78 t

The commercial energy under coal and oil do not include the nonenergy sector.

The demand for oil and hydel/nuclear and noncommercial energy has been taken as Case II from the Fuel Policy Committee report.

Resources of Metallurgical Coals

While the resources of such coals are inadequate compared to the vast iron ore resources of the country, a recent study [4] has shown that it should be possible to produce more than 4200 Mt of hot metal with the indigenous resources of metallurgical coals by taking to both conventional and nonconventional techniques of coal carbonization and beneficiation.

The country, therefore, possesses a great asset in her ample reserves of coal which can make a significant contribution not only to the growing energy needs but also to meet the foreseeable demands of the metallurgical, chemical, and gas industries.

IMPORTANCE OF COAL IN NATIONAL ENERGY SCENE

Coal provides and will continue to be the major source of commercial energy in India due primarily to the availability of large reserves, favorable mining conditions, and limited resources of petroleum. The national energy policy adopted by the Government of India highlights, amongst other things, the following:

- Oil will be substituted wherever technically and economically possible by other forms of energy.
- The exploration, exploitation, and utilization of coal will be programmed according to this policy, while indigenous production of oil is maximized and imports reduced by that extent.

- The national energy policy will require production of electricity from water, coal, and nuclear resources.

The consumption of commercial and noncommercial energy (in million tonnes of coal equivalent) from 1950-1951 to 1970-1971 and the projected demand up to 1990-1991 is shown in Table 9.

The largest single industry using coal is the power sector. This is followed by the steel industry. Consumption of coal by the Indian railways, who were formerly the largest buyers of coal, has been declining because of dieselization and electrification. On the other hand, the requirement of coal by the power sector, the steel industry, and by other industries is likely to go up.

Organizational Set-Up for Coal Mining Industry in India

Till 1956, the coal industry in India was largely in the hands of private companies. This gave a rather retarded growth of this basic industry. In view of this and a few other reasons, the Government had to come in to exploit coal reserves that so far had not been worked due to difficult mining conditions, location, nonavailability of essential infrastructure, etc. The first public sector enterprise--the National Coal Development Corporation (NCDC)--was set up in October 1956 with a nucleus of 12 mines owned by the then State Railways. Another public sector company (under Andhra State)--Singareni Coal Co. Ltd.--had been set up earlier. Later, in 1971, all the coking coal mines were nationalized and a new company--Bharat Coking Coal Ltd.--was formed. Subsequently, in 1973, all the remaining noncoking coal mines with the private sector were nationalized. At present, the entire coal mining in India is vested with the five public sector coal producing companies. These are Bharat Coking Coal Ltd., Western Coalfields Ltd., Eastern Coalfields Ltd., Central Coalfields Ltd., and Singareni Coal Co. Ltd. The first four are under Coal India Ltd., the holding company. However, a few captive mines, owned by the two major steel plants belonging to very large industrial houses were not nationalized and were left to be operated by these companies.

Simultaneously, the Government set up another company--the Central Mine Planning and Design Institute (CMPDI)--for comprehensive long- and medium-term planning, project design and appraisal, research, development, geological exploration, detailed engineering design, and scientific processing of geological data for all future plans of action in the coal sector and related jobs to give total planning support to the entire coal industry.

The coal industry is also supported by the Central Mining Research Station. Recently, the Trial, Research and Development Department of CMPDI under Coal India Ltd. has also started various field trials. CMRS has provided research in almost all fields of mining. Safety is enforced statutorily by the Directorate General of Mines Safety. Mining education of a high order is provided by about 20 Institutions located in various parts of the country.

Coal Exploitation

Coal is exploited by both underground and open-pit mining. About 25 to 27% of the total production comes from open-pit mines. The pit-head cost of production is quite low mainly due to cheap labor and the incidence of less capital. The sizes of the underground mines are quite small with an area varying between 1 and 4 km^2 and average production between 2 and 5 Mt/year. The size of the mechanized open-pit mines varies between 3 and 25 Mt/year.

India has followed a technology best suited to its socioeconomic and technoeconomic conditions as listed below:

Socioeconomic

- Lower wage costs and the necessity to create employment.
- Scarcity of capital.

Technical

- Hard coal seams; Protodykanov index generally 1.5 to 2.5.
- Dip generally 2° to 20°.
- Thickness 1.2 to 15 m.
- 1500 to 2000 Mt coal standing on pillars due to board and pillar mining.
- Multiple and contiguous seams.
- Seams liable to spontaneous heating.
- Present depth of mining in most of the mines 100 to 240 m.
- Generally less gassy seams.
- Considerable underground mining operation is below coal seams on fire and old goaves sometimes containing water.
- Shortage of stowing materials in most of the coalfields.
- Generally massive hard sandstone roofs.
- Easy mining conditions compared to coalfields in the UK, the FRG, France, Poland, the USSR, and China, but not as good as in the best coalfields of the USA.
- Quality of coal--both coking and noncoking--generally with ash from 13 to 45%.
- Difficult washing characteristics.

- Generally in-seam mining due to shallow depths and requirement of less development cost.

Opencast Mining

Wherever there is a single seam and a dip less than 10°, draglines are used at most of the places. Electric shovels with dumpers are the main equipment because of the presence of a number of seams and rather steep gradients. Recently, some scrapers have also been introduced. At present, 4.6 to 8.0 m^3 capacity shovels and 17 and 23.5 m^3 dumpers are in use in a fairly large number of mines. The capacity of the largest dragline in use is 30 m^3.

In future, it is proposed to increase the stripping ratio of opencast mines to 5:1 from the present day 3:1. The depth of mechanized opencast mines at present varies from 30 to 60 m. In another two decades, the maximum depth of mining will be about 150 to 180 m, for which belt conveyors and skips with crushers near the face are contemplated.

Opencast mines have also been planned for working of developed coal reserves of the Jharia Coalfield which are on fire in places.

The manufacture of opencast mining equipment, including shovels, dumpers, drills, and dosers, has already started and these are currently being used in the Indian mines.

Underground Mining

The board and pillar system of mining has long been in vogue--about 97% of production from underground coal mines is by this method. Although it is associated with numerous disadvantages such as low productivity, low production from the districts, greater loss of coal in the underground working, etc., because of its lower capital requirement and wage costs and because of its greater employment potential, this method was and is predominant in India. It is applied to thick coal seams either by using hydraulic stowing or by working in two lifts leaving a minimum of 3 m parting between two such working horizons. Location of working horizons was generally in good quality coal sections. Extraction of pillars is done either with open caving or stowing depending on the surface conditions. Reserves of 1500 to 2000 Mt, mostly in thick seams, are still standing in pillars lying developed.

So far, manual loading of coal into the tubs has been practiced. The country also manufactured all the machines required for board and pillar mining. Earlier, NCDC and a few other companies had introduced shuttle cars with "gathering arm loaders", and continuous miners. Both the technical and the technoeconomic results were found to be just compatible with manual loading, but with today's higher cost of imported equipment, mechanized mining is likely to be costlier. The same is also true for using the shearer on stowing faces.

A fairly large number of trial longwall faces are envisaged. At present five longwall faces with caving are being worked using 40 t friction props; and within a year a few more faces with shearers will be commissioned. For thicker virgin seams, successive descending slices using wire netting with caving and sublevel caving using wire netting are being adopted.

Output per manshift in the coal industry is now about 0.7 t and it is envisaged to improve it to 0.84 t by 1983-1984. While the technical competence to exploit the coal reserves by newer mining technology is available, the latter is proposed to be introduced in a phased manner for obvious reasons. Introduction of the mechanized longwall system in selected mines, improvements in hydraulic sand stowing techniques, methods of dealing with underground fires, and many other schemes have been initiated as a part of R&D efforts. Trials with scrapers, side loaders, and load haul dumper in board and pillar mining are being increasingly encouraged.

Underground Horizontal Transport and Winding

About 85% of coal production from underground mines is handled by rope haulage. Use of belt conveyors and locomotives has been made only when the production is higher and the technoeconomics justified it. However, diesel, battery, and trolley-wire locomotives are also being used in certain mines working flat coal seams. In the reorganized mines, the transport system is being modified to meet current requirements. The proportion of production handled or proposed to be handled by 1985-1986 is given in Table 10.

Table 10. Trend of types of main underground horizontal transport [%].

Method	1976-1977	1985-1986
Rope haulages	85	66
Belt conveyors	12	26
Locomotives	3	8

No facility for the transport of people underground is required in view of the short traveling distances. A few installations have been planned during the next decade for the transport of men in mines involving traveling over long distances and steep gradients.

Both steam and electric winders are in use. A few large mines also have Koep wheel (friction) winders with skip installations.

Coal Beneficiation

Run of mines coal is being beneficiated in 14 washeries having a total input capacity of about 26 Mt per year. At present about 72% of the total production of prime coking, medium coking and blendable coal is beneficiated in the various washeries. In respect of noncoking coals a number of beneficiation/deshaling installations are being developed.

Transportation, Coastal Shipping, and Export

Indian Railways constitute the primary mode for movement of coal to the consumers, the next important mode of transport being by road. Consumer's own railway systems, belt conveyors, and aerial ropeways are the other means of transport where geographical location of the points of production and consumption makes such means of transport convenient and economic. About 78% of the total production is moved by rail, 16% by road and the remaining 6% by other means. Due to the scarcity of crude oil, movement by road will gradually be restricted.

Having a long coast line, India takes advantage of it to supplement coal transport by coastal shipment specially for southeast and southwest consuming points. Shipping facilities presently available at the Indian ports are as shown in Table 11.

Table 11.

Port	Draft [m]	Average Loading Capacity
Haldia	12	3000 t/h (40,000 to 60,000 DWT ships can be accommodated)
Paradeep	10	2500 t/day (40,000 to 60,000 DWT ships can be accommodated)
Vishakapatnam	9	(Suitable for 30,000 DWT ships)
Calcutta (Diamond-Harbour)	Limited	Manual loading (only ships of 8000-9000 DWT can be accommodated)

Welfare Amenities

The coal mining industry in India provides welfare amenities of a high order in the shape of houses, colonies, schooling and medical facilities; scholarships and provision of holiday homes to its employees apart from providing a fair wage structure.

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THE PRESENT SITUATION OF THE JAPANESE COAL INDUSTRY AND THE OUTLOOK FOR THE EXPANSION OF COAL SUPPLY AND DEMAND IN THE FUTURE

T. Ishihara

HISTORY OF THE JAPANESE COAL INDUSTRY

Before the Oil Crisis

Domestic coal resources played a significant role in primary energy supplies and furnished the foundation for industrial rehabilitation; history underwent a dramatic transition.

Coal production was only 10 Mt in 1945 and increased year by year; the peak of production was attained in 1961, when 55 Mt was produced by 800 coal mines in Japan.

The number of laborers engaged in the coal industry was 280,000, while those in related enterprises exceeded one million.

However, due to the liquid energy revolution, a decision was taken in 1955 to decrease the cost of coal by $3.50/t to maintain the competition. The government rendered assistance to the coal industry five times but in spite of this, the coal industry went into a decline.

In 1973, just before the oil crisis, only 30 coal mines existed and the percentage of domestic coal in the primary energy supply decreased sharply to 3.8% (21 Mt) compared with about 35% in 1960.

Laborers in coal mines dropped to 24,000--less than one tenth of before. The reason why this level of production could be maintained with less laborers was due to a significant improvement in productivity to 70 t per man per month from 16 t.

Japanese coal mines operating underground provide quite bad natural conditions; a half of the production is mined from under the sea.

- Coal in Japan was created in the Tertiary period, a newer era than that in the main coal producing countries.
- The geological conditions are bad; that is, the roof and floor of coal seams, in general, are soft and coal seams have many faults and foldings, which separate into small blocks.

- The average depth of mining faces is 540 m, and hence the earth pressure is high and the methane gas gushing increases to average 45 m^3/t of produced coal bringing problems of safety. Water effusion, gas gushing, spontaneous combustion, etc. are overcome technically.

  A productivity of about 30 t of raw coal per man per shift is attained by the application of self-advancing supports for the long wall and by machanization at the mining faces.

After the Oil Crisis

Coal policies before the oil crisis were social policies in the direction of reducing production mainly by "scrap and build". However, coal policies after the crisis have been given another look as a part of the total energy policy in the following way:

- to maintain a domestic coal production of 20 Mt;
- to proceed smoothly and efficiently to the import of overseas coal by development; and
- to promote research on technologies for the efficient use of coal.

Consequently, there was a significant modification from a direction of calm retreat to one of positive reconstruction.

National assistance to the coal industry amounted to $\$440 \times 10^6$ per annum, but the subsidy related directly to production is about $\$230 \times 10^6$.

TRANSITION OF COAL DEMAND

The demand for the 55 Mt of domestically produced coal in 1961 was as follows:

6.0 Mt for the steel industry;
4.0 Mt for the gas industry;
2.0 Mt for the coke manufacturing industry;
16.5 Mt for electric power;
3.5 Mt for home heating; and
19.0 Mt for other industries (cement, etc.).

In all, the use for fuel purposes was 60%, while 12 Mt of metallurgical coal were imported for the steel, coke manufacturing, and gas industries.

Thus the total demand was 67 Mt, of which 51% was for coke manufacturing and 49% for fuel. The coal amounted to about 37% of the primary energy source.

Thereafter, the availability of cheap oil and severe restrictions on pollution, etc. had the effect of decreasing the demand for steam coal year by year.

The production of domestic coal in 1975 amounted to 19 Mt, which was used as follows:

6.3 Mt for the steel industry;
1.0 Mt for the gas industry;
1.7 Mt for the coke manufacturing industry;
8.0 Mt for electric power;
1.0 Mt for home heating; and
1.0 Mt for other industries.

Steaming coal and metallurgical coal had about an equal share.

The import of coal increased sharply because of the expansion of the steel market and amounted to 62 Mt, most of which was metallurgical coal but including some 500 kt of steam coal.

Total demand of coal was 81 Mt, out of which about 81% was metallurgical coal, and steam coal decreased its share to 18%.

The percentage of coal in the primary energy supply was 16.5%--45% of the share recorded 14 years ago.

FUTURE OUTLOOK FOR COAL SUPPLY AND DEMAND

On the basis that the oil supply will be increasingly restricted in the long term, the target is to switch to alternative energies to lower the ratio dependent on oil in Japan.

According to an interim report by the General Energy Council in June, 1977, another look must be given to the significance of coal and it is necessary to expand the demand for fired power plants.

The supply and demand for coal in 1985 will be 113 to 122 Mt and in 1990, 144 Mt.

Therefore, the percentage of coal in the primary energy supply will be 11.9 to 14.5% in 1985 and 15.9% in 1990.

From the viewpoint of supply, it is the present intention to maintain 20 Mt of domestic coal production, so that most of the increase will come by the importation of coal--93 to 120 Mt in 1985 and 144 Mt in 1990, out of which steam coal is 6 to 16 Mt and 40 Mt respectively.

The expansion of demand for imported steam coal is expected to result in new coal-fired power plants being constructed near the sea.

The followings are themes to be discussed as measures to promote the importation of coal from overseas:

- Acquisition of stabilized supply sources and diversification of sources;
- Rationalization of transportation;
- Reception system and consolidation of facilities;
- Acquisition of sites for coal-fired power plants;
- Countermeasures against legislation on coal industrial pollution by SO_x, NO_x, etc;
- Acquisition of an ash disposal area; and
- Financing.

The development of technologies for the changeover to coal is proceeding in both the government and the private sector. They are:

- Low temperatured gasification of coal;
- Extraction of SRC as a binder for coke manufacturing; and
- Liquefaction of coal.

Japan with 30% of the world's coal trade wants to promote stabilized sources with regard to quantity, quality, and price with the cooperation with coal producing countries.

POLAND'S ENERGY RAW MATERIALS--RESOURCES, EXTRACTION, AND UTILIZATION UP TO THE YEAR 2000

Z. Nowak, T. Muszkiet, and Z. Gendek

INTRODUCTION

A policy of maximum satisfaction of the growing energy needs of Poland by domestic primary energy carriers has been carried out since 1945. Hence, prospecting for energy raw materials and development of mining of these materials occupied the top position in the government's raw material policy and numerous new bituminous and brown coal deposits were discovered (Figure 1). Other organic energy raw materials are insignificant (Figure 2).

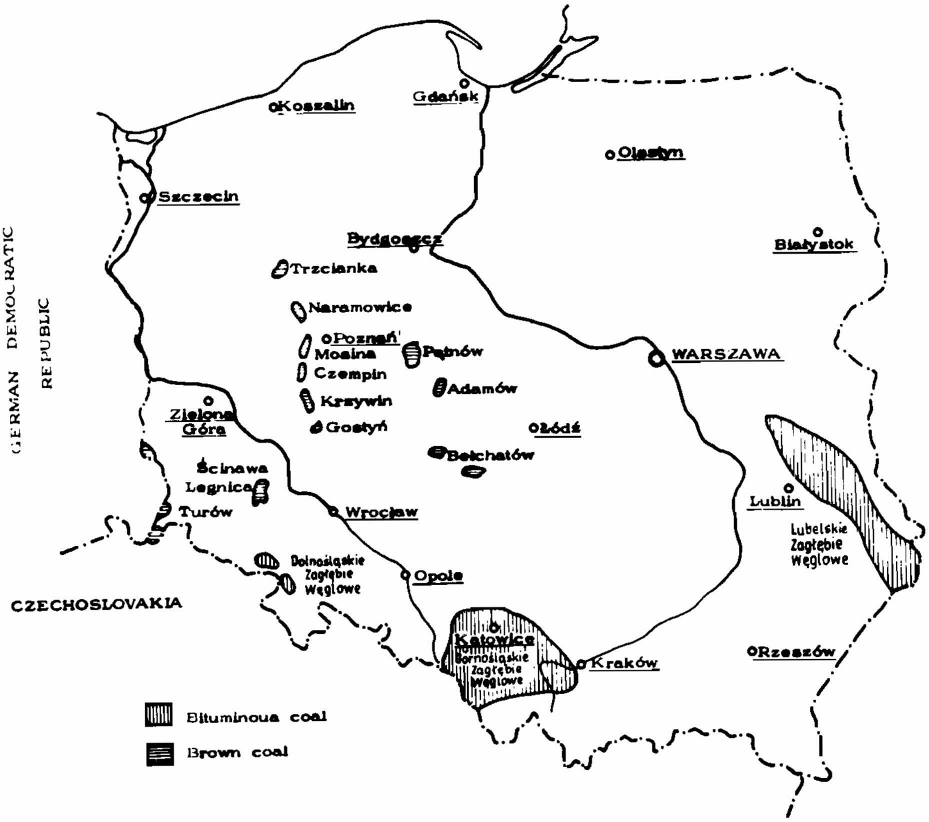


Figure 1. Location of the main Polish coalfields.

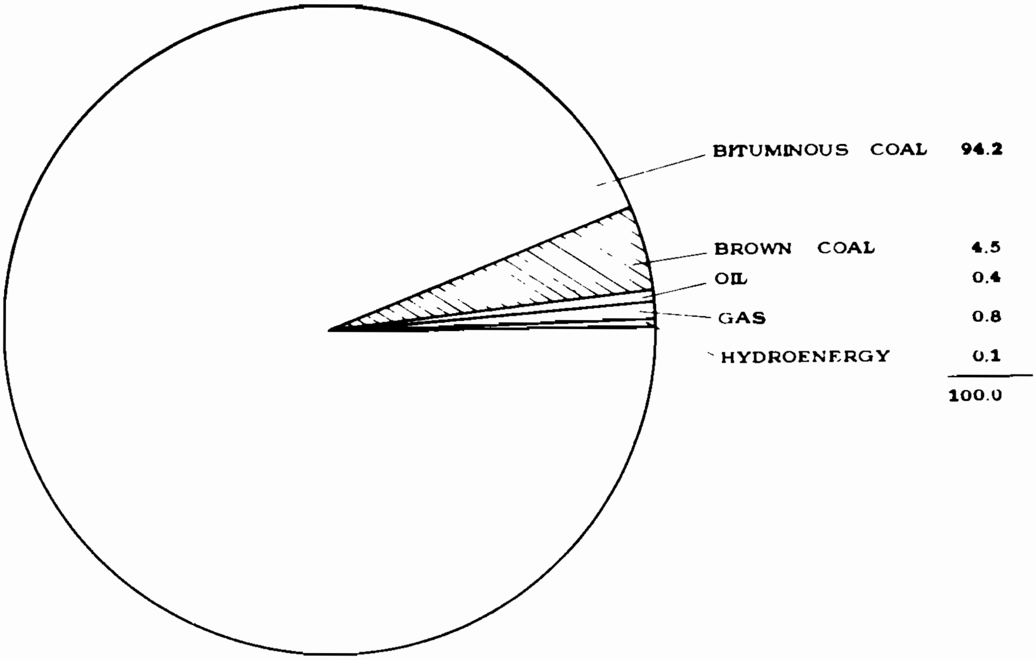


Figure 2. Energy resources of Poland–distribution.

The development of mining brought about an increase in the extraction of energy raw materials (Figure 3), both for home needs and for export. Poland occupies second place in the world's bituminous coal exporters with an export of about 40 Mt per year.

The limited resources of natural gas and particularly of crude oil constrains Poland to import these raw materials in quantities indispensable for the correct development of the economy though the principle of maximum utilization of home energy raw materials in the fuel and power balance still persists.

The latter policy has been reflected in the development of advanced methods for an integrated coal exploitation. Poland is one of the leading countries using combined heating and electricity generation for towns and big housing estates. The production of pelletized coke from noncoking coals is on commercial scale. And some years ago research work on new coal conversion methods was also started.

These techniques will be continued at higher intensity because of the need for further increases in energy consumption in the national economy up to about 300 Mt/year of bituminous coal and about 150-200 Mt/year of brown coal in 2000.

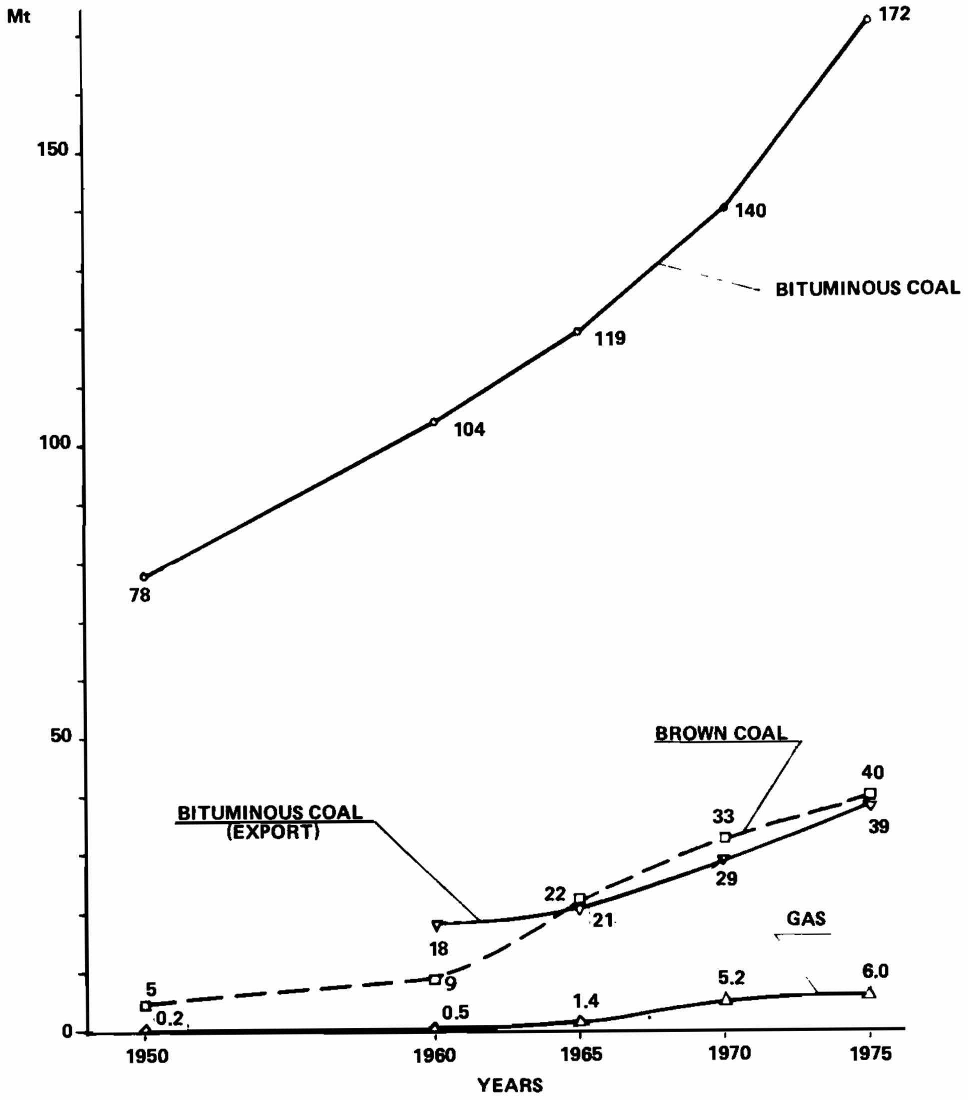


Figure 3. Primary energy production–1950 to 1975.

CHARACTERISTICS OF POLISH BITUMINOUS COAL DEPOSITS

The bituminous coal deposits in Poland are associated with the Carboniferous system which is some thousands of meters thick. Three coal-bearing formations are known so far:

- The foredeeps with which the Upper Silesian Coalfield is connected;

- The interplatform depression with which the Lublin Coalfield is connected;

- The coal-bearing formations of intermountain depression with which the Lower Silesian Coalfield is connected.

Reconnaissance of coal measures to a depth of 1000 m is precise, while to the depth of 2000 m it is sufficient to assess the state of potential resources. The aggregate bituminous coal resources according to actual reconnaissance and assessment of geologists are about 250 × 10^9 t. Details of the bituminous coal resources are shown in Table 1: the whole range of rank occurs. Polish bituminous coals have favorable characteristics for their use, namely, low ash content and therefore good washability, good grindability, and low sulphur content (about 1%, except for coals of the Siersza, Jaworzno and Libiaz areas), and this gives a relatively clean energy supply from coal.

Table 1. Bituminous coal resources of Poland.

Type of resources	10^9 t
To a depth of 1000 m	
workable*	51.5
nonworkable	9.7
estimated	5.3
Explored, total	66.5
Possible to a depth of 1000 m	69.1
Possible to a depth of 2000 m	74.5
Potential, total	210.1

*Criterion for workability: depth of seam not greater than 1000 m, seam thickness not less than 0.8 m for power coals and 0.6 m for coking coals, dip not more than 20°.

The geological and mining conditions vary in particular coalfields and also within a coalfield.

In the Upper Silesian coal field the formations occur in an area of 5400 km^2 and about 4500 m in depth; the rank increases with depth. Generally, power coals occur in the eastern and central part of the coal trough, while coking coals mainly in the western part.

The Lower Silesian coal field is the least important with respect to rich coal and has exceptionally hard geological and mining conditions--highly variable and irregular. These coals are worked primarily on account of their very high quality: they are coking coals with a very low sulphur content (0.1 to 0.9%), a very low phosphorus content (0.01 to 0.015%), and a very low ash content. The deposit is in two separate areas, the Walbrzych and the Nowa Ruda area.

Lublin Coalfield (Figure 4) is an extension of the north-western part of the Leopol-Wolynian coalfield where coal has already been worked. It is a very deep-lying deposit extending in Poland from the frontier with the USSR to the Vistula--an area of about 5000 km^2. The workable resources to a depth of 1000 m are about 40×10^9 t by present-day estimates, although only the central part of the coalfield, the Central Coal Area with reserves of about 4×10^9 t is being developed. The Lublin coals, both power and coking, do not differ from the Upper Silesian coals in quality.

CHARACTERISTICS OF POLISH BROWN COAL DEPOSITS

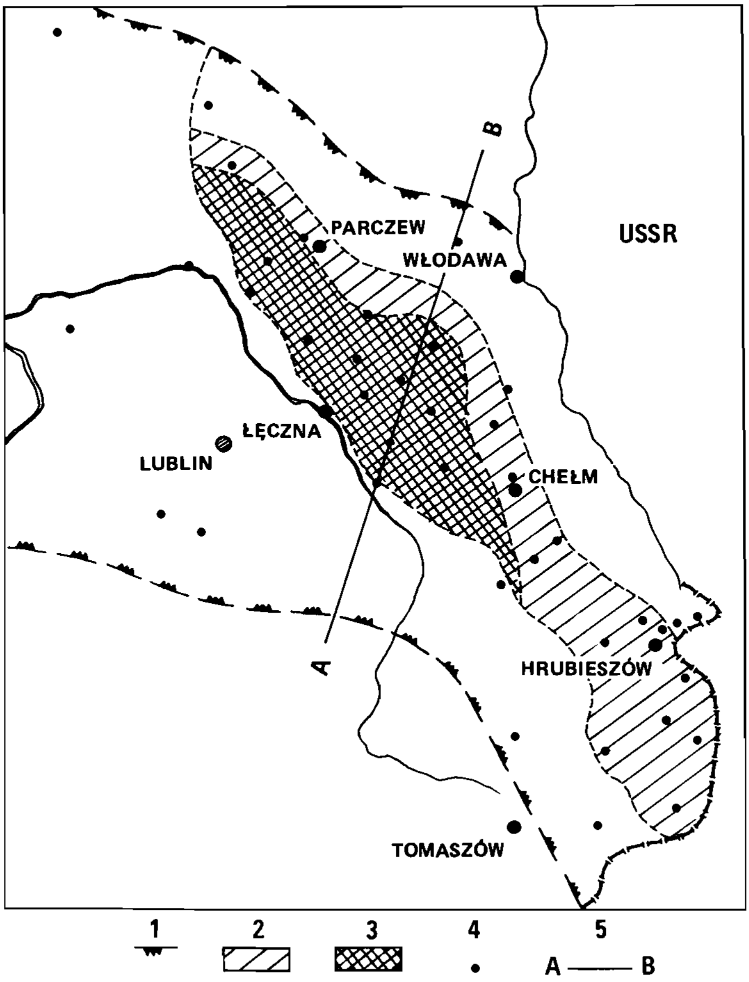
These occur in Poland mainly in Tertiary formations, and those of Miocene age are of the greatest commercial importance. They are found mostly in western, central, northern, and partly eastern Poland (see Figure 1). It is hoped that current intensive prospecting will lead to further discoveries.

A number of brown coal areas are distinguished:

- The Wroclaw Area covering the Turów, Babina, Ścinawa, Legnica, and Mosty deposits;
- The Poznań Area including, for example, the Patnów, Adamów, Mosina, Czempin, Krzywin, Gostyń, Naramowice, Trzcianka deposits;
- The Lódź Area covering, for example, the Belchatów, Rogoźno and Szczerców deposits; and
- The Zielona Góra Area covering the recorded deposits of Sieniawa, Gubin, and Cybinka.

These commercial deposits have different richness varying from some tens of millions to some milliards (10^9) of tons. The total proven and recorded deposits is about 14×10^9 t.

Brown coal deposits are highly differentiated with respect to geological and hydrogeological structure and this frequently calls for an individual approach to choice of methods for opening the deposit and for its working. The depth of seams is from some tens to more than 200 m (Figure 5). The ratio of overburden to coal varies from 2.6 to 9.0. The Polish brown coals are classed as earthy coals with an insignificant content of lignites. They contain about 50% water and their energy value varies from 1600 to 2400 kcal/kg.



1. The area of the occurrence of the Carboniferous deposits.
2. The occurrence of commercial coal seams.
3. The occurrence of numerous commercial seams (the area for coal mining prospects).
4. Borehole.
5. Cross-section line.

Figure 4. Lublin coal basin.

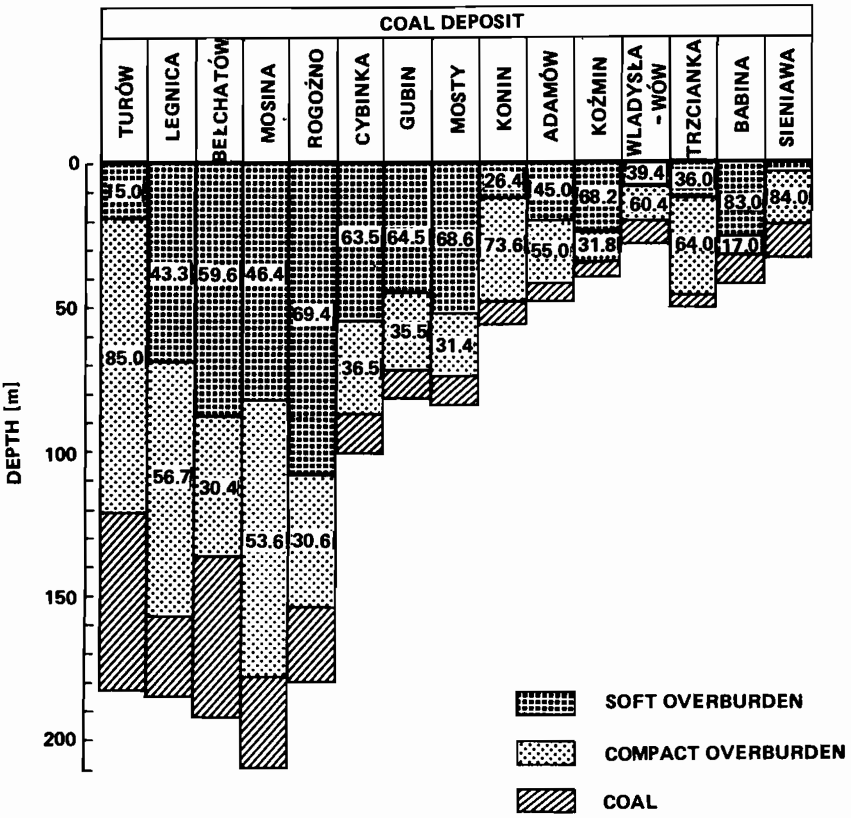


Figure 5. Profiles of the Polish brown coal basins.

TECHNICAL CONDITIONS FOR THE DEVELOPMENT OF BITUMINOUS COAL PRODUCTIONS

The development of the Polish coal mining industry after the second world war was characterized by a change of geological and mining conditions of mining coal deposits. At present, the average mining depth is more than 400 m: in the next decade it will increase to 500 m except for deeply lying seams in the Lublin Coalfield.

More than 40% of coal production is from seams of 3.5 to more than 20 m thick. They are worked by lifts with the use of hydraulic stowing. Most production comes from seams inclined up to 20°.

The problem of gassiness has appeared with the construction of new mines in Rybnik Coal Area and with the deepening of old mines.

The development of bituminous coal production in Poland during the past 15 years is shown in Table 2. This period showed a large increase in production, particularly in the past ten years during which intensive introduction of mechanized longwall working has taken place. The mechanical working index increased by about 3% per year on average and has virtually reached a limit of about 94%--hence the high productivity. Possibilities of further increases in productivity are to be expected from the use of longwall sets, i.e. of sets of equipment and machines allowing the mechanization (and partly automatization) of coal extraction and transport and of protection of the mine workings. The use of longwall sets and of machines for mechanization of development work is the highest stage of orthodox underground coal mining in Poland and determines the limit of productivity.

Table 2. Basic technical and economical indices of bituminous coal mining.

Index year	Net production [Mt]	Amount of cleaned coal [Mt]	Annual average increment in production [%]	Production from one working face [t/day]	Number of sets for integrated mechanization of mining	Production with the use of integrated sets [%]	Index of mechanized mining [%]	Employment [10^3 men]	Average production per man [t/year]	Average annual increment in production per man [%]
1960	104.4	61.9		256	-	-	32	318	328	
			2.6							2.0
1965	118.8	66.7		403	-	-	66	328	362	
			3.3							3.2
1970	140.1	78.3		608	22	3.8	83	330	424	
			4.1							2.9
1975	171.6	88.6		750	218	39.3	94	340	504	
1980	207.5	110		1100		70.0	95			

The quantity of bituminous coal in Poland allows its production to be further developed. The programs anticipate three lines of development:

- Extension of current mines with suitable coal resources;
- Development of a Central Coal Area in the Lublin Coalfield with a final coal production of 4 Mt/year; and
- Construction of new mines in the Upper Silesian Coalfield.

The training of miners for future mines will be a more serious problem. Modernization of existing mines and construction of new ones should result in an increase in productivity that will ease the problem of employment. But it seems improbable that a further increase in production will be attained without increasing employment. Effort made in this field during the past 15 years (1960 to 1975) resulted in an increase in production of about 70 Mt (65%) and this was obtained with an increase in employment of only about 7%. This exhausted the majority of reserves created as a result of application of integrated mechanization of coal mining. Poland is one of the leading countries of the world in productivity of underground working of coal.

The development of coal production will be accompanied by other activities:

- Extension and modernization of a transportation system to ensure the transport of about 1 Mt of coal per day from the most populated area of the country;
- Further development in coal cleaning techniques with particular reference to their desulfurization and corresponding technologies for industry;
- Construction of new settlement districts, municipal projects, services, etc.

The problem of the protection of the environmental from the effects of mining specific to the Upper Silesian area are in particular:

- Prevention of uncontrolled subsidence by appropriate control of the coal production process;
- Elimination of the contamination of water courses by saline mine water. At present, there are a number of ideas on how to prevent this;
- Utilization of about 100 Mt of waste material per year: it is hoped that this waste can be left underground more than at present, and that the rest can be used as building and road material.

TECHNICAL CONDITIONS FOR THE DEVELOPMENT OF BROWN COAL PRODUCTION

The geological structure of the overburden and of the deposit determines the mining conditions and the technology for extracting, transporting, and dumping. Usually, removal of overburden is possible with high-capacity bucket ladder excavators: in some cases blasting (compact boulder clays and cohesive rocks), or hydraulic mining are also necessary.

Protecting the stability of open pit slopes and dumps is a basic problem calling for a detailed analysis and prediction for safe working, sizing slopes, and the technology of dumping.

Brown coal mining was unknown in Poland before the last war, but has developed into a large industry (see Table 3). There are several possible ways that brown coal production could be increased and these will be the subject of further analyses as the balance of power and energy of the country become more precisely defined.

Table 3. Basic indices of brown coal mining.

Year	Production [Mt/year]	Employment [10^3 men]	Annual production per man employed [t]	Annual increments		Overburden removed	
				production [%]	employment [%]	volume [10^6 m^3]	per ton of coal [m^3]
1960	9.3	9.6	967			20	2.1
1965	22.6	13.2	1712	19.4	6.6	60	2.7
1970	32.8	13.1	2503	7.7	-	85	2.6
1975	39.9	12.9	3093	4.0	-	117	2.9
1980	41	13.0	3150	0.6	-	230	-

Figure 6 shows one possible development of brown coal production. Although inadequate for needs in the year 2000, its implementation will require a twofold increase in employment for the more than 2.5 times increase in production.

The increasing mining depth, in spite of higher coal concentration, will bring about an increase in coal production costs and capital expenditure. The necessity for full land reclamation after mining will be a substantial problem determining the rate of development of brown coal production. Particularly important is the further concentration of output and the use of machines with much higher capacities.

THE FUTURE STRUCTURE OF THE ENERGY BALANCE OF POLAND

The program of energy development involves a reconstruction of fuel and energy consumption in the following way:

- considerable development of electric energy industry;
- wider application of combined heat and electricity generation;
- gradual elimination of coal as a fuel used in a nonconverted form.

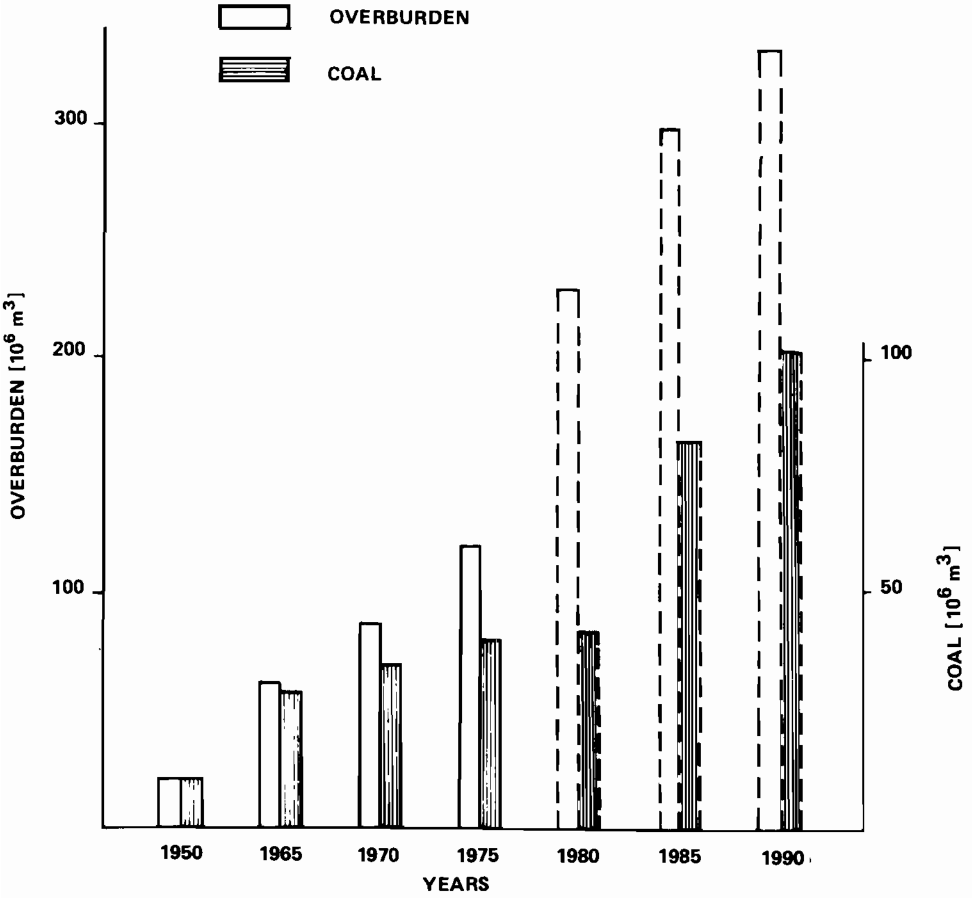


Figure 6. Brown coal production–1950 to 1990.

The implementation of these assumptions for energy development should bring a considerable proportion of so-called pure energy carriers in covering the fuel and power needs of the country and a reduction in losses during energy conversion. Figure 7 shows the expected modification of structure on the basis of results obtained so far.

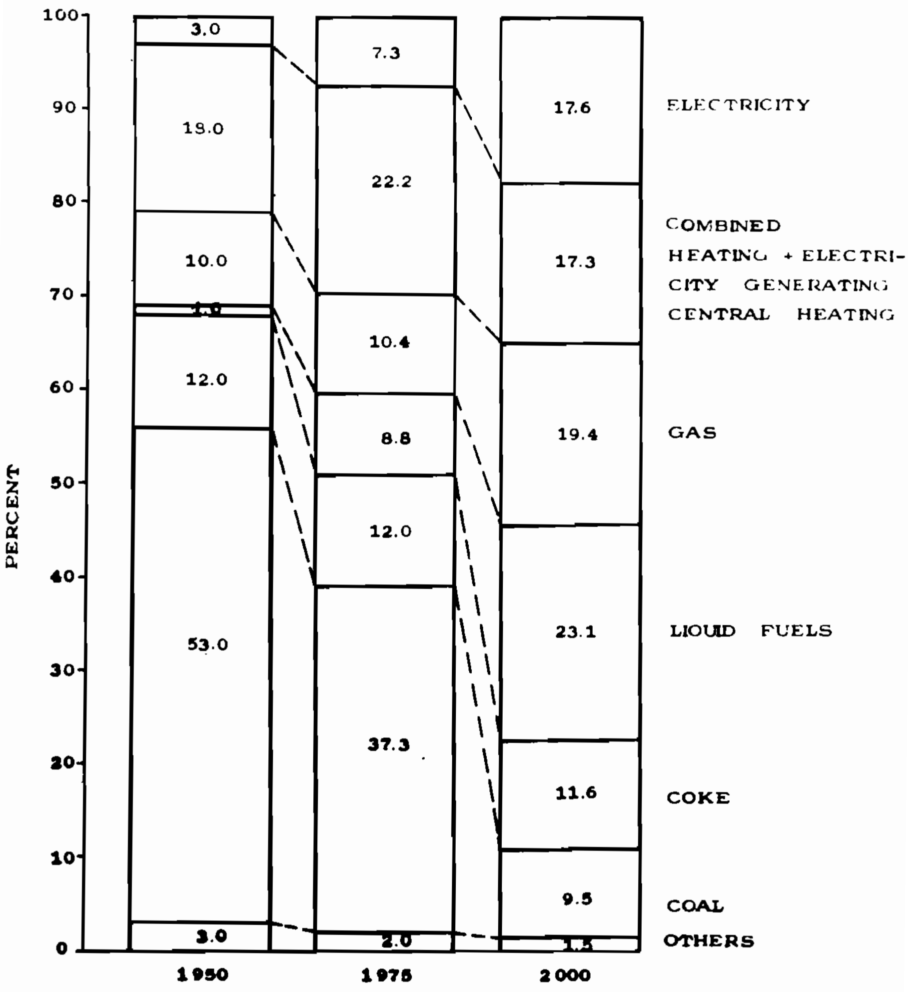


Figure 7. Final energy consumption–1950 to 2000.

THE COAL OPTION: A CASE STUDY OF THE UK

M.J. Sadnicki and R.J. Ormerod

ENERGY OPTIONS

There are only a few known sources of primary energy that would make a significant contribution to world energy demand when we look ahead to the time when global resources of oil and natural gas are nearing exhaustion. They are coal, nuclear fission, nuclear fusion, solar, and geothermal. IIASA's approach to energy systems is shown simply in Figure 1. Usually analysis proceeds from given demands and constraints to the evaluation of strategies in terms of resources and hence to the development of options. An alternative approach featured in the IIASA Energy Project reverses this procedure and specifies primary energy "options" in order to explore the special requirements and constraints that would result from major reliance on one particular energy source on a regional and global scale. Analysis of an option needs to include documentation of the global resources of the primary fuel, analysis of the technologies required to extract and convert the primary energy to the required form, and quantification of resource requirements and environmental consequences.

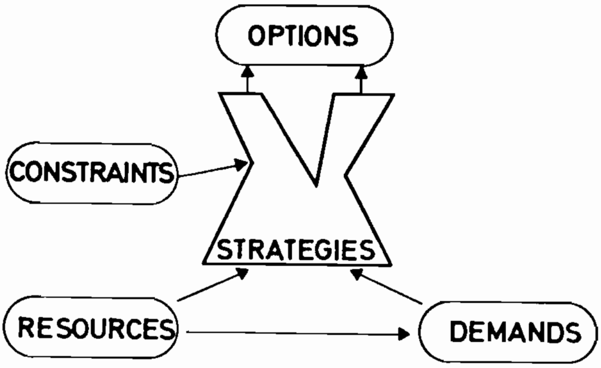


Figure 1. The IIASA approach to energy systems.

Source: [6]

THE COAL TASK FORCE

To facilitate the study of the coal option, IIASA formed a Coal Task Force in October 1975. Representatives of those institutions and nations most involved in coal production assemble at IIASA from time to time for periods of between one week and three months. At such sessions a common approach to the problem is discussed, and the initial groundwork performed. Membership of the Task Force was initially drawn from institutions representing two major coal-producing nations, the UK (Operational Research Executive, National Coal Board) and the FRG (Gesamtverband des Deutschen Steinkohlenbergbaus and Steinkohlen Bergbauverein). More recently we have been joined by representatives from the USA and the USSR.

This paper describes work carried out within the Coal Task Force by the British representatives in the initial period October 1975 to March 1976. A fuller account, now available from the authors, will be published [1]. The main aim is to illustrate the methodology, which has been agreed with representatives of the FRG coal industry and with scientists at IIASA. The UK energy economy is used as an example but it must be remembered that the analysis does not necessarily represent the views of either the UK Government or of the National Coal Board.

THE COAL OPTION

World coal resources could theoretically satisfy demand for many hundreds of years, and coal has shown in the past that it is flexible in use. Technologies exist for conversion to all the forms of energy that the consumer might require. However, up to 1973 the market share of primary energy supplied by coal had been declining in western Europe, the USA, and the world. The end of the era of cheap oil has meant a break in this trend, but the future role of coal is still not clear. It is the objective of the Coal Task Force to analyse by how much and how quickly the historic trend could be reversed.

Thus the underlying assumption is that oil and gas prices will continue to rise as world resources become scarce and the Coal Task Force analyses whether the disposition of coal resources and the availability of new extraction and conversion technologies will be such that coal can fill the gap between supply and demand. Thus a 100% reliance on coal is not implied and the use of other primary sources is not excluded.

In the UK the coal industry must negotiate a change of direction from contraction to expansion. Even if the analysis demonstrates the feasibility of a medium or long term option in the region, there will be special problems to be faced during the transition to such an option. How quickly can it be achieved? What are the research and development (R & D) implications? Such questions are particularly important when we consider the long lead times required to develop new energy technologies. The R & D that must be commissioned now might need to ignore current short term trends in the pattern of energy distribution and consumption. Because these factors are so important, this case study concentrated on the transition through to a coal option in the medium to long term (up to the year 2020).

THE METHODOLOGY

Any analysis that looks 50 years ahead is bedevilled by the wide range of uncertainties that must be considered. These uncertainties range from general questions as to the future life-styles that will be adopted to quite specific technological questions as to whether this or that process will be commercially viable. However, even given this uncertainty, it is still possible to derive robust conclusions, as long as the analysis is structured carefully. We have found that the structure that best fits the requirements of the coal option is a step by step analysis as follows:

Step A: Project Final (Supplied) Energy Requirements in Relation to Consumer Technologies

Future levels and patterns of energy demand are amongst the most important of the uncertainties referred to above. Ideally, analysis of future energy demand should be in terms of useful energy. However, current data on the uses of energy are still insufficient, especially in the industrial sector. In this study we have used instead final energy which gives an understanding of the form of energy required by the consumer and thus the implications for coal conversion processes can be analysed.

The carriers of final energy employed in this study are electricity, centrally supplied (high energy) gas, liquid, direct solid, and other (usually locally) networked heating. This last category includes any low or medium energy gas networks. We employ six market sectors, which fall into two distinct groups. The first group consists of two sectors where demand is freely substitutable between many carriers: residential space and water heating, industrial space and low temperature process heating. The second group comprises those sectors where specific usage does not allow free substitution: residential lighting and appliances, industrial motive power and high temperature process heat, chemical feedstock, and transport.

In order to arrive at the demands in each of the above sectors a view has to be taken as to the impact of past and future oil price rises on the trends of growth in, for instance, overall demand for energy and the use of electricity and liquid fuels. Different views can be taken resulting in a number of scenarios specifying the demand for each carrier of final energy.

Step B: For Each Final Energy Carrier, Identify the "Attraction Potential" for Coal-Based Technologies

The attraction potential is used to set up a hierarchy of the likelihoods that different coal-based energy carriers will be required in the future. This potential depends on:

- The availability of a suitable coal conversion technology;
- A possible shortfall in the supply of alternative primary energy to the energy carrier (e.g. scarcity of indigenous hydrocarbons, or lack of development of nuclear technology);
- The existence of a supply infrastructure to handle the coal-based energy carrier;
- The efficiency of the coal conversion technology (including, in the case of direct solid, the final efficiency of utilization at the consumer); and
- Anticipated comparability of possible costs of the coal-based final energy form and that of the alternative primary energy.

In further work it might be possible to analyse coal-based conversion processes in terms of a score obtained for each of these points, arriving at total scores for the potential of the process under different scenarios. In this way a ranked list of R & D priorities might be produced. For the moment, our scale is simpler, and potentials are categorized as high, medium, or low.

It should be noted that from the above definitions, the potential in any one energy carrier can change with time.

Step C: Introduce the Appropriate Coal-Based Conversion Processes with Penetration Rates Assessed from the Nature of the Process and the Nature of the Relevant Market.

In this step we draw on the research carried out at IIASA by Marchetti [2] and Peterka [3] to characterize the penetration of coal-based technologies. Thus for each penetration of a new technology into its market (final energy carrier) the problem is to establish t_1, the year of introduction of the first plant of commercial scale; t_2, the year when the process achieves a significant proportion (10%) of the market; and p, the allowable penetration rate after t_2 (which will be expressed as the time taken to go from 10 to 50% of the market). It is not necessary to estimate t_1 if it is clear that the technology will be available before the attraction potential indicates that it is required. We believe that this step rightly puts the emphasis in the analysis on timing possibilities and constraints and is a positive outcome of IIASA's research efforts.

Step D: Deduce the Requirements of Coal or Coal-Based Energy to be Extracted; Consider the Technologies to Extract This and Their Rates of Introduction.

Coal resources can be regarded as being distributed in a three-dimensional space [d,s,k], where d is depth, s, effective thickness, and k, knowledge. We change the distribution of resources in this space by two activities, extraction and exploration. Extraction may both remove quantities of coal from the "best-known" resources and render others unmineable (i.e. greatly reduce their effective thickness). Exploration causes a redistribution along the k axis in the direction of increasing knowledge.

At any one time we may require a measure of how much of the resources is available for extraction. This measure, usually called reserves, can be defined in a number of ways. The definition must encompass considerations of the mix of extraction technologies available, and of some external energy price. Both for physical reasons, and because of this external price, specific extraction technologies can only win coal at certain depths or thicknesses--for example, even the most modern opencast mining methods do not usually go beyond 1000 ft; current deep mining (which whether hand-filled or mechanized longwall involves manual labour at the coalface) is restricted to depths up to around 4000 ft and seam thicknesses of greater than 2.5 ft.

Extraction technologies cannot take all the coal available at appropriate depths and thicknesses, and an important parameter of any technology is the "recoverability". This is a measure of how much coal must be left in the ground for geological reasons, for organizational reasons (the disposition of the resources does not readily fit the necessary production layout), and safety reasons (e.g. pillars, roof coal left to protect the underground workings and/or surface structures).

The mixture of coal technologies must be consistent with the type of coal demanded as well as the distribution of reserves. A simple example is that of coal quality; the manufacture of coke currently requires a particular type of coal which occurs only in specific locations.

Finally, analysis similar to Step C for conversion technologies must be introduced, and likely penetration rates of new mining technologies must be estimated.

Step E: Consider the Likely Resource Requirements and Environmental Consequences for Coal Extraction and Conversion

One of the eventual aims of the Coal Task Force is to document coal strategies in terms of the resource requirements and environmental consequences associated with the use of coal technologies. Such documentation will be essential when a region comes to choosing the option, or mix of options, that will form a long term energy policy. The decision making will still be a political process--it is difficult to foresee any completely satisfactory analytical method for balancing, say, SO_2 emission and the stockpiling of nuclear waste. However, thorough documentation will allow the removal of factors common to alternative options, so that the real issues can be identified.

The "impact" or "technology" matrix we intend to document is as follows:

Resources

1. Capital
2. Labour
3. Materials
4. Land (area used)
5. Water (use of)
6. Consumer capital
7. Energy use

Environment

10. Air pollutants--CO_2, CO, NO_x, SO_2, particulates--(centralized)
11. Air pollutants (decentralized)
12. Water (pollution)
13. Radioactive emissions
14. Heat dissipation (centralized)
15. Heat dissipation (decentralized)
16. Solid waste
17. Occupational health and safety
18. Subsidence and effects on water table

The above list is based on that in the US ERDA study [4]. A separate IIASA project is investigating an important subset of the problem. The project uses the input-output based WELMM method (water, energy, land, materials, and manpower), and further details can be found in [5].

ENERGY IN THE UK

Consumption of primary energy in the UK since 1950 is shown in Figure 2. It can be seen that there have been several distinct phases. At the beginning of the period coal supplied most of the energy needed until in the late 1950s oil started to be imported in large quantities from the newly discovered Middle East oil fields. An early start was made with nuclear energy but this had little impact and we had essentially a two fuel economy until the late 1960s when North Sea gas started to come ashore in significant quantities. Throughout this period consumption of primary energy had been growing more or less steadily at about 2% and consumption of coal was falling until the 1973 oil price rises.

Today 37% of primary energy is supplied by coal, 41% by oil, 18% by gas, 4% by nuclear, and 0.5% by hydroelectric stations.

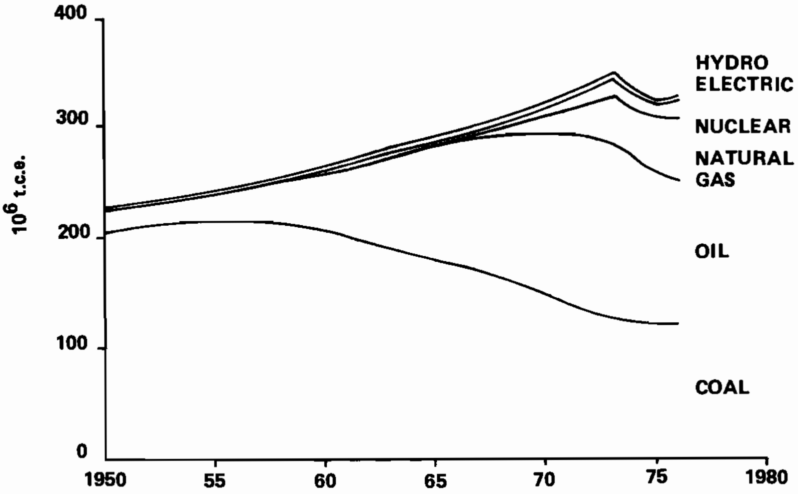


Figure 2. UK primary energy consumption.

The next phase of the UK's energy development will be dominated by the North Sea. The supply of gas will continue to grow and its impact in final and useful energy terms will be very great. North Sea oil will have a large impact on the UK economy and hence energy demand but as it will be priced at world prices should not affect consumption. Projected North Sea oil and gas profiles are shown in Figure 3.

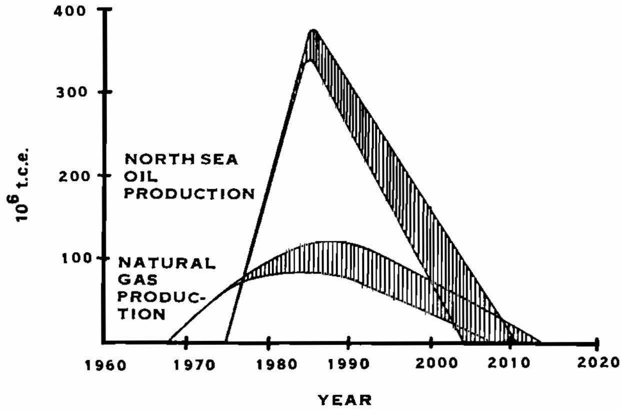


Figure 3. North Sea oil and gas production.

Source: [1]

SCENARIOS OF THE UK

Several scenarios of the UK energy future have been analysed by the methodology established in the previous sections.
Scenario 1 has been used as the base case from which the others are derived. It is the closest of the four to "business as usual", although this does not necessarily imply that it is regarded as the most likely. Final energy grows at 1.25% per annum, all electricity is centrally generated, oil and gas are increasingly reserved for premium use as indigenous supplies decline, and the nuclear industry gathers momentum once the next reactor type is proven.
Scenario 2 is identical to Scenario 1 except that it varies the proportions of final demand of the various market sectors of residential, industry, and transport.
Scenario 3 is more in the spirit of many commentators' view of a possible coal option--there will be pressure to provide energy from coal in a form other than electricity and where there must be electricity, local combined heat and power schemes will become increasingly important.
Scenario 4 investigates the possibility of no further nuclear power stations being built. Thus Scenario 4 is similar to Scenario 3 in that local power schemes assume in importance, but differs in that the energy carrier and coal attraction potentials alter.

RESULTS FROM THE SCENARIOS

The scenarios enabled us to develop broad conclusions on the viability of the coal option and the overall requirements for coal to regain a dominant share in the energy market. We emphasized earlier the importance of the availability of new technologies and the rate at which they could penetrate. Table 1 shows our estimates of the attraction potentials and the market penetration parameters. The timings indicate that there is some urgency in developing central electricity (coal-based combined cycle fluidized bed) but that all of the other new utilization technologies should be available by the time that they are needed in the UK. This is primarily caused by the depletion curve for North Sea gas which results in coal being market restrained until the mid-1990s. This is illustrated in Figure 4 which also shows the changing uses of coal. Up until 2000 coal is used for central electricity generation and direct burning in industry, thereafter the production of substitute gas and liquid rapidly builds up and to a lesser extent combined heat and power on a local basis.

Whilst up to the mid-1990s coal is likely to be market constrained, from then on the rate at which supply can be increased will be the constraint. Figure 5 shows that new mining processes and methods of extracting inferior coal will be required if the potential demand is to be met.

Table 1. Summary of attraction potentials, timings and penetration rates for coal based technologies.

	Attraction 2000	Potential 2020	Timing (t_1 or t_2)*	Rate p*
Central electricity	high	low	t_1 = 1990	17
Central gas	medium	high	t_2 = 1995	17
Liquid	low	high	t_2 = 2010	17
Direct solid	high	high	t_2 = 1990	16
Other networked heating (residential)	medium	medium	t_2 = 2000	80
Other networked heating (industrial)	medium	medium	t_2 = 2000	16

*See text for definition.

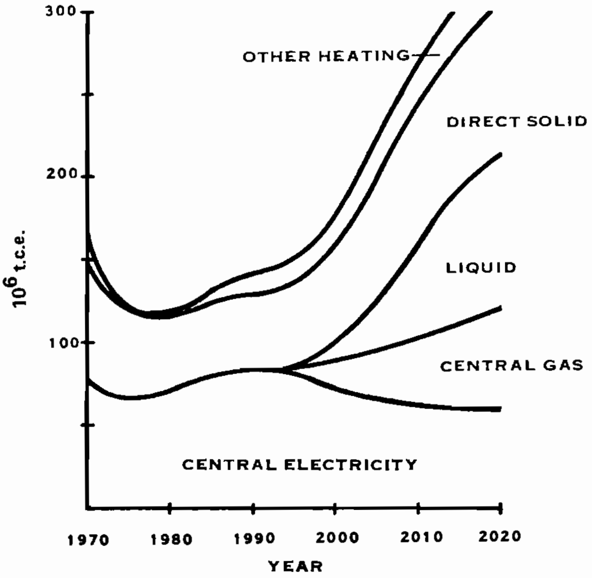


Figure 4. UK uses of coal 1975 - 2020: scenario 1.

Source: [1]

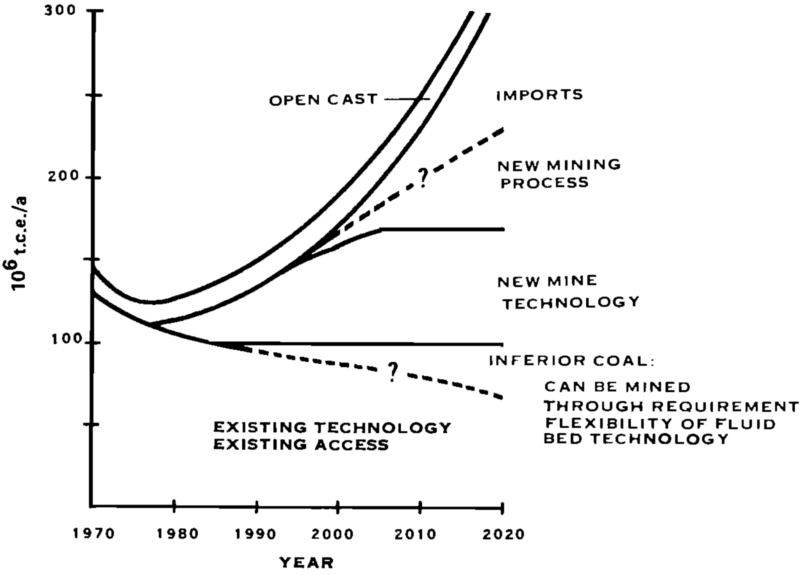


Figure 5. UK coal supply 1975-2020: scenario 1.

Source: [1]

In summary, analysis of the case study leads us to conclude that the following are the essential facets of the coal option:

- Up to the year 2000 the most important uses of coal will continue to be electricity generation and direct use in industry. Increased R & D in new conversion processes is required.
- Around 2000, the conversion of coal to substitute gas and liquid will become increasingly important. R & D in liquefaction should have the objective of producing the first commercially operating plant by the year 2000.
- Existing methods of mining will support an output of around 200 Mt per annum, providing there is continuing research in further automation and a continuing program of creation of capacity in new locations.
- To satisfy the full potential of coal demand, a completely new mining process will be required, for resources that cannot be recovered by existing methods. A pilot scheme demonstrating such a method would have to be available by 2000.

- The use of resources (labour, capital) in such a coal option does not, on a preliminary assessment, seem excessive. There will be major organization problems in mobilizing these resources.

The above points would add up to an extremely demanding task for the UK coal industry. The ability to develop new technologies, use new reserves, and mobilize resources of manpower and capital would be the limiting factor of the coal option. Such a task would have to be considered within a national energy strategy that might include shifts in R & D and investment priorities, conservation programs, and controlled depletion of North Sea oil and gas.

FUTURE RESEARCH

We have described the first of the case studies carried out by the Coal Task Force and it has necessarily been broad and lacking in detail in certain respects. It has dealt with a reasonably compact region and the question of transport has not been important. The US and USSR case studies will have to tackle this important dimension. We would see the way ahead as involving integration with other IIASA research such as the Resources, WELMM and Energy modelling efforts and the following additional steps:
Step F: Consider the implications of global coal trading on an appreciable scale.
Step H: Compare coal option strategies with strategies based on other primary fuels.
Step I: Suggest *mixed energy options* that seem good in the medium term by reason of generally lower resource requirements, or of flexibility in relation to the uncertainty of future estimates.

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THE NEAR-TERM ROLE OF COAL IN THE US NATIONAL ENERGY PLAN AND CONSTRAINTS IN COAL INDUSTRY DEVELOPMENT

S. Boshkov, G. Barla, and G. Zahariev

Although the imminence of the energy problem in the USA was forecast and discussed at length in some government and industrial circles many years ago, the seriousness of it was not recognized or admitted generally until its magnitude descended forcefully upon the country, aggrevated by the oil embargo to the USA by the Middle East Arab States and the ensuing energy shortages of 1973-1974. At that point the problem reached crisis proportions and signalled the beginning of a concerted effort to effect a workable solution to a complex riddle. Old studies were reviewed and updated in the light of changing conditions and recent trends and experience, and a multitude of new studies and proposals spawned in Washington and elsewhere. The population was innundated with a rehash of good, old, doubtful, meaningful, unreliable, and incomplete projections of energy data, all purportedly in support of the evolvement of an optimal national energy policy, designed to bring security and tranquility to the common citizen.

This enormous effort in searching for a prescription ultimately led to an obvious course of action put forth by the new administration of President Carter upon the serious study of a special task force.

This presentation will deal, in a very cursory manner, with the causes of the problem, the salient strategies of the national energy policy, which prescribe for the coal industry of this country a specific role, and examine, in greater detail, the problems and constraints that face this industry in achieving the objectives posed for it.

The diagnosis of the US energy crisis is quite simple; demand for energy is increasing, while supplies of oil and natural gas are diminishing. If a timely adjustment is not made before world oil becomes scarce and very expensive, the nation's economic security and the "American way of life" will be gravely endangered.

The crisis came about through lack of foresight. Americans have become accustomed to abundant, cheap energy. During the decades of the 1950s and 1960s, the real price of energy in the USA fell 28%. And from 1950 until the quadrupling of world oil prices in 1973-1974, US consumption of energy grew at an annual rate of 3.5 to 3.7%. As a result of the availability of cheap energy, the USA developed a large stock of capital goods, using energy quite inefficiently.

Figure 1 shows that the USA, which with less than 6% of the world's population consumes more than 30% of the world's energy, uses more energy per dollar of gross national product than any other industrialized nation. The USA consumes twice as much energy per capita as the FRG, which has a similar standard of living.

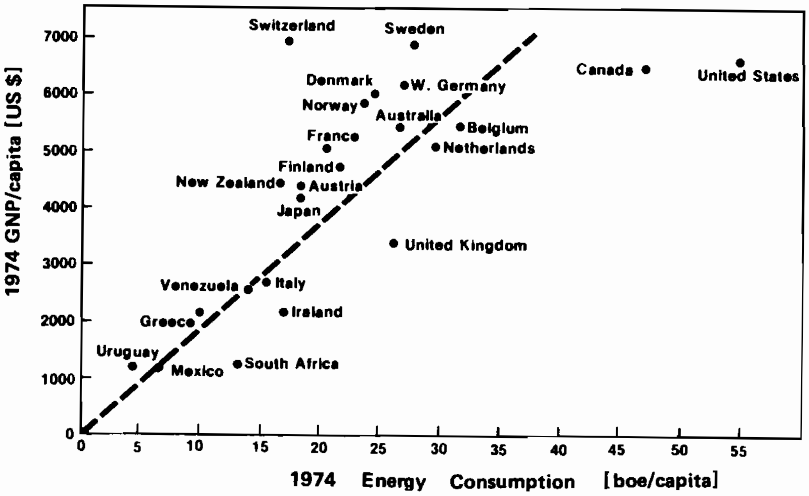


Figure 1. Energy consumption per unit GNP.

Source: UN Statistical Yearbook, 1975.

The relative inefficiency of use of this energy is exemplified in Figure 2 which relates to the industrial uses of energy, which amount to 37% of the nation's total energy consumption.

The US energy consumption by sector is shown in Figure 3, pointing out the heavy dependence on oil and gas as primary fuels.

Historically the fuel use pattern in the USA has shifted as shown in Figure 4. The immediate years ahead portend a crucial adjustment which is presently debated on the highest government levels.

The National Energy Plan is an outgrowth of some basic realizations and assessments:

- The principal oil-exporting countries will not be able to satisfy all the increases in demand expected to occur in the USA and other countries throughout the 1980s.

- Within about four generations, the bulk of the world's supply of oil will have been consumed.

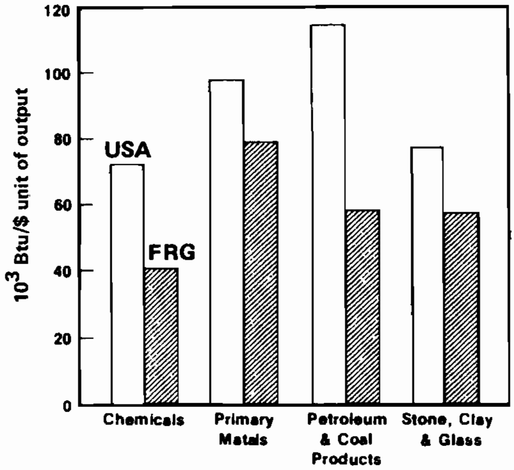


Figure 2. US industry energy efficiency compared to the FRG for major energy intensive-industries.

Source: Comparison of Energy Consumption Between the FRG and the USA, Stanford Research Inst., June 1975.

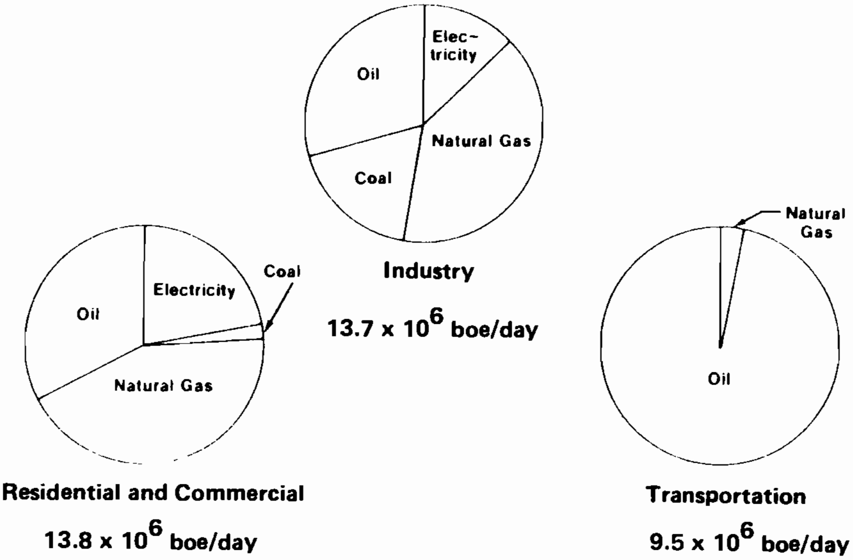


Figure 3. US energy consumption by sector, 1976.

Source: Federal Energy Administration.

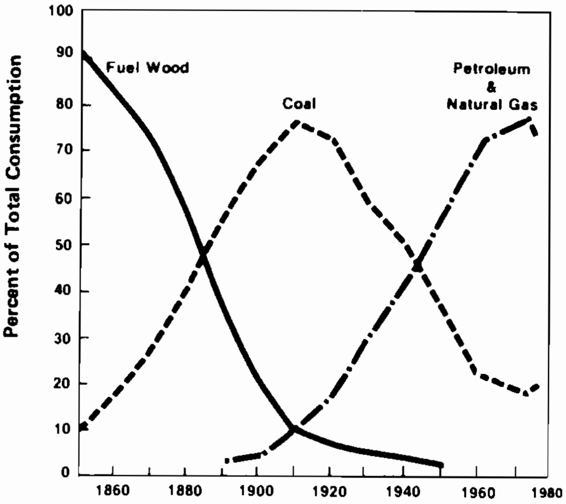


Figure 4. The USA has shifted to different fuel use patterns.
Source: US Bureau of Mines and Federal Energy Administration.

- The world now consumes about 20 × 10^9 bbl of oil per year. To maintain even that rate of consumption and keep reserves intact, the world would have to discover another Kuwait or Iran roughly every three years, or another Texas or Alaska every six months. Obviously, continued high rates of growth of oil consumption simply cannot be sustained.

Projected US oil consumption is shown in Figure 5 and the future of the US gas supply is projected in Figure 6. These illustrate the energy dilemma.

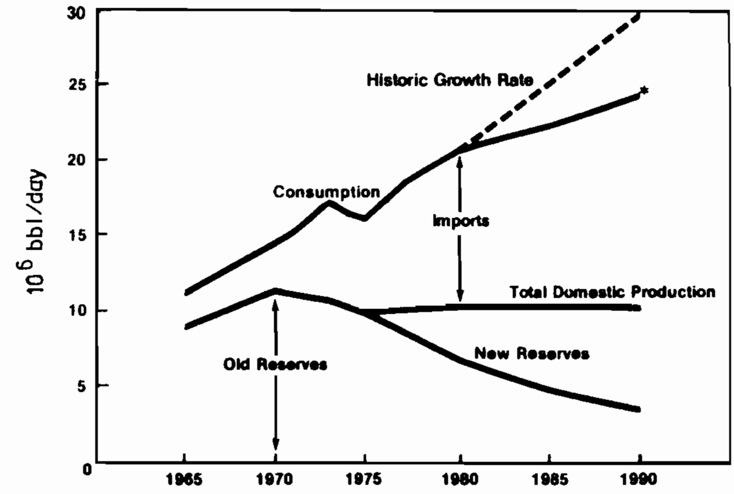
The three overriding energy objectives are:

- In the immediate future, to reduce dependence on foreign oil and vulnerability to supply interruptions;

- In the medium term, to keep US imports sufficiently low to weather the period when world oil production approaches its capacity limitation; and

- In the long term, to have renewable and essentially inexhaustible sources of energy for sustained economic growth.

Without belaboring the broad methodology to be pursued in accomplishing these objectives in all spans of time, we can



*Assumes implementation of mandatory fuel efficiency standards and reductions induced by higher gasoline prices.

Figure 5. US oil consumption without the National Energy Plan.

Source: US Bureau of Mines and Federal Energy Administration.

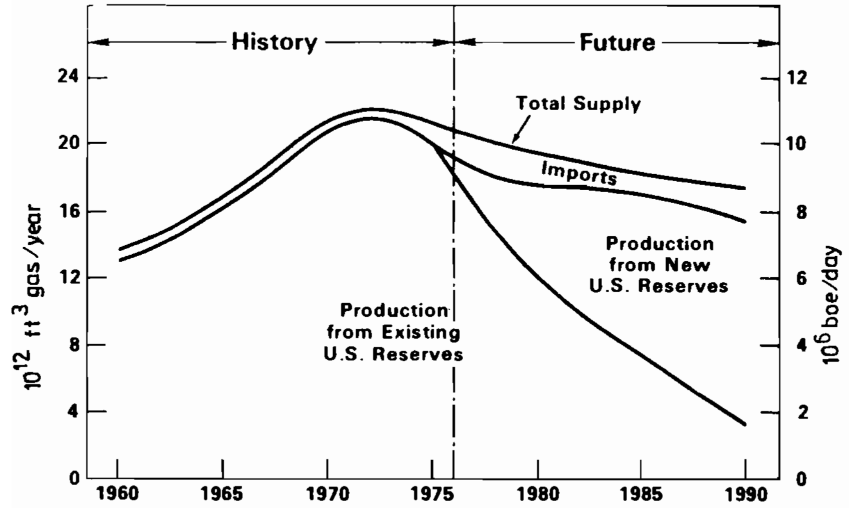
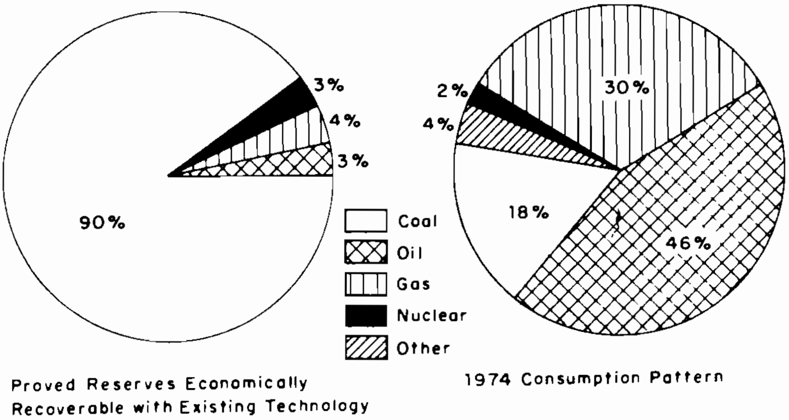


Figure 6. US gas supply without the National Energy Plan.

Source: Federal Energy Administration.

confine our discussion to a target date of 1985 and focus our attention to the main topic under discussion at this meeting; namely, the role envisaged for the coal industry and its short- and medium-term development.

The known reserves and present consumption of energy sources in the USA are shown in Figure 7 and the future total energy demand is depicted in Figure 8. It is evident that coal is the



Proved Reserves Economically Recoverable with Existing Technology

1974 Consumption Pattern

Figure 7. Reserves and consumption of energy sources.

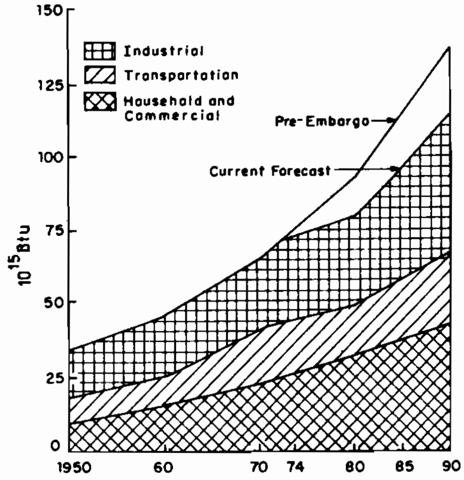


Figure 8. Future energy demands.

major reserve and that it is underutilized. One also sees the effect of the oil embargo of 1973-1974 on the energy use growth.

Domestic supply is forecast to increase by 40% between 1975 and 1985 with the main growth prescribed for coal and nuclear energy, as shown in Figure 9.

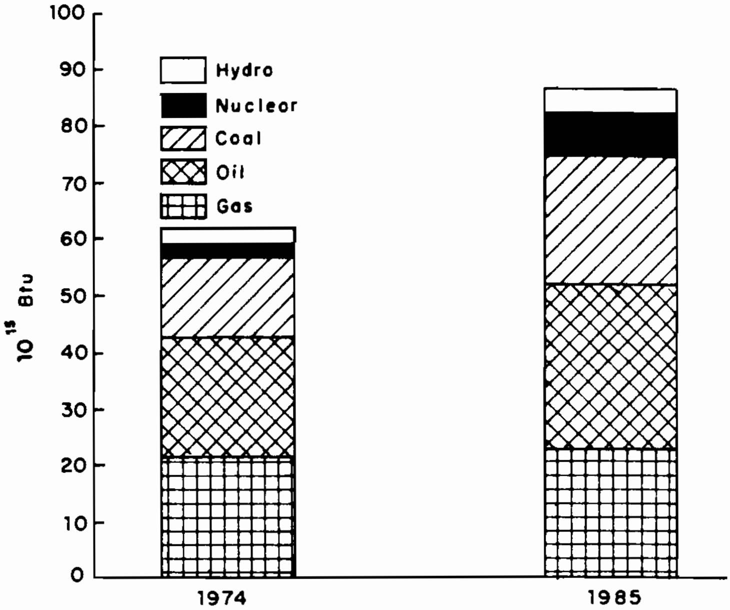


Figure 9. Future energy sources.

The pivotal energy sector is electricity. It is a supplier of energy as well as a consumer of primary fuels. The Atomic Energy Commission only several years ago projected the future demand for electricity as depicted in Figure 10, an obviously biased assessment. The nuclear energy industry is beset by numerous problems that are stunting its expected growth. Its share of electrical energy generation is expected to increase from 8.6% at present to 26% by 1985.

The inefficiency of primary fuel utilization in electrical generation is shown in Figure 11, suggesting that improvements in efficiency are needed and will help in alleviating the energy problem.

A more sober and more recent depiction of the future sources for electricity is shown in Figure 12. The use of coal in electrical generation could increase by about 80% in the next ten years.

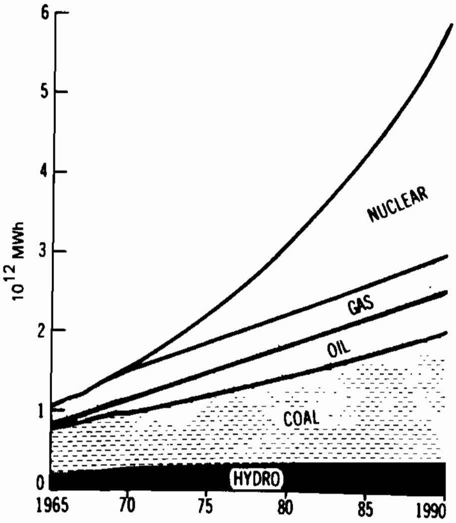


Figure 10. Estimated annual electric utility generation by primary energy sources.

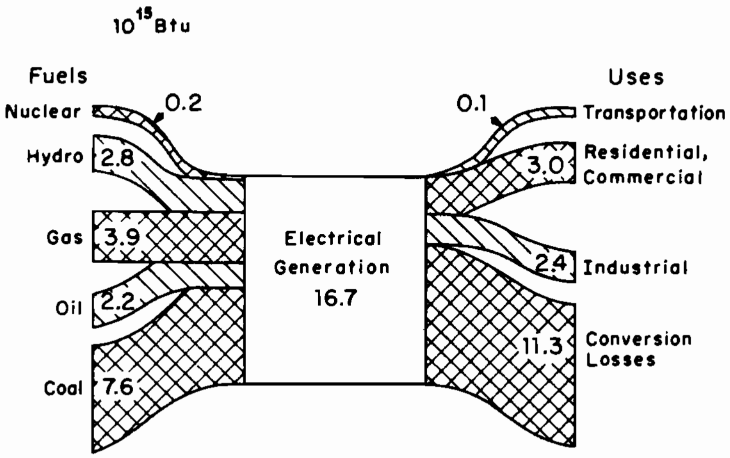


Figure 11. Balances in conversion to electrical energy.

The present supply-demand relationships of the three primary fuels and their projected roles without and within the constraint of the present national energy plan are shown in Table 1. The part coal is expected to play is obviously most vital and central. Whether the coal industry can respond fully to the challenge of doubling productive capacity within a ten-year span will depend

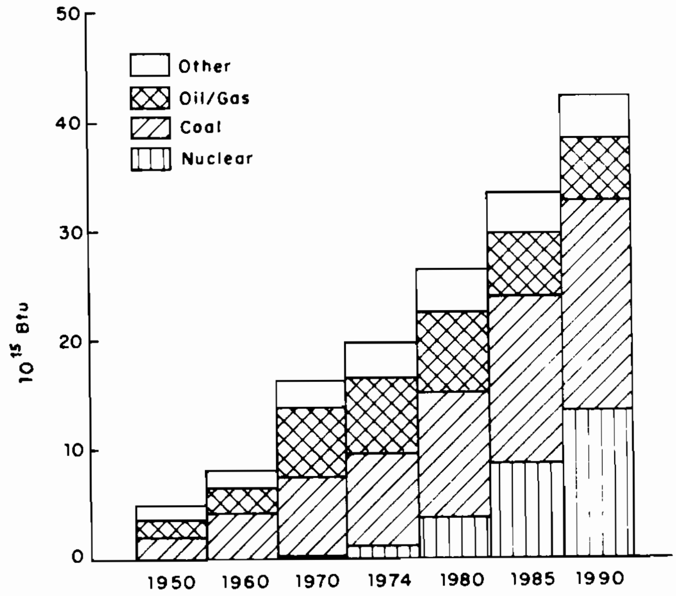


Figure 12. Future sources for electricity.

on its ability to effect a beneficial solution to the many formidable problems that face it. These problems have not only technological and financial components but also political, social, environmental, and labor facets that are hard to forecast and define. A short review of the problems facing the coal industry of the USA follows.

The known coal reserves in the USA can be roughly grouped into two major areas, namely eastern and western. Present production comes mainly from the eastern deposits. The known coal resources of the country include 394 × 10^9 t readily available for mining under very favorable economic conditions.

Because of major commitments by the Federal Government to preserve the quality of life, the sulfur content of coal exercises a major constraint on its availability for direct utilization without the need for upgrading by beneficiation on the employment of clean-up devices after burning. The sulfur content of the US coal resources is depicted in Figure 13. It is evident that low-sulfur coal predominates in the west, where production is low at present, and where deposits are distant from industrial centers.

If the US coal supply is to reach the targets prescribed for it in Figure 14, the envisaged expansion of productive capacity will have to derive from the sources given in Figure 15. This blueprint for action suggests a very large increase in surface mining of the western deposits.

Table 1. Balances by fuel [10^6 boe/day].[1]

	1976	1985 without Plan	1985 with Plan	1985 Plan plus additional conservation
Oil:				
Consumption	17.4	22.8[2]	18.2	17.0
Domestic supply[3]	9.7	10.4	10.6	10.6
Refinery gain	0.4	0.9	0.6	0.6
Imports	7.3	11.5	7.0	5.8
Natural gas:				
Consumption	10.0	9.4	9.4	
Domestic supply	9.5	8.2	8.8	
Imports	0.5	1.2	0.6	
Coal:				
Consumption	6.8	10.9	13.3	
Domestic supply	7.9	12.2	14.5	
Exports	0.8	1.2	1.2	

[1] Detail may not add up to total due to rounding.

[2] Assuming compliance with automobile efficiency standards under current law, and reduced driving as a result of higher gasoline prices. Without these assumptions, consumption would be 25 million barrels per day.

[3] Includes natural gas liquids.

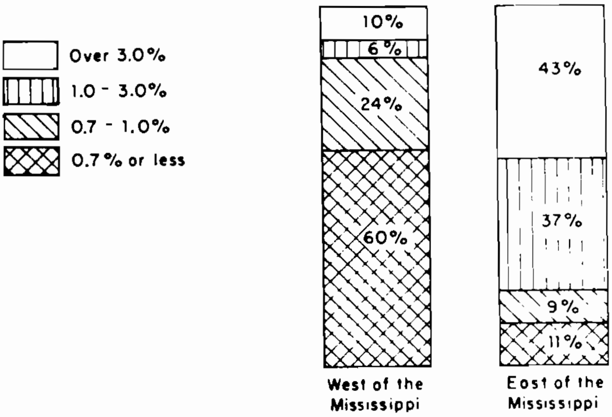


Figure 13. Sulfur content of US coal resources by region.

Source: US Bureau of Mines.

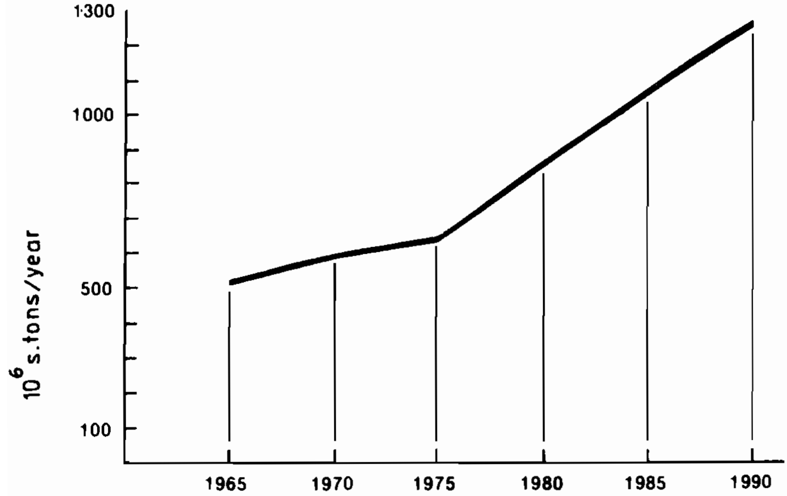


Figure 14. US coal supply.

Source: US Bureau of Mines and Federal Energy Administration.

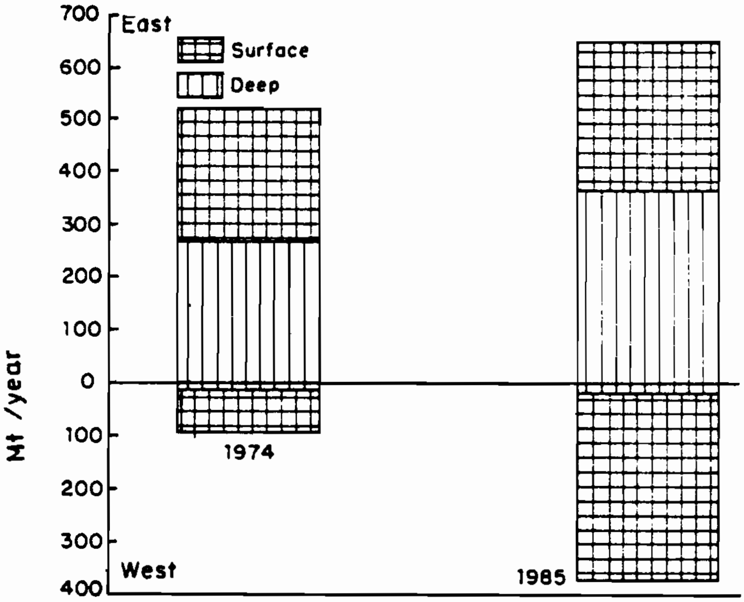


Figure 15. Projected sources for coal capacity expansion.

The obstacles facing the coal industry will now be briefly summarized.

Environmental Policy

Attainment and maintenance of the environmental goals set out in the Clean Air Act and its Amendments of 1970, the Federal Water Pollution Control Act, and the National Environmental Policy Act are high national priorities.

One specific of the Clean Air Act requires that all new coal-burning plants do not emit more than 1.2 lb of sulfur dioxide (0.6 lb of sulfur) per 10^6 Btu. For coal with 24 × 10^6 Btu, this is equal to a maximum sulfur content of 0.7%. Eastern coals, in general, have higher energy content as well as higher sulfur content than western coals. 8000 Btu/lb western coal must possess a maximum of 0.48 lb sulfur in order to meet the "new plant" government standard.

As of June 1, 1975, primary ambient air quality standards for public health became effective, limiting sulfur oxides to an annual average of 80 $\mu g/m^3$ of air. In addition, secondary standards, for the protection of property and wildlife, are set at 60 $\mu g/m^3$, and are to be met within a reasonable time, defined as 1½ to 3 years, after the primary standards are implemented. Because each area of the country has different atmospheric conditions, this standard cannot be readily translated into a corresponding coal sulfur content limit. Many States have passed unnecessarily restrictive sulfur content standards surpassing the Federal edicts. It has been estimated that over one half of the coal currently produced in the east would fail to qualify for use if the State sulfur content standards are implemented.

The standards can be met by either burning low sulfur fuels directly or burning high sulfur coal in conjunction with sulfur removal devices--principally stack gas scrubbers at present. Stack gas removal, although technically feasible, is not expected to be commercial before the late 1970s, because its use has not been sufficiently well proved for use by utilities.

Surface Mining Legislation

On the fourth try, the US Congress finally found a President receptive to the passage of a surface mining bill. The latter prohibits surface mining on lands where reclamation is not feasible and requires that surface mined lands be restored to their approximate original topography (unless there is inadequate soil to achieve this, as in the west).

Land reclamation as presently practised involves removal of topsoil for storage, leveling the highwall and overburden left in the mining process, to restore original contour or, in some cases, create a more useful terrain, replacing the topsoil, and revegetation of the area. Reclamation follows mining by a few months. Reclamation costs per acre are $1000 to $4000 in the west and $3000 to $5000 in the east. Because of the thicker coal deposits in the west, the cost per ton of coal mined is much lower. Although relatively high in the east, this cost related to the kilowatt hour charge to the electrical consumer would add only 2 to 3% to the average residential electric bill.

Government Leasing Policies

The US government owns over 40% of all western coal reserves, including an estimated 85% of all US low sulfur reserves. The Bureau of Land Management of the Department of the Interior has been slow in issuing leasing permits. Aside from its desire to assure maximum environmental protection and provide for an orderly development of coal resources, the Department has also been constrained to a great degree in its leasing policies by the National Environmental Policy Act, which requires an environmental impact statement to be filed prior to any significant federal action.

The delays in compliance with this Act are lengthy, often resulting in postponements of commencement of mining for periods longer than two years.

Aside from the three items of constraint listed above, all of which are related to political decisions and, therefore, subject to revision or relaxation by political action, there are several other constraints upon the productive capacity of the coal industry that relate to technological and operational abilities.

Improvements in Mining Technology to Arrest Recent Sliding Productivity and Escalating Costs Brought about by Conformance to the Health and Safety Act of 1969

The impact of the Act has been far-reaching for the coal industry, especially for the segment dealing with underground mining. It was precipitated by increased public awareness of the plight of the miner, the depressed mining activity in some sections in the Appalachian region, and the unfortunate occurrence of a disastrous mine explosion about the time of decision. The product was a very stiff set of federal regulations, which, by and large, neglected industry opinion in their passage.

It is a basic premise of life that one does not speak against motherhood, the flag of the country, or the safety of the coal miners. There was no objection to the spirit of the Act, but there were numerous objections to the timetable prescribed for meeting many of the objectives set forth. The timetable forced changes in operational procedures, decreed changes in equipment design, and imposed financial burdens on the mine operators.

Enforcement of the provisions of the Act fell on the shoulders of an inspectorate that, at the time, was quite limited in manpower.

Demand for additional inspectors was partially met by raiding the middle management personnel in industry ranks, thus compounding the existing lack of trained and competent men needed to effect the changes mandated by the legislation. Although this factor cannot be quantified, there is little doubt that it contributed to a general polarization between the government and the coal mine operators. Arbitrary enforcement by overzealous inspectors also took its toll in productivity.

The result of the Act was to cause underground productivity to plummet as shown in Figure 16. The present underground productivity is 8.5 tons per man shift. It is difficult to say precisely what this Act cost the industry. A number of studies have attributed a 15 to 25% production loss to compliance with the provisions of the Act. As a result of this loss of production and additional labor and supply requirement, as reflected in Figure 17, underground mining costs have increased 20 to 30% over the cost of production before the Act.

Figure 18 exhibits the immediate short history of coal production and number of operating mines in surface and underground mining and the increasing spread in costs between the two types of mines.

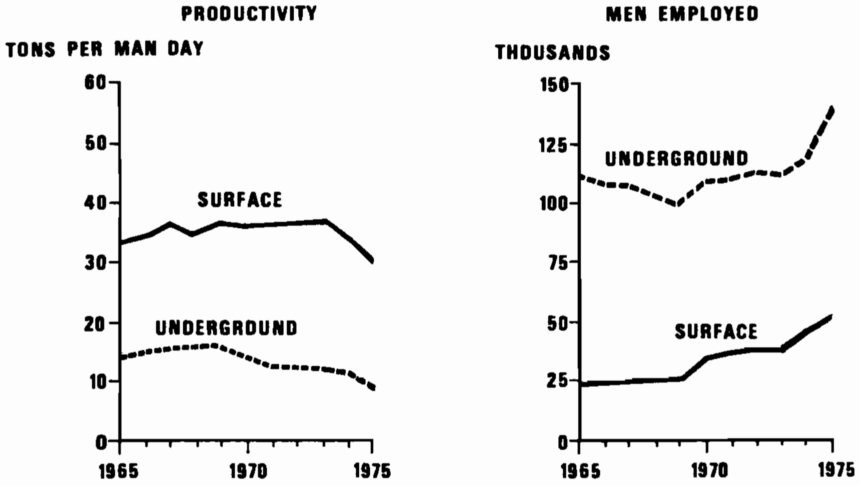


Figure 16. Bituminous coal and lignite underground and surface mining trends.

Source: US Bureau of Mines and Mining Enforcement and Safety Administration.

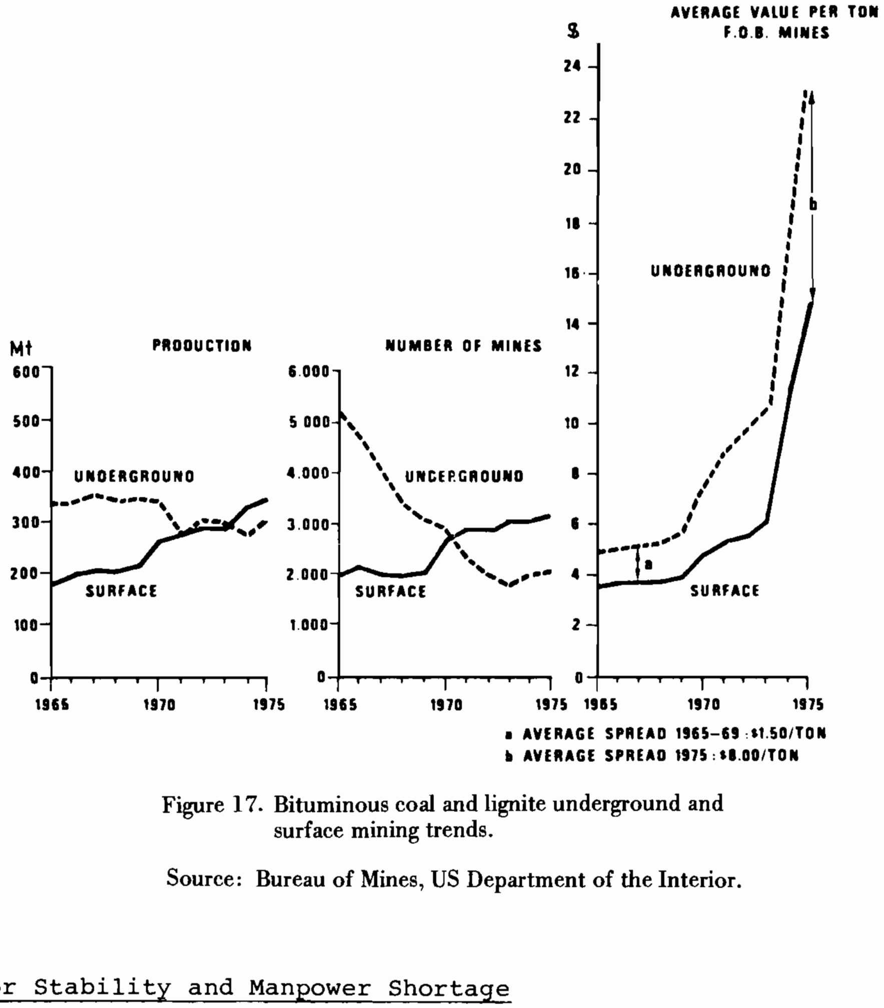


Figure 17. Bituminous coal and lignite underground and surface mining trends.

Source: Bureau of Mines, US Department of the Interior.

Labor Stability and Manpower Shortage

Labor-management relations in the coal industry have historically been poor, and organized and wildcat strikes have been commonplace. A statistical measure of worker attitude may be gathered from Figure 19, showing the number of man-hours lost by industry due to strikes. The big industry strike years, 1959 and 1971, can be easily identified. It is also noteworthy that, since the early 1960s, there has been a gradual increase in wildcat strikes which generally result from local disputes at individual mines. In addition, with coal mine labor in short supply and wages rising to the forefront of workers in basic industries, a sociological-psychological outcome of high absenteeism has resulted. Mondays and Fridays are notoriously poor production days, because of labor shortages on these days. It is not uncommon to find a 25 to 30% absentee rate at some coal mines.

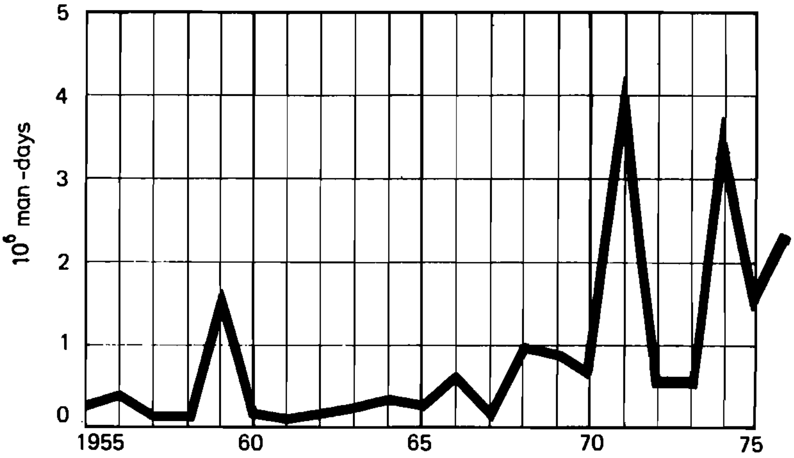


Figure 18. Total man-days lost due to strikes.

Source: US Bureau of Labor Statistics.

December 6, 1977, marks the date for the renewal of the three-year labor contract in the coal industry. We may be headed for another peak on the chart.

There is a most critical shortage in the US coal industry of both experienced mine workers to take on supervisory positions and new labor to staff new mines. There is also an acute shortage of mining engineers and other technical support staff.

These shortages are the outgrowth of the general lack of interest in coal mining since the early 1960s until recently, resulting in a peculiar demographic make-up of today's work force in coal. The age distribution is bi-polar with the peaks occurring in the over 45 and under 30 age groups, and a deep gap present in the 30-45 category. The labor force thus lacks the basic component of labor stability and exhibits a grandfather-grandson distribution.

The industry must look to an increasingly younger work force at all levels and to some means of substituting training and development for years of experience. Whether this can be done is one of the most crucial issues affecting coal development on the scale necessary to make the nation self-sufficient in energy.

Adequate Transportation Facilities, Supplies and Equipment

Transportation is a vital part of the coal industry and is often a substantial portion of the total coal cost to the consumer. In 1975, bituminous coal and lignite, loaded for shipment, used the following carriers:

Railways	66%
Waterways	12%
Truck	11%
Other	1%
Transportation to Electric Utility (Plants Adjacent to Mine)	10%

The four largest coal carriers, all located in the eastern half of the USA, together account for over one half of total railroad coal loadings. Transportation bottlenecks are becoming commonplace despite the innovation of the unit-train practice, which accounts for slightly over one third of coal transport by rail. The bottlenecks are particularly critical in the northeast, where the rail system is in virtual collapse because of bankruptcy proceedings, thus suffering the disadvantage of inability to attract capital in order to develop additional coal carrying capacity. Transport of coal to electric utilities adjacent to or near mines is growing in importance, with high voltage power generating stations sited near coal mines in order to eliminate the need to ship over great distances.

Water transportation is relatively low in cost, averaging around 2.5 mills per ton-mile. This compares to 5 mills/ton-mile for unit-trains and 10 mills/ton-mile for usual rail haul.

It is axiomatic that if coal production is to advance materially, the industry's equipment and supply requirements will rise sharply, especially for surface mining equipment. Any shortfall in availability could significantly hamper expansion.

Capital Availability

The coal industry's projected financial requirements are simply staggering. The National Energy Plan estimates coal's capital needs to be $\$18 \times 10^9$ by 1985, projected on the basis of 1975 dollars and on the assumption that Mid-East oil would continue to be available. For an industry with a current capitalization of about $\$6 \times 10^9$, the magnitude of the task seems almost unattainable.

Coal must compete for investment funds. To do so successfully it must be an attractive investment opportunity with a competitive short- and long-term rate of return. Recent history has shown that the rate of return on net worth rose from 6.6% in 1960 to 10.6% in 1965, declined since then, except for 1970, and rose again after 1974.

The latest study projects the capital requirements for successful attainment of the National Energy Plan to be as depicted in Figure 19. The requirement investment of $580 billion in

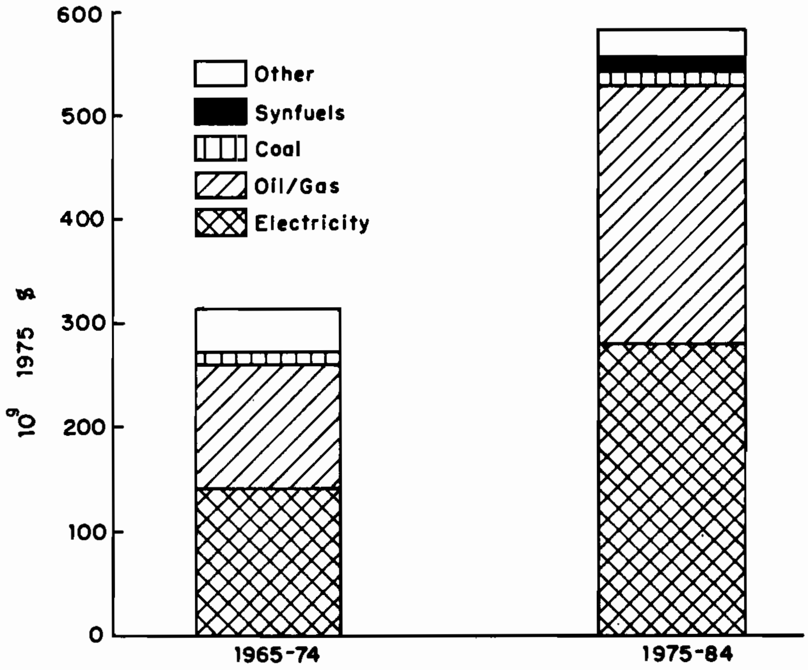


Figure 19. Estimated investment cost.

the next 10 years seems large. It represents about 30% of fixed business investment, which is energy's historical share. It may not be difficult to attain.

The above presentation is a short summary of the problems and constraints facing the US coal industry in fulfilling the prescribed role for it during the coming 10 years. Acceptable resolutions to these problems may allow the industry to reach the 10^9 t per year production level by 1985. The road ahead, however, is fraught with uncertainty.

Source Material

Executive Office of the President, US Department of the Interior, National Petroleum Council, Federal Power Commission, Federal Energy Administration, United Nations Statistical Yearbooks, US Bureau of Mines, National Coal Association, *Engineering and Mining Journal*, *Coal Age*, Private Reports of Investment Houses.

ENERGY STRATEGIES AND OPTIONS: AN ANALYSIS OF COAL IN THE USA

G.C. Ferrell

INTRODUCTION

Recent events, such as the peaking of domestic US gas and oil reserves, the oil embargo of 1972, and the subsequent price increases for formerly accessible and economic fuels, have had substantial impacts on the US coal industry. In order to meet national policies for decreasing dependence on imports while providing reliable and economic US domestic energy supplies, goals commensurate with prospects for future world oil trade and for the long-term health of the global energy and economic systems, the US coal industry has been gearing up for a major revival. In light of recent events, and given the fact that the coal industry has declined relative to other energy industries during the past several decades, this paper examines some major energy strategies and options for coal in the USA.

The IIASA Energy Systems Program is studying the possibilities of strategies and options on global and regional scales. In this effort a Coal Task Force has been formed to conduct methodological investigations and case study analyses within national contexts, in order to identify potential strategies and options for coal on a global scale. This paper is a summary of investigations that characterize the role of coal in the USA and that have been conducted at IIASA and within the USA during 1977. A full report on this case study is to be published during 1978. In order to characterize a national view of coal that matches with global considerations, the long-term and large-scale perspective is addressed. The paper includes a brief review of the historical role of coal, a report of important recent events affecting the coal industry, and an assessment of future US coal options as embodied in several major national planning efforts. In conclusion, a 200 year summary of the history and possible future options for coal in the USA is presented, including an analysis of the consumption and depletion of coal in comparison to present characterizations of resources and reserves.

THE HISTORICAL ROLE OF COAL

Coal has been the keystone of energy resources for the USA, providing the power that industrialized the American economy during the 19th century. Beginning in the 18th century, coal production increased by several orders of magnitude into the early 1900s, reaching a level of over 600 × 10^6 short (s.) tons per year by 1920 [1,2]. During this time, the increase in coal consumption exceeded that of energy consumption as a whole, and the fraction of primary energy provided by coal rose from about 9% in 1850 to over 75% in 1910. From the early 1900s until about 1970, the relative role of coal diminished. Beginning with the commercialization of oil and gas around the turn of the century, the share of primary energy from coal declined during this period to a level of about 20% in 1970. This long-term pre-1970 rôle for coal in the USA has been studied at IIASA using a market share characterization as shown in Figure 1 [3]. By contrast, more recent trends for primary energy consumption (see Figure 2, which includes the dates of recent major economic- and energy-related events) show the beginning of a revival for the US coal industry.

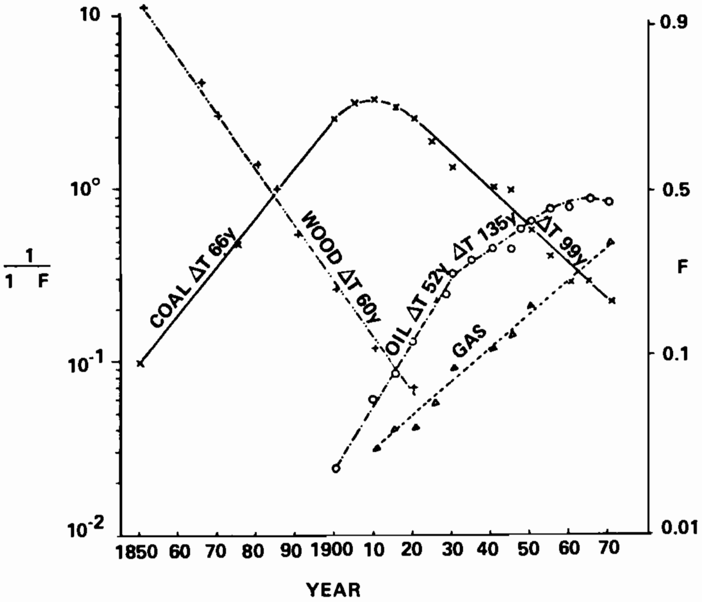


Figure 1. Historic trends for primary energy consumption in the USA.

Source: [3]

Long-Term Energy Demand Substitution

Before discussion of recent coal industry events, a longer-term perspective of energy demand is presented with emphasis on the substitution of fuels. For the three major economic sectors--household/commercial, transportation, and industrial activities--a major long-term solid-liquid-gas-electricity substitution phenomenon has been occurring with different rates of market penetration.

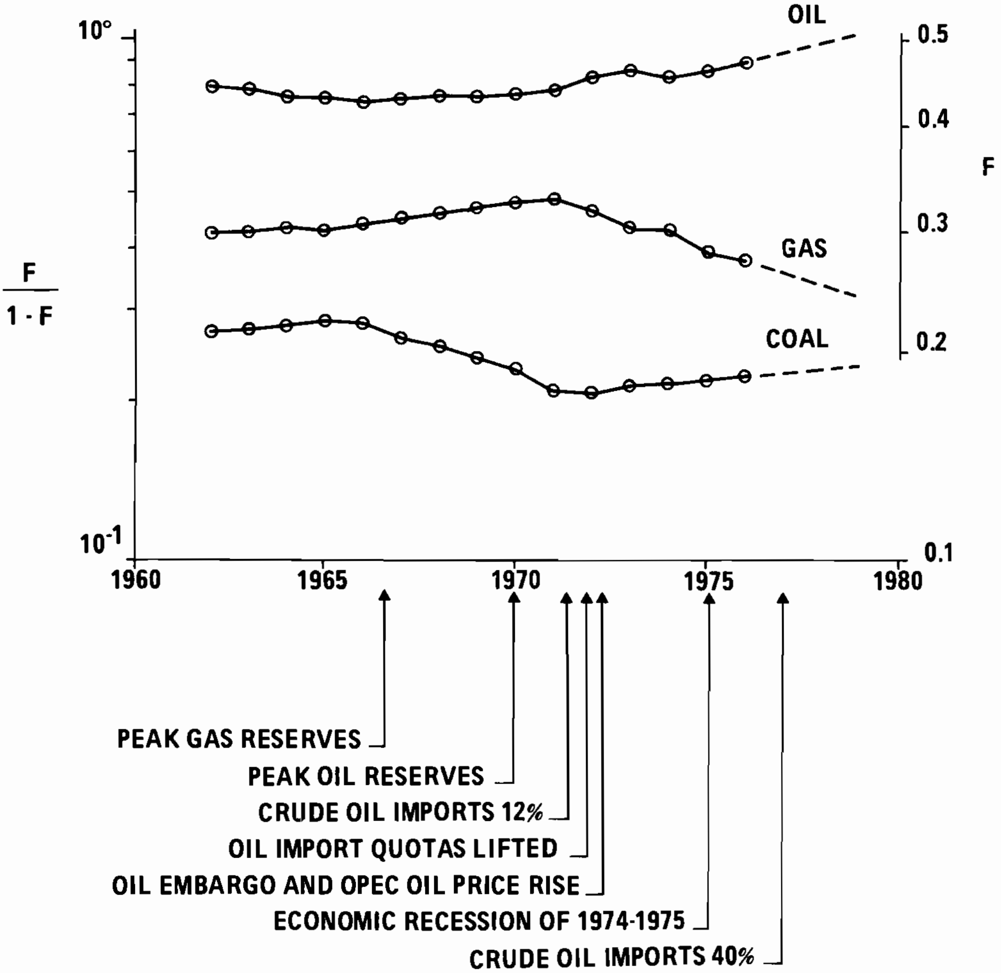


Figure 2. Trends of primary energy consumption in the USA, 1960 - 1980.

and starting periods [4]. It is important to gain a perspective on this changing preference for fuels in order to develop strategies and options for the utilization of coal.

Household/Commercial Sector

For the past two decades, energy consumed by household and commercial activities in the United States has more than doubled, reaching 20 quads* per year, and averaging about 30% of the final

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* 1 quad = 10^{15} Btu.

energy total. However, the fuel mix used in this sector has changed dramatically, as shown in Figures 3 and 4. Before 1950, the market share for coal exceeded 50% of the total, but by 1960,

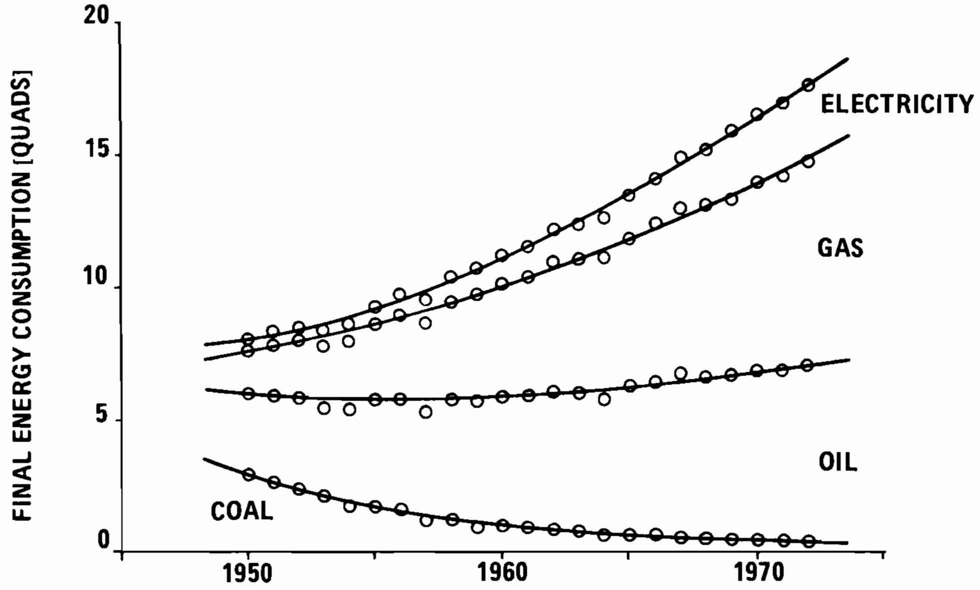

Figure 3. Household and commercial final energy consumption, 1950 - 1972.

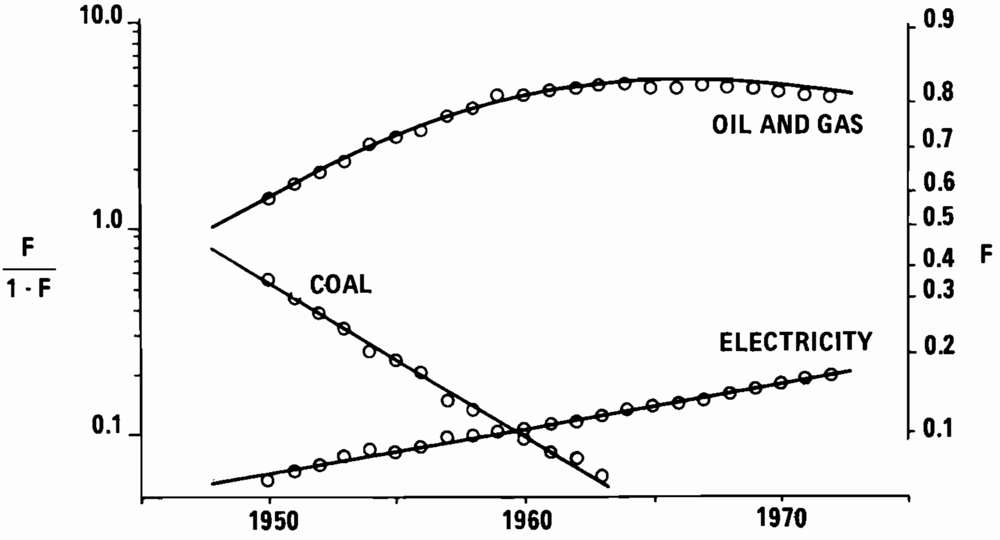

Figure 4. Trends for household and commercial final energy consumption.

this decreased to less than 10%. Oil and gas replaced coal over this time period, and now have a market share of around 80%. The balance of final energy consumption is supplied by electricity. Thus, in this sector, a solid-liquid-gas-electricity substitution has taken place, a process occurring because of the progressive increase in convenience, and because of the progressive decrease in environmental impact and direct cost for the consumers. (The solid-liquid-gas-electricity substitution process is characterized by the increased use of secondary energy forms over primary forms at points of final energy consumption. In this process, the burden of energy supply and the control of environmental impact is shifted away from the consumer toward the producer. This is desirable for the consumer, who is able to reduce his overall cost, even at the expense of increasing delivered fuel prices.)

Transportation

Consumption of energy in the transportation sector accounts for about 30% of the final energy, and has reached some 20 quads per year today. As shown in Figures 5 and 6, the use of coal has been discontinued, while oil has dominated the sector for the past two decades. Unlike the fuel substitution in the household/commercial sector, no major substitution for oil is occurring. (A minor but increasing use of gas and gas-liquids has been occurring in the transportation sector, but thus far no significant use of gas-driven modes is evident--about 4% in 1972.)

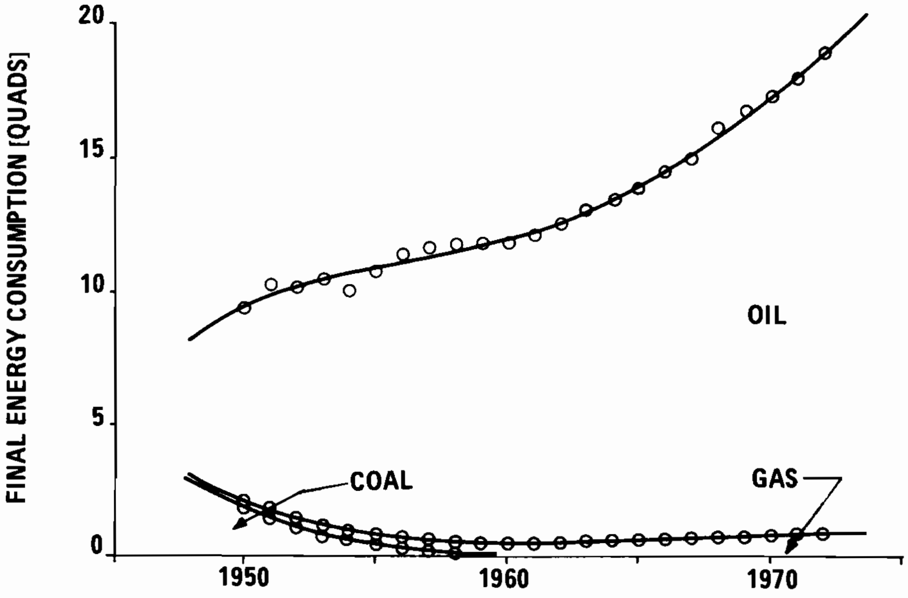

Figure 5. Transportation final energy consumption, 1950 - 1972.

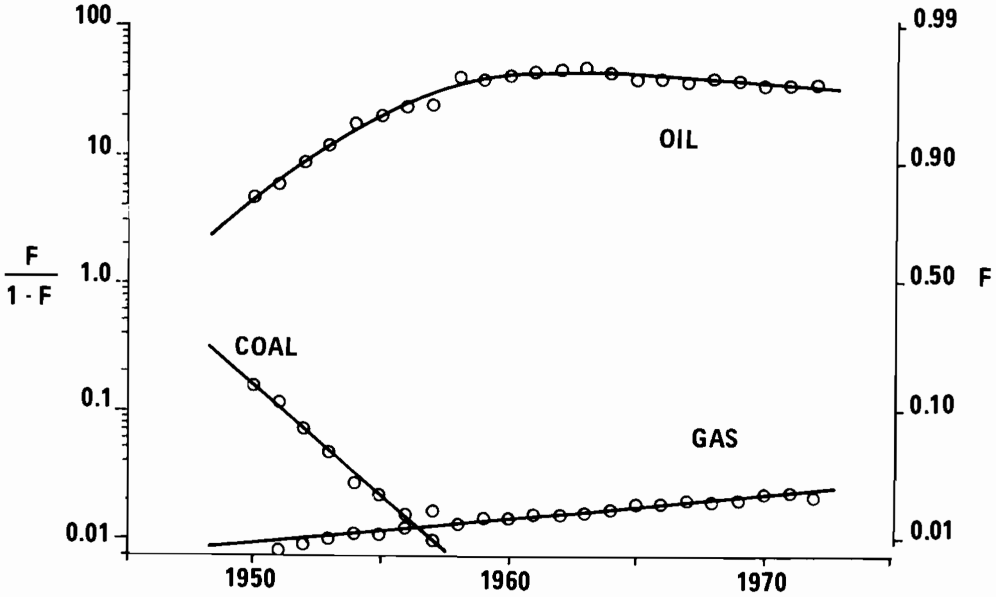

Figure 6. Trends for transportation final energy consumption.

Industry

The largest of the three major sectors for energy consumption is industry, which accounts for about 40% of the final energy total, or some 24 quads per year today. Long-term trends reveal that the use of coal has declined relative to other fuels as shown in Figures 7 and 8. Gas now accounts for one half of final energy consumption by industry, which was the level for coal in 1950. Oil has gradually increased from 20% in 1950 to about 25% today, while the use of electricity has steadily increased to a share of over 10%. The industrial sector, more than any other consumer group, has a relatively complex market structure. Many industrial categories use only selected fuels, and major industrial processes are "fuel specific". For example, the iron and steel industry consumes about 16% of total final uses, but over 40% of all industrial-related coal. Still, on an aggregate industrial level, the solid-liquid-gas-electricity substitution phenomena has been evident over the long term.

Recent Coal-Energy Industry Developments

In light of the long-term fuel substitution trends, recent energy developments have significantly influenced the US coal industry. Because coal may be used directly or may be converted to liquids, gases, and electricity, it has a unique position as an energy resource for the USA, and will have an increasingly important role in the future.

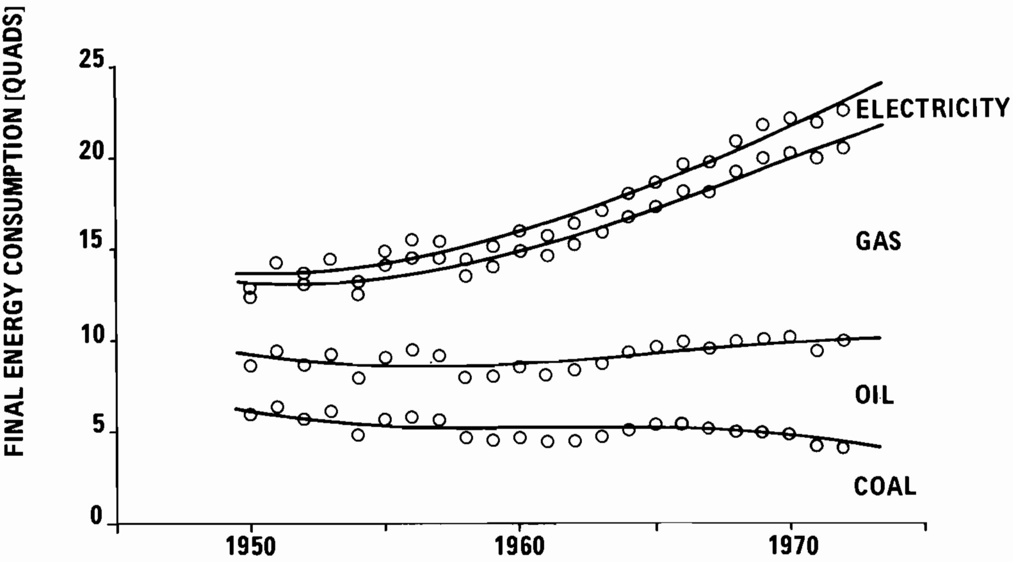

Figure 7. Industrial final energy consumption, 1950 - 1972.

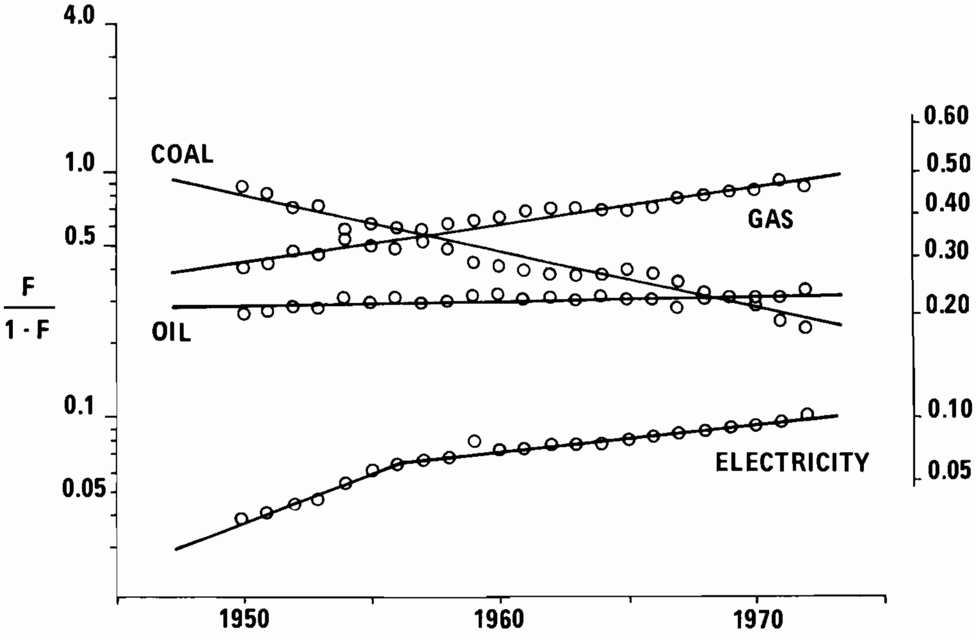

Figure 8. Trends for industrial final energy consumption.

The production of coal in the USA has increased steadily since 1960 from about 420 × 10^6 s. tons per year to over 700 × 10^6 s. tons per year today, an average annual growth rate of about 3%. This expanding capacity has supplied a growing electric utility market which now consumes over two thirds of the total coal produced. The rest is used by industry and for export, with very little coal consumed by the household, commercial, and transportation sectors. Recent US coal industry trends are shown in Table 1.

Table 1. US coal industry trends*

Sources: *Statistical Abstracts of the United States,* US Department of Commerce, Washington, DC, 1976.
Coal Mine Development and Expansion Survey, *Coal Age,* p. 83, February, 1977.

	1960	1965	1970	1971	1972	1973	1974	1975	1976**	1977**
Production [10^6 s.tons/year]	416	512	586	561	573	609	611	621	657	707
Annual change [%]	-1.2†	+3.6†	+1.5	-4.3	+2.1	+6.3	+0.3	+1.6	+5.8	+7.6
Consumption [10^6 s.tons/year]										
Electric Utilities	174	243	319	326	349	387	388	403	444	480
Industry	205	219	196	178	168	169	163	152	153	162
Export	37	50	71	57	56	53	60	66	60	65
Total [10^6 s.tons/year]	416	512	586	561	573	609	611	621	657	707
Consumption [%]										
Electric Utilities	42	47	54	58	61	64	63	65	68	68
Industry	49	43	34	32	29	27	27	23	23	23
Export	9	10	12	10	10	9	10	11	9	9
Total [%]	100	100	100	100	100	100	100	100	100	100

*Excludes Pennsylvania anthracite which accounts for about 1% of total production.

**Coal industry estimates, *Coal Age,* p. 83, February, 1977.

† ± 3 year moving average.

Electric Power Production

The importance of coal for electric power production is displayed in Table 2. Since 1960, the amount of coal used by the electric utility industry has steadily increased from 180 × 10^6 s. tons per year to 400 × 10^6 s. tons per year in 1975, an average annual growth rate of over 5.5%. By contrast, the use of oil and gas for electric power production increased at a much

Table 2. Fuel consumption by US electric utilities.

Source: *Statistical Abstracts of the United States*, US Department of Commerce, Washington, DC, 1975 and 1976.

Annual Fuel Consumption

Fuel	1960	1965	1970	1971	1972	1973	1974	1975
Coal [10^6 s. tons]	177	245	321	326	352	390	392	406
Oil [10^6 bbl]	85	115	336	400	494	560	536	507
Gas [10^9 ft^3]	1724	2321	3932	3991	3977	3644	3429	3147

Annual Change [%]*

Coal	+4.9†	+5.3†	+3.6	+1.6	+8.0	+11.0	+0.5	+3.6
Oil	+4.1†	+16.5†	+28.3	+21.8	+23.2	+13.3	-4.3	-5.4
Gas	+8.0†	+8.7†	+11.7	+2.5	-0.4	-8.4	-5.9	-8.2

* $(f_{t+1}-f_t)/f_t \times 100$

† ±3 year moving average

faster rate throughout the 1960s, but has experienced a remarkable trend reversal since about 1970. The use of these fuels for electric power production is now declining significantly since the peaking of US domestic oil and gas reserves in 1967 and 1970 respectively, and because of other international events and rather dramatic price changes for fuels used to produce electric power have occurred (see Table 3) [5]. Today, coal is the cheapest domestic fossil fuel for electricity production.

Table 3. Relative fuel costs for electric utilities 1973-1976 [1975 cents/10^6 Btu].

Source: [5]

Fuel	1973	1974	1975	1976
Coal	52.7	77.4	81.4	81.9
Oil	104.4	209.5	202.0	191.0
Gas	43.9	52.4	75.4	98.8

Nuclear energy is the major national alternative for generating electric power. Recent events related to environmental, safety, risk, and legal concerns, however, have made the nuclear future unclear at present [6] and discouraged nuclear power plant capacity additions during the mid-1970s (see Table 4). The long-term role for nuclear power will undoubtedly be influenced by these recent events, but the US electricity industry has made a substantial commitment to nuclear power, so that future capacity additions will probably increase again. The future of electric power generation in the USA belongs to coal and nuclear; some of the options are outlined in the next section.

Table 4. Nuclear power capacity in the USA.

Source: FEA, 1977

	Number of Plants		Capacity [MW]	
Year	Annual Additions	Cumulative At Year End	Annual Additions	Cumulative At Year End
1965	0	12	0	1,052
1970	2	16	987	5,160
1971	5	21	3,572	8,722
1972	6	26	4,367	13,028
1973	6	35	7,021	20,049
1974	12	44	10,044	29,698
1975	10	54	8,870	38,568
1976	2	56	1,709	40,277

Direct Coal Utilization

As shown in Figure 8, the long-term direct use of coal by industry has declined. In contrast, the prospects for greater use of coal by new boilers has recently changed. In 1973, only 6% of the total capacity of new industrial boilers were coal-fired [7]. However, estimates for new steam-generating boilers ordered by industry in 1976, reveal that as much as one third were coal fired. This is an increase in capacity by a factor of five in three years, but much of it is to replace older equipment, which will limit the net increase of direct industrial coal-fired capacity. Other important areas of recent interest for the direct use of coal by industry include the possibility of increased industrially generated electricity, and the use of coal for cogenerating both electric power and heat for industrial, commercial, and residential customers. This interest is in part generated by recent price differentials for fossil fuels as shown in Table 3. However, even with these developments, the immediate prospects for the substitution of coal for direct utilization in the industrial sector may be still somewhat limited [5].

ASSESSMENT OF FUTURE US COAL OPTIONS

The future for coal in the USA will very much depend on how the long-term preferences for clean and efficient energy forms are modified by recent energy resource and economic events. Also, in addition to influences due to the final energy substitution process, absolute levels of future coal use will be affected by the rates of growth of population and the overall economy, differences in output between economic sectors, the cost of energy relative to that of other commodities, and the domestic availability of oil, gas, and other resources in relation to imports. Lastly, and as important as these factors, is the influence of government policy on every aspect of the coal industry from mining to utilization. US Government decisions affect everything from the type of mining allowed, and the rate a railroad can charge for hauling coal, to the sulfur content of coal a utility is allowed to burn. The current administration's *National Energy Plan* for example proposes a number of policies including a regulatory program to require coal use by utilities and large industries, and an oil and gas users tax and rebate/ investment tax credit system to provide economic incentives to convert to coal.

In order to assess future coal options for the USA, several extensive national planning efforts have been reviewed and summarized. These studies were conducted between 1975 and 1977, and include the work of the US Bureau of Mines (BOM-1975) [10], the US Federal Energy Administration (FEA-1976) [11], the Workshop on Alternative Energy Systems (WAES-1977) [12], the National Energy Plan for the Executive Office of the President (NEP-1977) [9] and the Panel on Demand and Conservation of the Committee on Nuclear and Alternative Energy Systems (CONAES-1977) [13]. The data from NEP-1977 were converted at 5.85×10^6 Btu/bbl, with electricity calculated at 3412 Btu/kwh, assuming 34% conversion efficiency.

The key areas for the future of coal are its use by industry and its use for electric power generation. Industrial uses are here categorized as the direct utilization of coal in processes such as steelmaking, the direct combustion of coal to produce process steam and heat, the on-site combustion of coal for self-generation of electricity, and the on-site conversion of coal to synthetic fuels such as low energy gas. Electric power generation from coal will continue to be by conventional methods until around the 1990s, when fluidized beds and combined cycle gasification systems will become commercially available. Central station conversion of coal to synthetic fuels is also an important aspect for the US coal future, but, as discussed below, without favorable economic incentives or government policies, this industry will experience little growth for several decades.

Coal-related aspects of several of the US national planning efforts are briefly summarized in this paper according to three categories: final energy consumption by industry, primary energy consumption by electric utilities, and primary coal consumed for central station synthetic fuel production. This terminology is defined in Figure 9, and has been adopted for use at IIASA [14]. Along with a quantitative comparison of future projections for energy consumption, the factors that have been assumed to influence each forecast are briefly highlighted. A summary of these forecasts in contrast to historical trends, and in comparison to US coal resource availability is included in the next section.

Final Energy Use by Industry

A comparison of several recent forecasts of final energy consumption by US industries reveals that the share of coal may range from 15 to 50% of the total by the year 2000. This wide possibility spans the range of forecasts from the "business as usual" declining industrial market for coal, to scenarios that represent vigorous government policies and maximum direct use of coal or coal converted to secondary energy forms. More recent forecasts have stressed the latter considerations.

As shown in Table 5, total industrial energy consumption in the USA has been forecast to grow at a rate of between about 3 and 4% per year. "Business as usual" forecasts conducted by the US Bureau of Mines [10] and by the US Federal Energy Administration [11], portray the decline of coal's share to about 15% of final energy consumption by the year 2000. Even with a doubling of the price of imported oil from $8 to $16 per barrel, the substitution of coal in the FEA reference case only increases coal's share by about 1%. There is a major dependence on oil and gas in these scenarios, with a strong trend for industrial electrification. However, even these "business as usual" forecasts are above the historical trend for industrial coal consumption as shown in Figure 10.

Also shown in Table 5 and Figure 10 are more recent forecasts of industrial energy consumption by US industry. These projections suggest that coal's share could well reach 50% by the year 2000 if options for increasing both the direct combustion and the production of secondary energy forms from coal are pursued. For the WAES Scenarios C and D [12], coal substitutes for oil and gas by its conversion to synthetic fuels. This provides one half of the US industrial energy needs by the turn of the century, and reduces oil's share to about 15%. As the cost of coal-synthetic fuels will likely exceed that for oil and gas, even after the year 2000, this option could require a major economic incentive or government subsidy to industry.

In a more recent analysis, the National Energy Plan indicates a vigorous policy oriented toward the substitution of oil by coal. With the plan, coal provides 31% of industrial energy consumption by 1985, whereas coal's share could decline to 16% without the suggested governmental incentives. Incentives in the plan include a regulatory program to require coal use by large industries, and an oil and gas users tax and rebate/investment tax credit system to provide economic incentives to convert to coal.

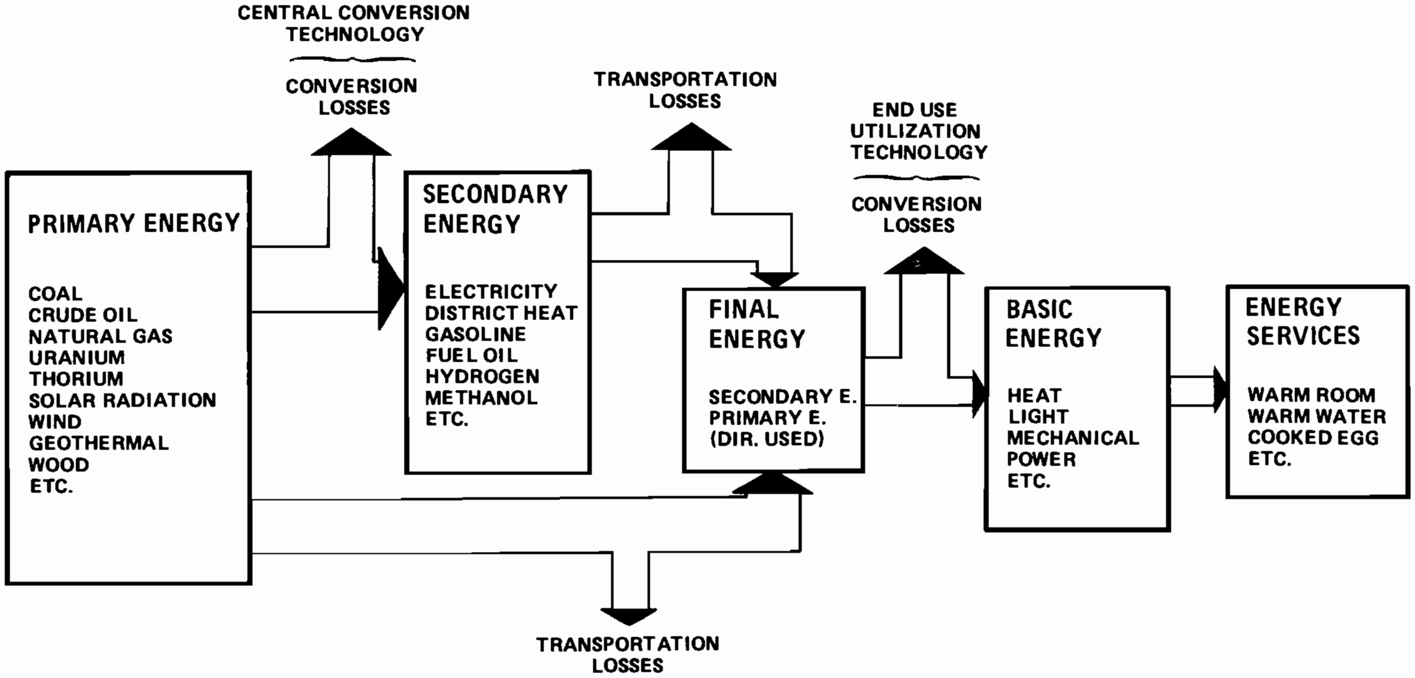

Figure 9. Energy system terminology.

Source: [14]

Table 5. Comparison of final energy consumption in US industry 1975-2000 [Quads/year = 10^{15} Btu/year].

Scenario	Year	Coal	Oil	Gas	Electricity	Total	Comments
Actual [9]	1976	4.06	6.83	9.40	3.05	23.34	Total annual growth rate of 2.3%. Coal's share declines from 17.5% in 1974 to 13.6% in 2000, and electricity increases from 11.2% to 33.8%.
BOM-1975 [10]	1980	4.80	7.50	10.00	3.60	25.90	
	1985	4.93	8.50	9.74	5.62	28.79	
	2000	5.91	11.60	11.26	14.68	43.45	
FEA-1976 [11]							
$8/bbl oil	1980	3.99	7.29	12.69	3.18	27.15	FEA reference case or "business as usual". Total annual growth rate of about 3.1% regardless of imported oil price. Coal's share declines to 15.5% in 1990 at $8/bbl and to 16.6% at $16/bbl, while electricity increases to only 12.8% and 13.9% respectively by 1990.
	1985	4.75	9.03	14.39	3.78	31.95	
	1990	5.71	10.79	15.62	4.72	36.84	
$16/bbl oil	1980	4.04	6.50	12.25	3.13	25.92	
	1985	4.84	7.88	14.05	3.92	30.69	
	1990	5.89	9.33	15.24	4.94	35.40	
WAES-1977 [12]							
C	1985	8.48	3.17	9.62	2.98	24.25	Total annual growth rate of 3.9% for case C-1, and 2% for case D-8. Coal's share increases to about 50% by 2000 for cases C-1 and D-8 because of the assumed industrial production of coal-based synthetic fuels to substitute for oil and gas.
D	1985	8.06	3.21	7.65	2.69	21.61	
C-1	2000	17.99	2.48	8.99	6.34	35.80	
D-8	2000	14.35	4.16	4.44	6.09	29.04	
NEP-1977 [9]	1976	4.06	6.83	9.40	3.05	23.34	Total annual growth rate of 4.2% with plan and 4.7% without. With the plan coal substitutes for oil and provides 31% of final consumption by 1985. Without the plan coal's share is 16% by 1985.
"with plan"	1985	10.68	8.54	9.61	5.15	33.98	
"without plan"	1985	5.77	14.95	9.61	5.23	35.56	
CONAES-1977 [13]							
A	2010	15.98	7.15	3.20	1.76	28.09	Total annual growth rates range from about 0.5% to 1.6%. Coal's share is above 55% by the year 2010 for all cases.
B	2010	18.53	8.03	3.53	2.05	32.14	
C	2010	21.15	8.91	3.86	2.36	36.28	
D	2010	23.80	9.82	4.19	2.66	40.47	

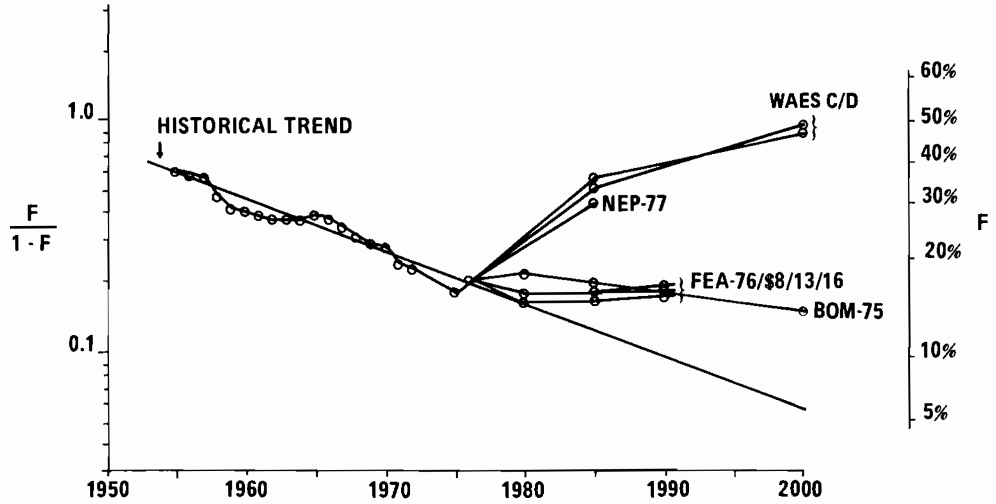

Figure 10. Prospects for final energy consumption of coal by industry in the USA to the year 2000.

The direct industrial use of coal may also be influenced by the degree to which industries will generate their own electricity in the future. This degree of self-generating capacity is affected by several factors including the cost of industrial scale steam-electric plants, and the long-term availability of fuel supply, both of which favor coal-fired units. In addition, conservation of energy by the use of coal-fired steam and electric cogenerating facilities for industrial applications could be a major option. With an emphasis on conservation, the Panel on Demand Conservation of the Committee on Nuclear and Alternative Energy Supply Systems has forecast that coal may provide over 55% of industrial energy consumption by the year 2010 [13]. This panel assumed that industrial steam generation, which accounts for more than 40% of all industrial fuel consumption, will exclusively utilize coal by this time. The additional 15% is accounted for by the use of coal in the iron, steel, and other industries.

In summary, options for the direct use of coal by industry appear to be brightening. The use of coal in industrial boilers for producing process steam and self-generated electricity, as well as for its conversion to synthetic fuels, could increase coal's share of the industrial energy supply market to 50% by the year 2000.

Primary Energy Use by Electric Utilities

A comparison of several recent forecasts of primary energy consumption by US electric utilities reveals that the share of coal may range from as low as 20-30% to as high as perhaps 50% or more in the year 2000. Today, coal's share is about 45%. The major question facing the utility industry that influences these figures is the relative roles for coal and nuclear in the future.

Traditional planning for the electric utility industry has given a high priority to nuclear, as shown in Table 6. Growth rates of over 10% per year have been suggested for nuclear capacity additions, while coal-fired capacity has been planned to increase at about a maximum of 6%. The overall rate of growth of US electricity demand has historically been 7%, while most of the present forecasts for future electricity consumption range around 5 to 6% for the near-term, with declining growth rates over the long term. The 28th Annual Electrical Industry forecast assumes a 6% national electric growth rate for the next few years, which gradually declines to 4-4½% in the 1990s [15]. Fossil and nuclear steam capacity net additions are 19,120 MW for 1990, and 28,500 MW for 1995.

Factors that most directly influence coal-fired capacity forecasts include the price of alternative fossil fuels and the vigor of government policy. For example, as shown in Table 6 for the Federal Energy Administration's reference case, the future annual growth rate for coal-fired plants increases from 2.4%, for imported oil at $8 per barrel, to 6.3% when oil prices double to $16 [11]. Also, the share of coal remains high for government policies directed at the conversion to coal, as illustrated by the forecast of 54% coal-fired generation in 1985 with the National Energy Plan, an increase over today's share of 45%.

Coal-fired capacity as a fraction of steam-electric fossil units increases at nearly every forecast (see Figure 11). Very little oil and virtually no gas-fired units are currently being planned for installation in the USA, in light of recent events and government restrictions.

In summary, the electric utility future belongs to both coal and nuclear. Traditionally, nuclear has been given a priority but coal could continue to provide perhaps 50% or more of the required primary energy. Indeed in the most recent electrical industry forecast, fossil and nuclear-steam electric capacity additions are equal in magnitude for 1990 and 1995 [15].

Table 6. Comparison of primary energy consumption by US electric utilities* 1975-2000 [Quads/year = 10^{15} Btu/year].

Scenario	Year	Coal	Oil	Gas	Hydro	Nuclear	Solar/ Geothermal	Total	Comments
Actual [9]	1976	4.90	1.60	1.50	1.50	1.0	--	10.50	Total annual growth rate of 5.2%. Coal's share declines from 44% in 1980 to 26% by 2000.
BOM-1975 [10]	1980	12.25	5.10	2.00	3.65	4.55	0.15	27.70	
	1985	15.70	6.20	1.50	3.40	11.84	0.45	39.09	
	2000	20.70	4.70	1.00	4.55	46.08	1.52	78.55	
FEA-1976 [11]									
$8/bbl oil	1980	11.30	4.74	2.58	3.70	3.66	See Comments	25.98	Solar/geothermal are included in hydro. Total annual growth rate of about 5% regardless of imported oil price. Coal's share increases in 1990 from 34% for $8/bbl oil to 50% for $16/bbl oil.
	1985	12.50	8.34	0.55	3.94	7.94		33.27	
	1990	14.30	10.90	0.12	4.17	12.66		42.15	
$16/bbl oil	1980	11.49	2.79	3.81	3.70	3.86		25.65	
	1985	16.29	1.96	3.26	3.94	8.68		34.13	
	1990	21.56	3.15	1.56	4.17	13.28		43.72	
WAES-1977 [12]									
C	1985	7.95	4.09	1.44	4.60	8.48	0.50	27.06	Total annual growth rate of 3.8%. Coal's share decreases to about 10% by 2000.
D	1985	11.67	5.56	1.62	3.40	6.57	0.20	29.02	
C-1	2000	4.56	3.05	1.00	4.60	25.96	4.50	43.67	
D-8	2000	4.05	4.01	1.40	3.69	33.12	1.70	47.97	
NEP-1977 [9]	1976	4.90	1.60	1.50	1.5	1.0	--	10.50	Total annual growth rate of 4.3% with the plan and 4.9% without. The share for coal in 1985 with the plan is 54%, and 50% without.
"with plan"	1985	8.30	1.30	0.50	1.6	3.8	--	15.50	
"without plan"	1985	8.20	2.00	0.90	1.6	3.6	--	16.30	
FPC 383-1976*	1980	12.21	3.87	3.41	3.74	3.89	0.93	28.05	Total annual growth rate of 6.6%. Coal's share is 44% in 1980 and 41% in 1985.
	1985	15.90	4.07	3.40	4.60	8.90	2.22	39.09	

*Estimated by the author from FPC Docket R-362, Order 383-3, 1976.

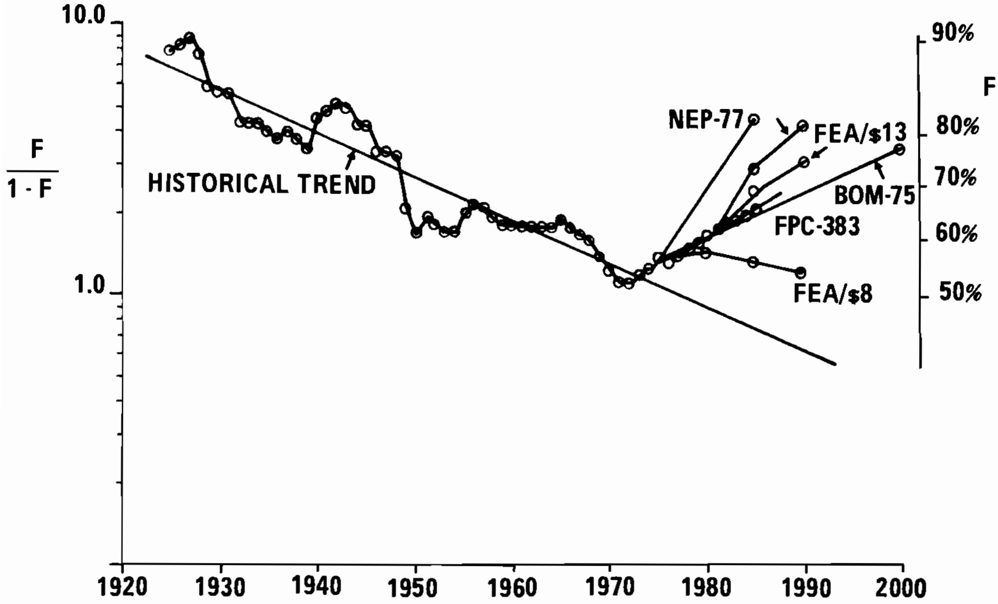

Figure 11. Prospects for coal consumption in fossil-electric power plants in the USA to the year 2000.

Primary Energy Use for Synthetic Fuels

Synthetic fuels from coal have been relatively important for the United States. The low energy gasification of coal to produce "town gas" was practiced before the advent of less expensive and higher energy content "natural gas". For some time, forecasters have been predicting a return to coal-based synthetic fuels, as nature-made oil and gas reserves diminish. Within the concept of a centralized coal-synthetic utility industry, the US National Petroleum Council in 1972 predicted that by 1985, as much as 3.3 quads per year of coal (about 130 × 10^6 s. tons per year at 25.2 × 10^6 Btu/s. tons) might be used to produce synthetic high energy gas, and perhaps 2.2 quads per year (87 × 10^6 s. tons) for synthetic liquids. The US Bureau of Mines in 1975 also reflected this thinking at a reduced scale, and forecast that coal-synthetic gas production could require 0.52 quads per year of primary coal in 1985, and perhaps 6 quads by the year 2000. With the addition of coal liquefaction (Table 7), the Bureau of Mines forecast that as much as 320 × 10^6 s. tons of coal per year could be converted to synthetic fuels by the turn of the century. Although significant, this would represent only about 5% of primary energy supply.

Table 7. Comparison of coal-synthetic fuel options for the USA* [Quads/year = 10^{15} Btu/year].

Scenario	Year	Primary Fuels for Coal Gasification	Primary Fuels for Coal Liquefaction
NPC-1972*			
I	1980	0.77	0.27
	1985	3.32	2.24
II	1980	0.50	-
	1985	1.82	0.30
BOM-1975 [10]	1980	-	-
	1985	0.52	-
	2000	6.00	2.14

*National Petroleum Council, *U.S. Energy Outlook*, December, 1972.

Recently, the interest in centralized facility coal-based synthetic fuels has somewhat diminished. This is based perhaps on a realization that the economic viability of coal-synthetic fuel production in central facilities, as suggested by the relative price forecasts in Table 8, may not be proven for several decades. If these facilities are to become commercialized before the next century, government incentives may be required, or alternatively, the prices of conventional fossil fuels will have to rise considerably. In contrast to this, and perhaps as a leading indicator, the use of coal gasification for specific industrial and commercial purposes on a localized scale is gaining some interest. In special situations, especially as a substitute for industrial gas consumption, the use of coal solves the long-term fuel availability problem in the USA [16-18].

Table 8. Estimates of fossil fuel prices [\$1975/10^6 Btu].

Source: [7], p. 2.31.

Fuel	1985	2000
Oil	2.24	2.87
Gas	1.93	2.19
Coal	0.61	0.69
Synthetic crude	3.45	3.57
High energy gas	3.54	3.65

In summary, the prospect for central station coal-based synthetic fuels does not appear promising, especially from an economic standpoint. However, the use of coal for site- and process-specific industrial application is gaining some attention.

TWO CENTURIES OF US COAL SUPPLY AND DEMAND

To assess national strategies and options for coal within a global context, a long-term time perspective is necessary. In addition, a perspective on long-term resource availability is required. This includes a look at the past century of coal use in the USA, as well as the prospects for the 21st century and beyond.

US Coal Supply: 1850-2050

From the early 1800s until about 1910, the supply of coal in the USA grew at an average annual rate of about 6.5%. As shown in Figure 12, with the commercialization of oil and gas at the turn of the century, the US coal industry began to gradually decline. However, with the increased use of coal-fired electric power generation since 1960, the production of coal has risen again. Prospects for the revival of coal have continued to mount throughout the 1970s, because of the peaking of US domestic oil and gas reserves, the oil embargo of 1972, and the relative rise in price of non-coal fossil fuels.

Several alternative national plans for coal supply in the USA have been summarized relative to the long-term historic trends. These plans are displayed in Figure 12. Projected growth rates for the expansion of the US coal industry range from a low of perhaps 2% (WAES-D, FEA/76-$8 oil), to a high of over 6% (NEP-77). These growth rates range over the types of forecasts from near "zero energy growth", and "business as usual", to strong futures for coal, with major programs by industry and government. The latter type of forecast predicts that the supply and utilization of coal will "double by 1985", so that over 10^9 s. tons per year will be produced by the middle of the next decade.

As suggested by the range of projections, the contest over coal in the USA is the subject of much discussion. A current debate is whether the US coal industry can achieve the goals of the *National Energy Plan*. Many have their doubts (cf. the GAO analysis [5]) but the coal industry itself, through its spokesman the National Coal Association, believes that the goal of reaching 1.2 to 1.3 × 10^9 t per year by 1985 can be achieved [19]. The switch to coal will involve many elements of society that will require changes of a structural nature. In any event, the outlook for coal is positive, and a long-term expansion with a growth rate of perhaps 3 to 5% per year is most likely.

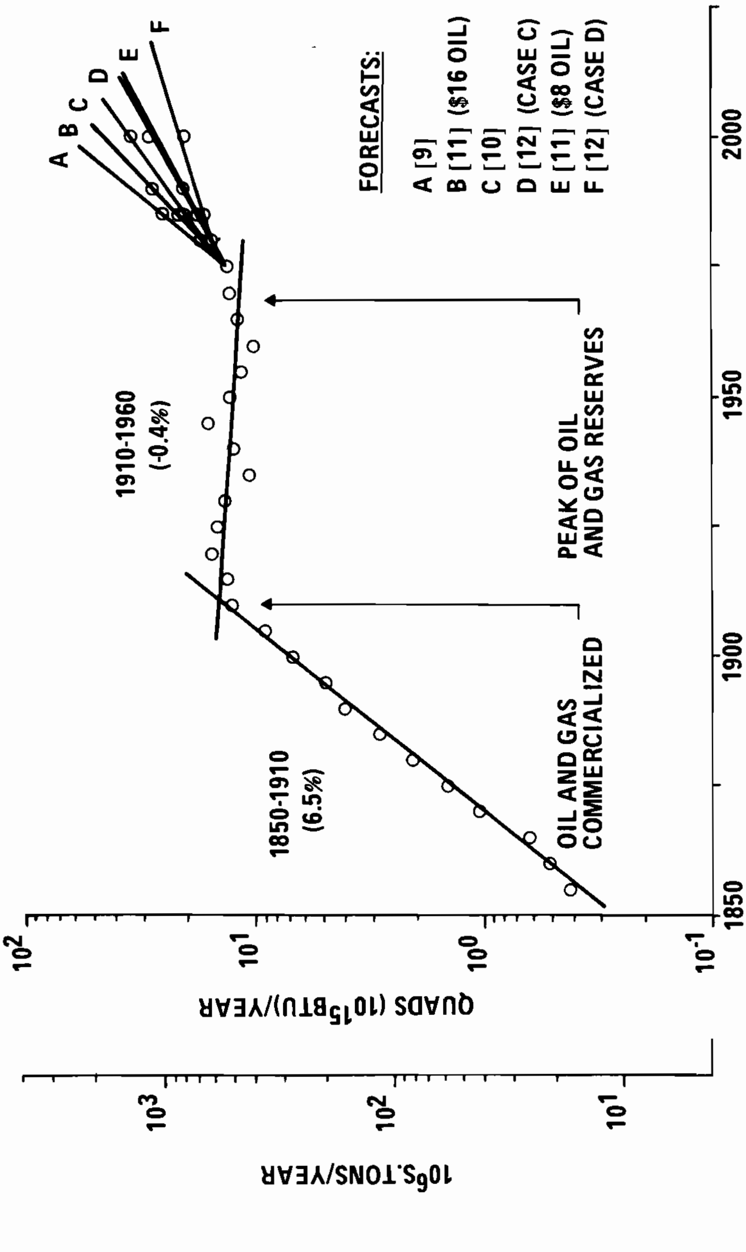

Figure 12. US coal supply, 1850 - 2050.

US Coal Resource Consumption: 1850-2050

A national strategy and option for coal in a global context must also be assessed within the perspective of long-term resource availabilities. To gain this view, it is necessary to integrate the area under the curve of Figure 12, and add up all the coal that has been consumed in the past, as well as that which may be consumed according to future projections. This is illustrated in Figure 13.

Through the early 1900s, coal resources were consumed at an exponential rate, so that by 1910, approximately 200 quads of coal had been mined and utilized. This represented approximately 9×10^9 s. tons. The rate of coal consumption then declined, so that by 1960, a total resource of about 900 quads (42×10^9 s. tons) had been consumed, which increased to some 1100 quads (50×10^9 s. tons) by 1975.

From the range of growth rates expressed in the forecasts of Figure 12, resource consumption options resulting from extrapolated future coal production scenarios have been calculated. It should be stressed that these extended scenarios no longer correspond to the characteristics of the plans shown in Figure 12, but are simple extrapolations in order to determine possible future coal options in the light of estimated coal resources and reserves. Beginning in 1975, coal supply scenarios ranging over annual capacity increases of from 1.5 to 6.5% generate the range of future consumption options shown in Figure 13.

Under the assumption of large annual production capacity additions represented by scenario a in Figure 13, the lifetime of the estimated surface reserve base extends to approximately the year 2010, while the total reserve base is consumed by about the year 2035 [20]. For the low production scenario, surface reserves last until about the year 2040, while total reserves are not consumed until well past the year 2100. If the medium range scenario c is extrapolated, surface reserves are exhausted by about 2020, while total reserves last until the year 2060. The characteristics of these scenarios are summarized in Table 9. The major point of this exercise is to estimate the possible durations for the US coal option, and to compare the relative variations so that potential key dates may be established.

With the coal resource and reserve estimates represented in Figure 13, it is clear that even with moderate long-term growth rates in production capacity of 3 to 4% per year, the reserves of US coal will last beyond the middle of the next century. By comparison, the reserve base of surface mineable coals may not last beyond the year 2025, if exploited at moderate rates, and may be exhausted by 2010 for high growth rates. Thus the US coal option is characterized by a lead time of not more than about 50 years for the use of its surface reserves, and perhaps by as much as 100 years or more for the use of its

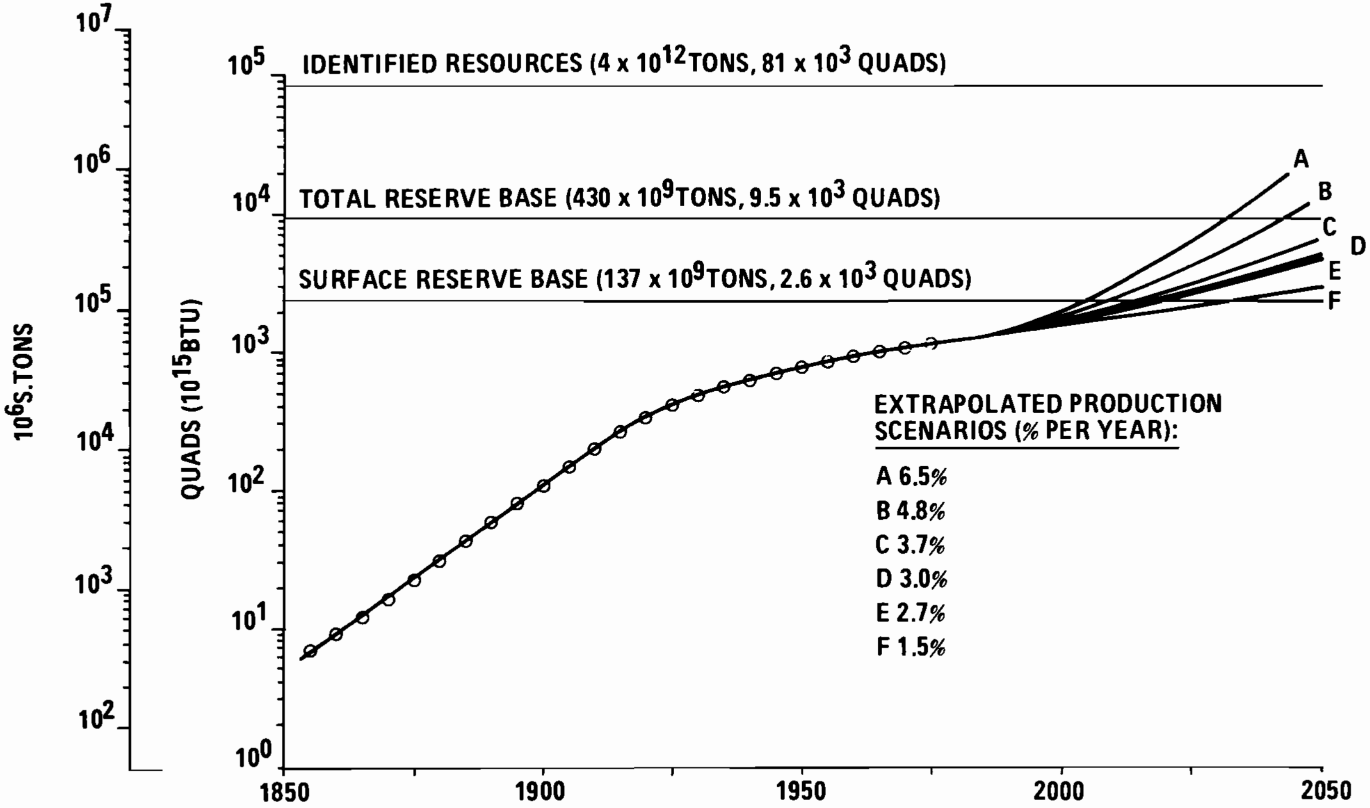

Figure 13. US coal resource consumption, 1850 - 2050.

Table 9. US coal resource consumption scenarios.

	Year by which Resource is Consumed	
Scenario*	Surface Reserves	Total Reserves
a (6.5%)	2010	2035
b (4.8%)	2015	2045
c (3.7%)	2020	2060
d (3.0%)	2025	2075
e (2.7%)	2025	2080
f (1.5%)	2040	>2100

*Scenario defined in Figure 13.

total present reserve base. These are considerable lead times that depend significantly on the assumed coal reserve estimates, the rate at which different reserve classifications are consumed, and the overall rate of coal use. The times may be considerably extended by advances in coal mining technology or by reductions in assumed growth rates due to energy conservation and reduced population growth. A glimpse of the potential for extending the US coal option is possible by calculating the lifetime of the total identified resources for various future rates of growth. At a moderate growth rate in production capacity of 3% per year, the total identified resources, if exploitable by technological advances, would provide energy for the USA into the middle of the 22nd century. For a long-term growth rate of 1%, which has been the historical difference between the rate of growth of energy consumption and population growth, or the rate of growth of energy consumption per capita, the total identified coal resource could supply energy for the USA almost indefinitely.

CONCLUSIONS

Recent events affecting the availability of oil and gas have had a significant impact on the US coal industry, and have signaled the beginning of a major coal revival in the United States.

A long-term fuel substitution trend in final energy markets has led to the decreased direct use of coal. Recent coal industry developments suggest a modification and likely reversal of the long-term fuel substitution trends, especially for fossil-fuel electric utilities and industrial markets. The relative fossil fuel cost for electric utilities now favors coal.

Several alternative national energy plans for the USA are summarized that for the most part show a major revival for coal in electric utility and industrial markets. The essential forecast for several of these plans is that coal will in principle replace all other fossil fuels for electric power generation, and could provide up to about 50% of all primary energy needs for electric utilities through the year 2000. The industrial use of coal may also reach a share of some 50% by the year 2000, which could provide energy to industry directly or in the secondary forms of electricity and synthetic fuels.

Centralized coal-synthetic technology may not become commercialized before the year 2000 because these fuels could continue to be more expensive than nature-made fossil fuels.

A two century summary of historical and possible future coal supply and demand trends in the USA lead to the conclusion that surface reserves of coal will last approximately 50 years at moderate annual growth rates of 3%, while the lifetime of total reserves will be extended for some 100 years at the same rate. Technological advances and reduced energy growth rates could extend these lifetimes considerably, so that the US coal option could extend even into the 22nd century.

Environmental considerations were not mentioned specifically in the text but are the subject of much discussion and current activity. An overview of the technologies that control environmental emissions in the coal-fuel cycle may be found in [21]. The author feels that although environmental considerations are a concern, advances in technology and modest increases in energy prices will essentially solve any potential problem.

ACKNOWLEDGMENTS

This review and analysis of coal options and strategies for the United States could not have been possible without the help of many people including M. Grenon, R. Tomlinson, W. Häfele, C. Marchetti, W. Sassin and others at IIASA, and the members of the US Advisory Committee to the IIASA Coal Task Force, which included: S. Berman, Lawrence Berkeley Laboratory, Berkeley, California; J. Oxley, Battelle Memorial Laboratory, Columbus, Ohio; M. Gaffen, Coal Analysis Division, Department of Energy, Washington, DC; R. Gordon, Pennsylvania State University, University Park, Pennsylvania; E. Koenigsberg, Manalytics, Inc., San Francisco, California; D. Meadows, Dartmouth College, Hanover, New Hampshire; P. Meier, Brookhaven National Laboratory, Upton, New York; P. Nagarvala, Bechtel Corporation, San Francisco, California; J. Quinn, Office of Program Planning and Analysis, Department of Energy, Washington, DC; E. Rubin, Carnegie-Mellon University, Pittsburgh, Pennsylvania; R. Schmidt, Electric Power Research Institute, Menlo Park, California; and A. Squires, Virginia Polytechnic and State University, Blacksburg, Virginia.

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PROSPECTS AND PROBLEMS OF A RAPID INCREASE IN ENERGY FROM COAL

S.W. Gouse

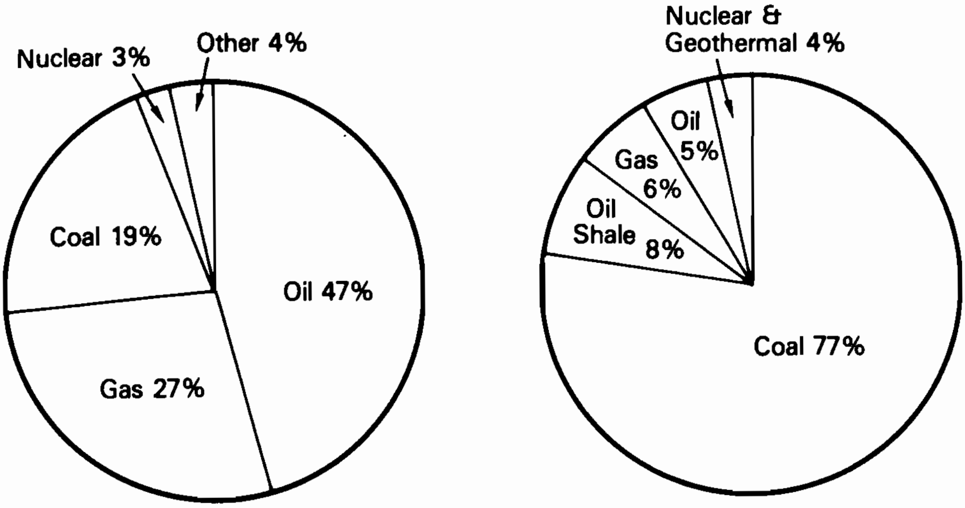
The energy situation in the USA, as in the whole world, is changing very rapidly. More now than perhaps ever before, national leadership is required to help direct our countries' energy policies toward the use of more abundant and more secure energy resources. This energy will not be cheaper, but ideally the quantity of these resources will be sufficient to allow reasonable economic growth at costs that are neither restrictive nor burdensome. Such a policy should also minimize the burden placed on the environment.

A shift in the source of energy from oil and gas to more abundant resources and eventually to renewable or nonexhaustible resources is inevitable. Because this change may be rapid and in any case will require large financial commitments, our government will have to assist in the transition.

In the USA we have recently adopted a National Energy Plan [1]. The cornerstone of that plan is conservation. But it also contains a major commitment to the transition from oil and gas to coal since coal is our largest fossil resource as shown in Figure 1. Shale and peat are also major resources but have not yet been selected for major development.

As you can see, oil and gas account for only about 11 percent of known US recoverable reserves while they account for about 75% of US energy consumption. Coal on the other hand, makes up about 77% of national recoverable reserves, while constituting less than 20% of energy used. Shale represents roughly another 8% of the US energy recoverable reserves and currently it makes virtually no contribution to satisfying energy demands. The energy resource situation presents a very different perspective as shown in Figure 2. The USA has large amounts of energy resources that are not now considered to be economically recoverable. These are primarily unconventional natural gas (gas in geopressurized zone, methane in coal seams, gas in tight sands and shale), peat and oil shale. A major part of our research is directed towards shifting these energy resources to economically recoverable reserves.

To give you a better idea of the absolute magnitude of our reserves, Figure 3 shows known world coal reserves. As many of you know, world coal reserves are estimated at 1.5×10^{12} t. Of this, approximately 30% is found in the USA.



Energy Consumption (1975)

Proved Reserves Recoverable With Existing Technology (1975)

Figure 1. US energy consumption and reserves by fuel source.

Source: [10]

The primary intent of the National Energy Plan is to avoid major energy problems between now and 1985. However, it is well recognized that our energy problems will not end in 1985 and so programs exist to develop new and improved technologies that will be needed in the years beyond 1985. The shift to a more coal-based energy system is important for the near-term and it becomes increasingly so as we get farther into the future.

Recent Congressional actions on environmental matters will effect the expansion of coal utilization. The Clean Air Act Amendments of 1977 require the use of pollution control technologies regardless of coal sulfur content [2]. This will reduce the premium paid for low sulfur coal and will probably result in increased utilization of high sulfur coal. The legislation also calls for the prevention of serious deterioration of air quality. This will probably restrict the location of coal conversion facilities. In areas that currently fail to meet pollution standards, it means that no factory can switch to coal unless another one reduces its emissions by a greater amount.

The Surface Mining Control and Reclamation Act of 1977 mandates increased reclamation efforts [3]. This will result in a small increase in the cost of surface mined coal. It may also delay the opening and development of new surface mines. Overall, these two acts will probably reduce somewhat the rate of conversion to coal and raise the cost of using coal. However, coal use will still increase.

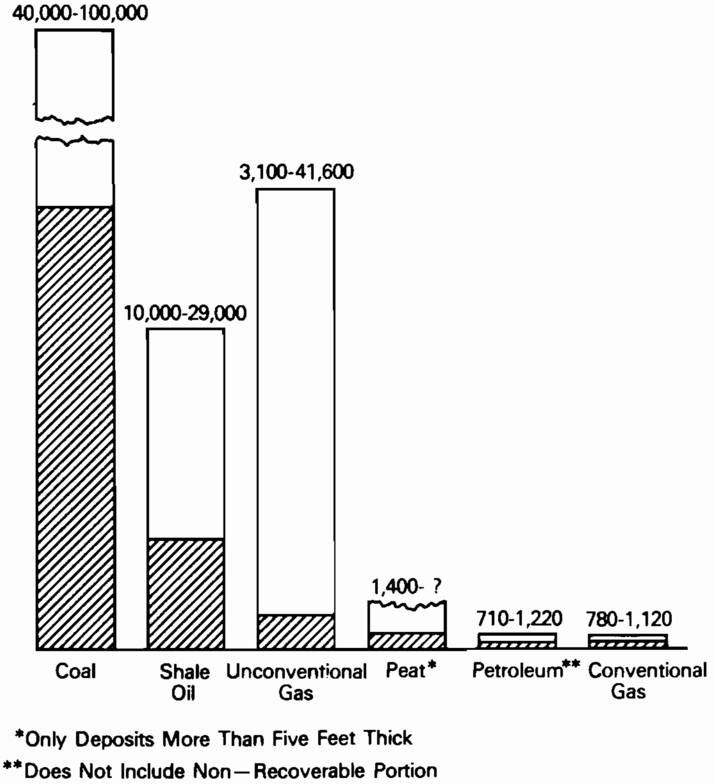


Figure 2. US energy resources (quads).

Sources: [10]. Peat and Unconventional Gas Estimates from Unpublished US Department of Agriculture Soil Survey Data and ERDA Studies.

Accomplishing the objective of conversion to coal is a much bigger problem than simply mining the additional coal. Increased use of coal will affect all aspects of our energy system. For example: How do we get the coal mined? At what cost to the natural environment? At what cost to nearby communities? In what form will energy from coal be used? Where will coal gasification/liquefaction/electrification occur? How will the energy be transported? What investment will have to be made in conversion and end use facilities?

The complexity of the problem makes it difficult to determine the "best" solutions. The first part of our strategy has been to try to identify available options for satisfying end use service demands--as well as the consequences of each option in terms of social, institutional, and economic impacts. The second

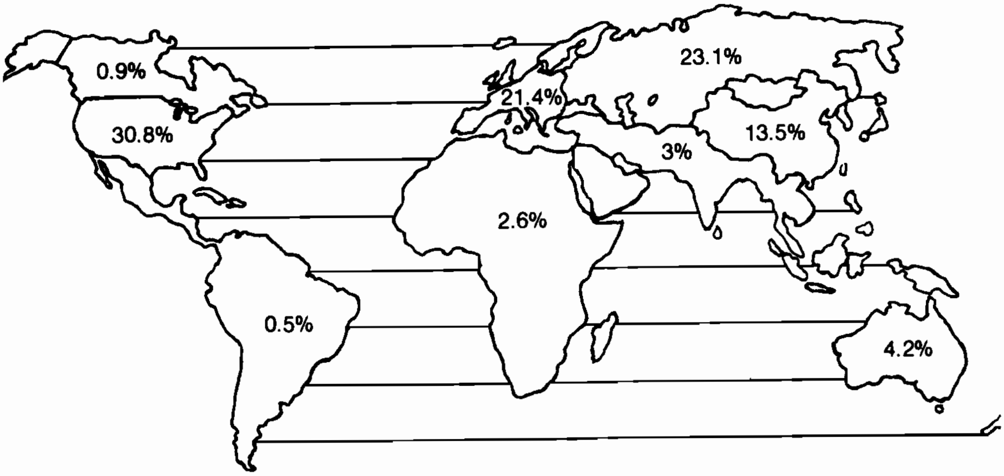


Figure 3. Recoverable coal reserves of the world.
Source: National Coal Association, Coal Facts 1974-1975.

is to provide the information to stimulate a productive national debate which we hope will lead to a consensus on acceptable alternatives. It is only after these initial steps have been taken that an adequate research and development program can be designed.

There are several dimensions to the energy picture, and that fact accounts for much of the complication. Two basic dimensions are the energy resources and the activities required to use them. These are effectively shown by the fossil pathways diagram in Figure 4 for coal, natural gas, oil shale, and petroleum. This figure also shows options associated with the fossil fuel cycles. For example: surface or deep mined coal; crushed, clean, or direct conversion; transport by rail or slurry pipelines; conversion to liquid or gas; and so on.

In the USA we are using a large number of analytical techniques and models to assist in developing energy policy and establishing an energy research program. These techniques range from a comprehensive assessment of the market potential for all of the developing technologies to a detailed model that estimates the cost of coal from a strip mine.

One comprehensive model was developed by Stanford Research Institute and is an equilibrium model of energy use [4]. The model covers all major energy forms, conversion technologies, transportation modes, demand sectors, and US geographical regions. It explicitly models supply elasticity, interfuel competition and demands for energy services. It also treats energy market dynamics such as investment, financing, technological change, demand growth, and resource depletion from the present to the year 2025. Perhaps most significantly, given supply and demand curves by

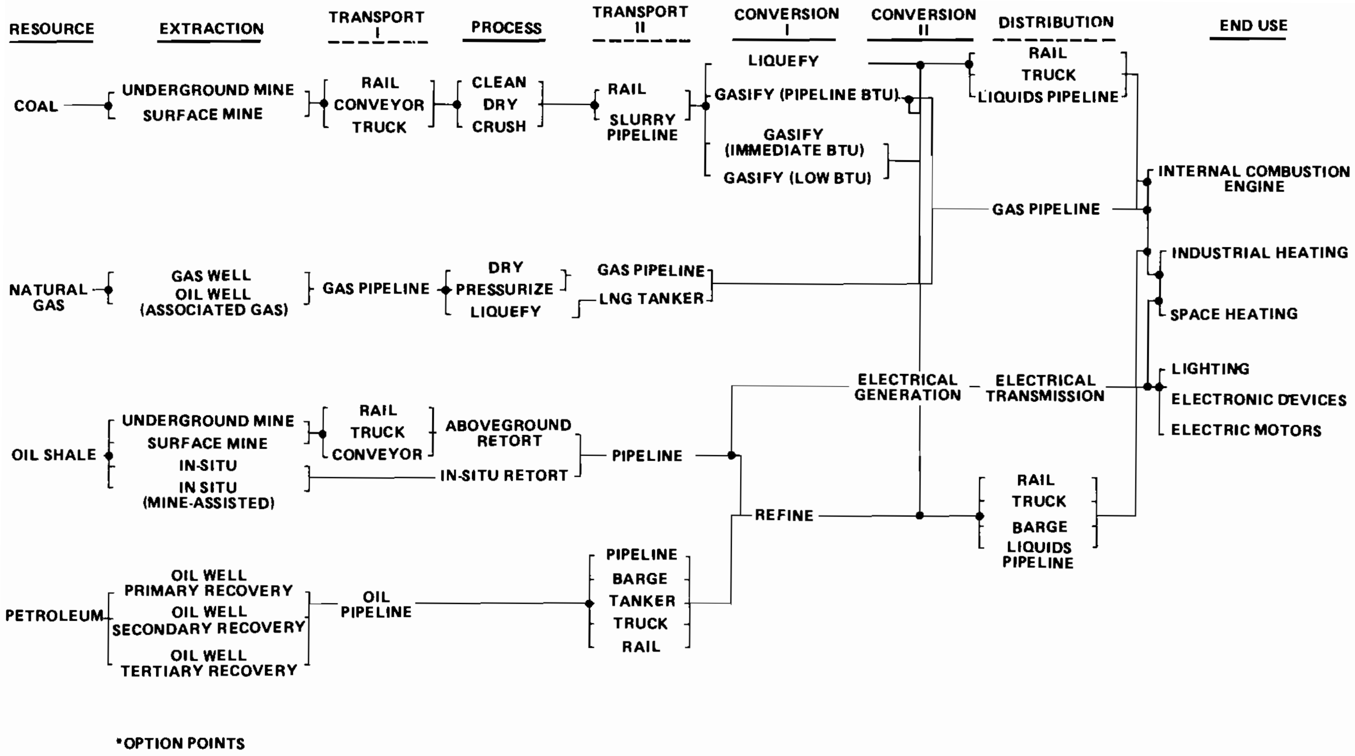


Figure 4. Fossil pathways.

region, and transportation and conversion costs, this model computes market clearing prices and quantities for each energy resource in each region. An example of the output is shown in Figures 5 and 6. A recent comprehensive Energy Research and Development Administration (ERDA) market oriented study also provides some insights into which options for meeting end use energy demands are preferable [5]. It is an interactive technique that integrates analytical model results with the judgments of scientists. This project, which started about a year ago, was an attempt to provide information to be used in developing this year's energy research and development plans. It included the three end use sectors--transportation, residential and commercial, and industrial--and a supply sector consisting of electric utilities, oil and gas transportation, coal and oil shale conversion, and primary energy production.

The amount of service demand by the end use sectors was determined in advance. The Stanford Research Institute model, described above, was used to provide the first estimate of equilibrium prices. With that information, each sector estimated the potential market penetration of all technologies (including conservation technologies) applicable to that sector. For all sectors this was done with some kind of computer analytical model. In some cases several models were used and integrated or consensus solutions were generated. The results suggest that by the year 2000, up to 40% of the potential energy demand could be avoided by the use of conservation technologies. It also demonstrated that the market penetration potential for most of the supply technologies was highly sensitive to the availability of natural oil and gas (whether produced in the USA or imported). In turn, the availability of natural oil and gas was discovered to be extremely uncertain.

The results indicated a significant increase in the demand for coal, mostly for direct combustion. There was limited demand for low energy gas from coal and an even smaller demand for synthetic medium and high energy gas. Nonetheless, it is most likely that the use of coal in the short term will be constrained by demand, not supply. In the long term there appear to be no real constraints to producing enough coal to satisfy the projected demand. Sample results are shown in Table 1.

Another analysis of the systems problems created by increased coal production was obtained by using a linear programming model developed by Bechtel Corporation that analyzes the response of the national energy system, particularly the coal sector, to changes in energy supply and demand [6].

Given energy end use service demand by regions, the Bechtel model predicts the least-cost method of utilizing coal and other energy sources to satisfy the demand. Outputs of the model include: the quantity and type of coal mined in each supply region; the load on coal and other energy transport systems; the usage pattern for existing energy conversion facilities and the preferred location of additional facilities; a determination of the

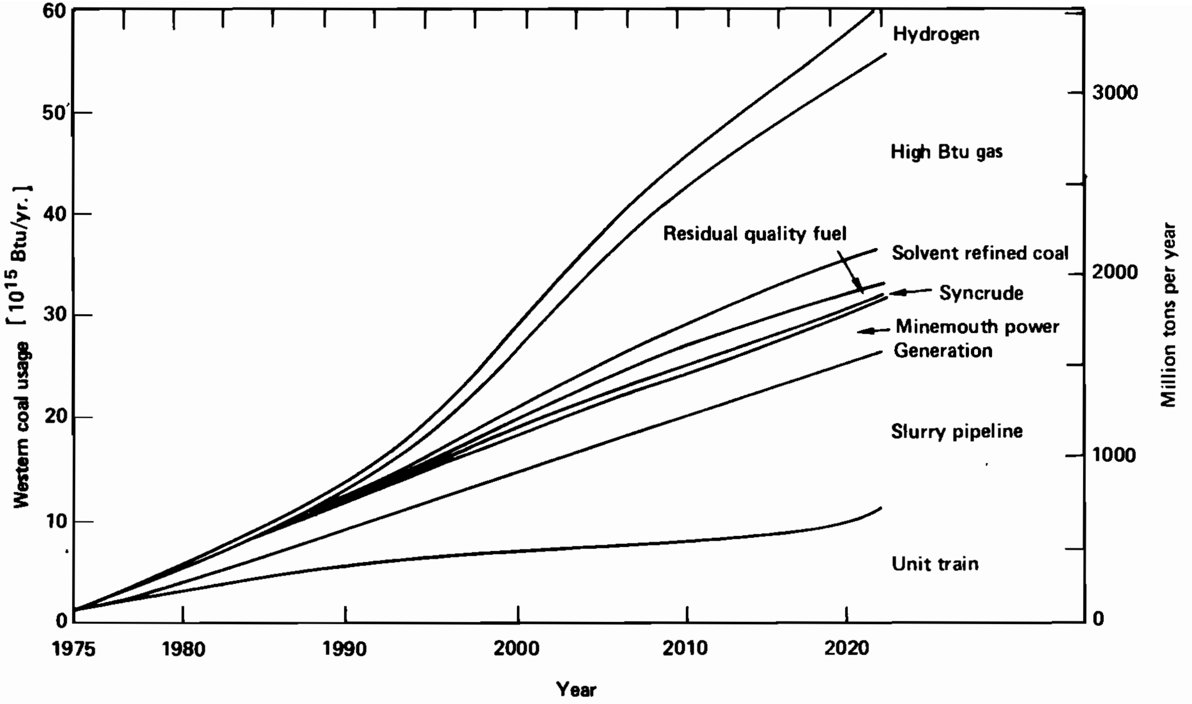


Figure 5. Sample Stanford Research Institute energy model output western coal usage: nominal case.

Source: [5]

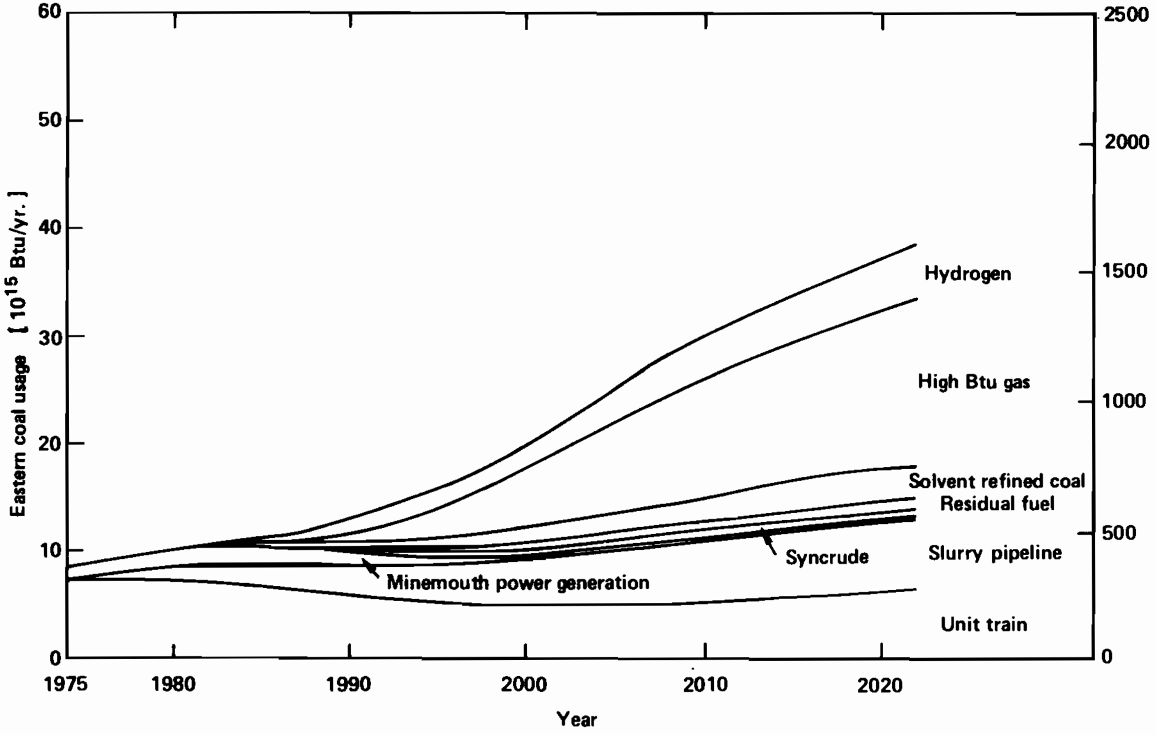


Figure 6. Sample Stanford Research Institute energy model output eastern coal usage: nominal case.

Source: [5]

Table 1. Sample ERDA market oriented study output.

	Fuels Delivered to End-Use Sectors			Primary Fuels Demanded		
	1985	2000	2010	1985	2000	2010
Liquids	------- QUADS -------			--------- QUADS ---------		
Residential/ Commercial	5.000	3.780	3.720	7.107	4.424	4.310
Industry	4.089	5.174	6.654	5.964	5.844	7.289
Transportation	18.990	17.990	23.250	20.151	19.005	24.544
Liquified Petroleum Gas	1.346	1.159	0.999	1.416	1.220	1.052
	29.425	28.103	34.623	34.638	30.493	37.195
Gas						
R/C	8.200	7.780	8.070	9.398	8.640	8.967
Industry	6.464	6.925	8.526	7.439	7.694	9.473
Transportation	0.770	0.540	0.700	0.880	0.613	0.778
	15.434	15.245	17.296	17.717	16.947	19.218
Electricity						
R/C	4.800	6.490	7.131	---	---	---
Industry	4.288	5.842	7.465	---	---	---
Transportation	0.420	1.000	1.290	---	---	---
	9.508	13.332	15.886	0.0	0.0	0.0
Coal						
R/C	0.250	0.460	0.840	8.656	9.603	9.067
Industry	4.716	11.476	17.484	12.358	20.301	27.071
Transportation	---	---	---	0.725	1.385	1.460
Metallurgical Coal*	3.588	4.368	4.975	3.777	4.598	5.237
	8.554	16.304	23.299	25.516	35.887	42.835
Industrial Waste	1.833	2.631	3.807	1.833	2.632	3.807

---

*Excluding exports

Table 1. (cont'd)

Fuels Delivered to End-Use Sectors				Primary Fuels Demanded		
	1985	2000	2010	1985	2000	2010
Nuclear	-------	QUADS	-------	--------	QUADS	--------
R/C	---	---	---	3.614	8.985	10.488
Industry	---	0.008	0.028	3.228	8.101	11.008
Transportation	---	0.010	0.010	0.316	1.375	1.881
	0.0	0.018	0.038	7.158	18.461	23.377
Solar, Geothermal, Biomass, etc.						
R/C	0.124	0.697	0.799	1.507	2.762	4.206
Industry	0.096	0.560	1.233	1.127	2.470	4.766
Transportation	---	0.010	0.010	0.101	0.324	0.608
Lubricant/Coal Oil	1.900	2.460	2.710	1.900	2.460	2.710
	2.120	3.727	4.752	4.635	8.016	12.290
Total	66.874	79.361	99.701	91.497	112.436	138.722

incremental value of additional fuels, and amount of conversion facilities and transportation capacities. Both current technologies and those that might be brought on line in the next two decades are considered by the model. Sample results are shown in Tables 2 and 3.

Other studies examine smaller pieces of the coal fuel cycle. A model developed by Fluor Utah, Inc., for example, focused on the economics of large-scale surface coal mining [7]. Fluor has developed micromodels--which provide detailed information on mining systems and equipment to assist in mine design and equipment selection--and broad macromodels--which provide a first order evaluation of new ventures for an entire coal mining complex. The models have been used to estimate mining costs for hypothetical situations in each of the eight major surface mining regions in the USA. Combinations of the most applicable mining method and region were used in this exercise. The results of the test cases show potential coal prices for a range of geological and economic assumptions. Each major operation in the coal mining process is represented in these models so that the best methods and equipment may be selected and so that the impact of such selection will be reflected in estimates of capital investment, operating costs, and sales price. Sample results are shown in Table 4.

Table 2. Sample Bechtel model output 1985 energy demand.[(a)]

Source: [6]

M-PAD	Electric Power		Crude Oil		Natural Gas		RCI Coal		Total	
									w/o Elec.	All
	10^6 MWh	TBtu	10^6 bbl	TBtu	10^9 st. ft^3	TBtu	Mt	TBtu	TBtu	TBtu
1	331.1	1,130.0	68.6	381.0	1,222.3	1,197.9	7.8	185.0	1,763.9	2,893.9
2	405.9	1,385.3	918.2	5,101.3	2,151.4	2,108.4	39.9	950.0	8,159.7	9,545.0
3	345.1	1,177.8	38.9	216.3	1,271.6	1,246.2	21.6	515.0	1,977.5	3,155.3
4	369.9	1,262.5	759.7	4,220.7	2,909.3	2,851.1	85.1	2,026.0	9,097.8	10,360.3
5	187.1	638.6	118.8	659.9	611.2	599.0	22.5	535.0	1,793.9	2,432.5
6	160.7	548.5	702.6	3,903.4	1,319.8	1,293.4	22.2	528.0	5,724.8	6,273.3
7	102.6	350.2	132.8	737.9	831.7	815.1	19.4	462.0	2,015.0	2,365.2
8	184.3	629.0	626.7	3,481.8	2,640.7	2,587.9	24.4	581.0	6,650.7	7,279.7
9	20.8	71.0	33.0	183.4	73.9	72.4	3.9	92.0	347.8	418.8
10	209.8	716.0	1,228.5	6,825.2	3,080.6	3,019.0	6.1	145.0	9,989.2	10,705.2
11	241.2	823.2	2,191.4	12,174.6	4,984.7	4,885.0	3.6	86.0	17,145.6	17,968.8
12	11.2	38.2	31.0	172.4	318.0	311.6	4.2	99.0	583.0	621.2
13	38.5	131.4	175.7	976.1	195.9	192.0	6.9	165.0	1,333.1	1,464.5
14	41.3	141.0	104.3	579.7	342.6	335.7	4.2	99.0	1,014.4	1,155.4
15	156.1	532.8	272.3	1,513.0	293.4	287.5	1.4	33.0	1,833.5	2,366.3
16	303.1	1,034.5	1,076.0	5,977.5	2,200.7	2,156.7	4.2	99.0	8,233.2	9,267.7
Total	3,108.7	10,610.0	8,478.5	47,104.2	24,447.8	23,958.9	277.4	6,600.0	77.663.1	88,273.1

[(a)] The total demand, 88.27 quads, shown in this table is different from the 107.3 quads of total resource consumption given in the original ERDA scenario. This difference is due to conversion efficiencies in the electric power section.

Table 3. Sample Bechtel model output base case: 1985 energy supply.

Source: [6]

M-PAD	Electric Power				Crude Oil				Gas				Coal Mining Capacity	
	10^6 MWh Existing	New	TBtu Existing	New	10^6 bbl Natural	Syn	TBtu Natural	Syn	10^9st.ft^3 Natural	Syn	TBtu Natural	Syn	Mt	Tbtu
1	296.7	0.0	1,012.6	0.0	183.2	0.0	1,017.8	0.0	31.0	0.0	30.4	0.0	0.0	0.0
2	469.2	0.0	1,601.4	0.0	1,200.2	0.0	6.667.8	0.0	384.0	0.0	376.3	0.0	344.0	8,190.5
3	436.4	0.0	1,489.4	0.0	458.6	0.0	2,547.8	0.0	24.0	0.0	23.5	0.0	0.0	0.0
4	415.1	0.0	1,416.7	0.0	581.6	0.0	3,231.1	0.0	288.0	0.0	282.2	0.0	96.0	2,285.7
5	214.4	0.0	731.1	0.0	55.0	0.0	305.6	0.0	96.0	0.0	94.1	0.0	210.0	5,000.0
6	173.6	0.0	592.5	0.0	70.0	0.0	388.9	0.0	48.0	0.0	47.0	0.0	102.0	2,428.6
7	107.7	0.0	367.6	0.0	327.0	0.0	1,816.7	0.0	130.0	0.0	127.4	0.0	0.0	0.0
8	231.8	0.0	791.1	0.0	184.3	0.0	1,023.9	0.0	2,542.0	0.0	2,491.2	0.0	10.0	238.1
9	16.0	0.0	54.6	0.0	33.1	0.0	183.9	0.0	48.0	0.0	47.0	0.0	29.0	690.5
10	280.6	0.0	957.7	0.0	603.8	0.0	3,354.4	0.0	6,857.0	0.0	6,719.9	0.0	40.0	952.4
11	255.7	0.0	872.7	0.0	1,880.1	0.0	10,445.0	0.0	7,938.0	0.0	7,779.2	0.0	24.0	571.4
12	25.3	0.0	86.3	0.0	69.7	0.0	387.2	0.0	1,199.0	0.0	1,175.0	0.0	23.0	547.6
13	40.0	0.0	136.5	0.0	202.8	0.0	1,126.7	0.0	720.0	0.0	705.6	0.0	204.0	4,857.1
14	40.8	0.0	139.2	0.0	60.3	0.0	335.0	0.0	288.0	0.0	282.2	0.0	51.0	1,214.3
15	200.3	0.0	683.6	0.0	247.0	0.0	1,372.2	0.0	132.0	0.0	129.4	0.0	6.0	142.9
16	278.7	0.0	951.2	0.0	2,329.5	0.0	12,941.7	0.0	3,741.0	0.0	3,666.2	0.0	30.0	714.3
Total	3,482.3	0.0	11,884.3	0.0	8,486.2	0.0	47,145.6	0.0	24,466.0	0.0	23,976.7	0.0	1,169.0	27,833.3

Table 4. Sample Fluor Utah model output cash flow analysis results for test cases baseline solution.

Source: [7]

	Illinois Basin	Four Corners	Fort Union	Texas Gulf	Appalachia-Ohio	Powder River	Appalachia, W. Va.	Green River
Financial summary report								
Sales price in base dollars : $/prepared ton	13.10	7.55	5.93	6.23	12.70	7.33	21.52	18.82
: $/10^6 Btu	0.54	0.42	0.42	0.44	0.50	0.45	0.84	0.91
Return on investment* : Percent	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Return on paid-in capital** : Percent	10.83	10.86	10.87	10.87	10.83	10.95	10.86	10.87
Cumulative investment to steady state: M$	157307.	128290.	137395.	141268.	161752.	119766.	160270.	189851.
Cumulative investment total project : M$	217289.	169744.	179628.	195436.	222268.	224316.	522582.	507648.
Annual operating cost at steady state: M$	24800.	16909.	15630.	18146.	26135.	23045.	61373.	60204.
*Discounted cash flow internal rate of return assuming project is financed completely by internal capital.								
**Discounted cash flow internal rate of return assuming project is financed by the user set ratio of internal capital and external debt.								
Case description								
Mining parameters								
Index to plant type***	1	1	1	1	1	1	1	1
Coal demand ROM tons/year (complex)	5,451,390	7,260,450	9,952,710	9,318,610	5,191,800	7,977,640	5,130,720	6,382,110
Stripping ratio (bank yards/recovered ton)	17.8643	4.89130	3.80434	3.80434	12.3977	3.0344	13.0080	7.00000
Height of topsoil - feet	1.0	0.33	1.25	0.83	0.50	0.00	0.00	0.00
Height of coal in feet	4.0	12.0	12.0	10.0	4.0	50.0	11.5	38.0
Prepared coal tons/year	5,396,870	7,187,850	9,160,180	9,225,420	5,139,880	7,897,860	5,079,410	6,318,290
Energy demand for complex 10^{12} Btu/year	130	130	130	130	130	130	130	130
ROM coal heat value Btu/lb	12000	9010	7070	7020	12600	8200	12750	10250
Reclamation - other costs - $/acre	900	1000	600	900	900	300	1000	900
Financial assumptions								
Capital/debt ratio	2	2	2	2	2	2	2	2
GAA-mineral rights ($/acre)	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
GAA-royalty amount ($/ton)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
GAA-surface rights ($/acre)	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
GAA-severance tax ($/ton)	0	0	0	0	0	0	0	0
Rate - cash flow discount	.10	.10	.10	.10	.10	.10	.10	.10
Rate - federal income tax	.48	.48	.48	.48	.48	.48	.48	.48
Rate - long term interest	.08	.08	.08	.08	.08	.08	.08	.08
Rate - short term interest	.10	.10	.10	.10	.10	.10	.10	.10
Value - reg. price of coal - $/ton	0	0	0	0	0	0	0	0
***Preparation plant types: 1 = Crushing and screening 2 = Baum jig 3 = Heavy media								

A variety of studies have attempted to predict underground coal mining costs. The Bureau of Mines has issued a series of documents on estimated capital investment and operating costs for underground bituminous coal mines of various sizes using continuous and longwall mining [8]. The NUS Corporation has developed detailed underground and surface coal mining production cost models [9].

These cost studies are all useful inputs into national or regional models. They provide information that is helpful in choosing desirable fossil pathway options.

The models and analysis help set energy policy and select research and development programs, but the solution to the energy problem lies in the implementation of energy technology. We have a very broad program to develop and demonstrate energy technologies. We are actively supporting coal conversion, magnetohydrodynamic (MHD), in situ coal gasification and other programs as shown in Figure 7. Coal research is the major part of our program and most of the attention here is on technologies that convert coal to some other fuel form. In addition, other agencies have programs for the development of technologies to extract methane from coal seams and to improve existing mining technologies.

The information developed by our research program provides the basis for decisions to implement the technology and produce needed energy. It also provides information that is fed back into the models and analyses. This, in turn, leads to changes in energy policy and in the research and development programs.

The set of models and analytical techniques we have outlined allow us to consider the energy system from several perspectives. This provides many insights into the nature of the energy problem and possible solutions. The models and techniques are evolving and becoming more comprehensive and detailed with respect to the entire energy system. The major shortcoming of all these techniques is the lack of precise input information. This is because many aspects of the energy system have not been adequately characterized and information on future technologies is not known.

For example, detailed characterization of the fossil resource base is not yet available. There is great uncertainty about the extent of natural gas and oil resources, about the amount of coal available of given characteristics and at given costs. Also, estimates, and often crude estimates, have to be made about the economics and performance characteristics of future technologies. All the models and analytical techniques are sensitive to these parameters and as long as there is great uncertainty about them, there will be great uncertainty in the results of the analysis.

Now that energy has been recognized as a major problem, major efforts are underway to obtain the needed information.

Magnetohydrodynamics (MHD) programs.

- Open-cycle plasma
- Inert gas plasma
- Liquid metal

In situ coal gasification programs:

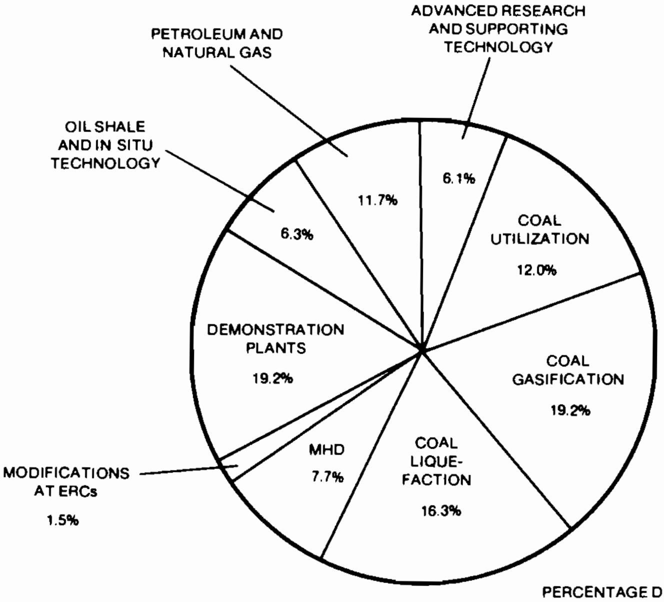
- Linked vertical wells/medium thick seams
- Packed bed/thick seams
- Longwall generator/thin seams
- Steeply dipping bed

Coal gasification programs:

- Hygas
- Bi-gas
- Synthane
- Hydrane
- Fixed bed
- Fluidized bed
- Entrained bed
- Molten salt
- Hydrogen from coal

Coal liquefaction programs:

- Direct hydrogenation
- Solvent extraction
- Pyrolysis
- Indirect liquefaction



PERCENTAGE DISTRIBUTION
OF FOSSIL ENERGY BUDGET
ESTIMATES IN
FY 1978 SHOWN AS FOLLOWS

FY 1978%

Figure 7. Fossil energy fiscal year 1978 funding percentages.

As these efforts proceed, the models and analytic techniques will improve. International conferences like these help to communicate new information about energy systems and energy technologies. This will help us all to improve our analytic capabilities and make more intelligent choices between national energy options.

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ENVIRONMENTAL IMPACTS OF INCREASED MINING AND USE OF COAL IN THE USA

R.S. Greeley

INTRODUCTION

A major aspect of the National Energy Plan (NEP) published by the Carter Administration on April 20, 1977, is the stimulation of an increased use of coal for US energy supplies. The most recent projections of existing trends would envision the increased mining and use of coal from the current roughly 600 Mt/year (the equivalent of about 15×10^{15} Btu or 15 Quads) to about 1000 Mt (24 Quads) in 1985 and to 1500 Mt (38 Quads) in the year 2000. The regulations and incentives proposed in the National Energy Plan would increase this coal utilization to nearly 1200 Mt (28 Quads) in 1985 and about 1800 Mt (45 Quads) in the year 2000. Coal would then represent over 36% of the total energy supplies in the year 2000, in contrast to the projection of current trends under which it would represent only 27% of the energy mix. Current coal use is about 21% of the energy mix.

There are two major questions with these projections from the NEP. First, what are the environmental, economic and sociological impacts of such a rate of coal use? Second, can the environmental, economic, and sociological constraints to such a production and use rate be overcome and such rates actually achieved?

The MITRE Corporation has been involved in studies evaluating answers to these two questions for a number of years. In 1975 we published *An Analysis of Constraints on Increased Coal Production* (MITRE Technical Report 6830) for the Department of the Interior, Bureau of Mines. In August 1977 MITRE assisted in preparing the *Preliminary Draft Environmental Impact Statement* (WP-12517) for the Energy R&D Administration Coal, Research, Development and Demonstration Program. This impact statement considers in depth the environmental impact of producing 18, 36 or 67 Quads of energy from coal, the equivalent of between 1000 and 3000 Mt of coal per year during the early part of the 21st century. Finally, in a September 1977 document, MITRE assisted the Assistant Administrator for Environment and Safety of the Energy R&D Administration in a Preliminary Environmental Analysis of Energy Technologies using the assumptions of the National Energy Plan (*Annual Environmental Analysis Report*, MTR-7626). In this latest effort we were assisted by the CONSAD Research Corporation, Control Data Corporation, and the International Research and Technology Corporation.

The environmental impacts described below are taken primarily from the latter report. To prepare this report a comprehensive simulation model was calibrated to represent the Energy Plan energy and environmental control initiatives and economic assumptions for the period 1975 to 2000. The model was developed previously for the Environmental Protection Agency. The model calculates the pollution residuals from the mining, transport, and use of fuels throughout the USA together with estimates of land use, occupational accidents and other environmental impacts on a regional and national basis.

To sum up briefly, the major expected results of adopting the NEP: by the year 2000 it is projected that coal production will increase by a factor of 3 compared to 1975; uranium production will increase by a factor of 10; gas production will decline by 18%; oil production will remain about the same; oil and gas imports will increase 18%; and energy used in producing electricity will increase from about 28% to 38% over the period 1975 to 2000.

A major NEP initiative to mitigate air pollution is the stipulation that the "best available control technology" (BACT) be applied to all new electric utilities and industrial boilers to reduce sulfur oxide and particulate emissions instead of the less stringent new source performance standards and state implementation plans currently in effect. The use of BACT to the year 2000 and beyond results in reduced emissions of particulates, carbon monoxide, and hydrocarbons, but still permits slightly higher emissions of sulfur oxides and nitrogen oxides. Regarding water pollution, dissolved solids in the year 2000 exceed the 1975 level, primarily due to the major increase in coal mining.

COAL PRODUCTION--ENERGY SECTOR CONTRIBUTIONS TO ENVIRONMENTAL IMPACTS

According to the NEP scenario, coal production in 2000 will increase to 2.9 times the 1975 level, primarily for use by utilities and other industrial boilers. Without the NEP, an increase to 2.5 times the 1975 value is expected. It is anticipated that the mining, cleaning, and transport of this coal will have the following significant environmental effects:

- Dissolved solid effluents will increase significantly due to increased coal mining activities. Coal mining has a relatively low dissolved solid removal rate (6%) compared with other industrial sectors (58%), and accounts for 31% of national total net dissolved solids emissions in the year 2000. The most significant increases will be experienced in the North Central and Middle Atlantic Regions (Regions 8 and 3).

- Mining wastes from coal extraction will increase from 50 Mt in 1975 to 130 Mt in 2000. According to the NEP scenario, the larger portion of this waste in any year is from underground mining, although strip mining wastes grow more rapidly during the study period. In 2000, more than half of the wastes are in the Appalachian area (Regions 3 and 4). Because of the abundance of rainfall in this area, rapid reclamation will be required to avoid significant runoff and leaching. The most rapid increase from 1975 to 2000 is in the North Central Region (Region 8) where coal mining wastes increase from 1 to 11 Mt. Because this region has areas with a limited water supply, significant reclamation efforts will be required to restore the strip-mined area.

- Increased occupational health and safety incidents will result from increased coal production primarily due to increased underground coal mining and coal transportation activity. Accidents along railroad beds are responsible for many of these incidents. Because of the large rail volume in the midwest Region 5, this region is projected to have the largest number of deaths and person-days lost (29 and 25% of national totals, respectively) and a significant portion (21%) of injuries.

Table 1 summarizes the preceding and other major environmental factors and regional impacts associated with coal mining, beneficiation and transportation.

COAL COMBUSTION CONTRIBUTIONS TO ENVIRONMENTAL IMPACTS

According to the NEP scenario, coal consumed in combustion systems for industrial boilers and electric utilities is expected to double from 1975 to 1985 and nearly triple by 2000. Without the NEP, this use is expected to increase to 2.5 times the 1975 level by 2000. Conventional and new combustion systems are responsible for the dominant environmental impacts of the entire coal fuel cycle and include the following:

- Conventional coal combustion systems are responsible for sustained growth of SO_x and NO_x air residuals, even with mandatory BACT for these facilities. No_x emissions are not affected by BACT, and particulate releases are still more than 80% of those without BACT. If SO_x and NO_x are to be reduced and the growth in particulates reversed, BACT will require continued improvement. Areas currently showing high levels of SO_x and particulates--the Midwest Region (Region 5) and the states of Pennsylvania and New York--do not show major decreases from 1975 to 2000, while surrounding areas--the Southwest Region (Region 6) and parts of the South Atlantic and Central Regions (Regions 4 and 7)--show large increases in these residuals. The result may be an increasing portion of the country troubled by high SO_x and particulate levels.

Table 1. Coal production.

Energy Activity	Year	Quads* Pre-NEP	Quads* NEP
Extraction		Underground	
	1975	7.3	7.3
	1985	10.8	9.8
	2000	13.3	15.7
		Surface	
	1975	7.9	7.9
	1985	13.2	18.3
	2000	24.7	29.2
		Total	
	1975	15.2	15.2
	1985	24.0	28.1
	2000	38.0	44.9

Major Environmental Factors

The increased coal production needed to meet NEP requirements will also bring about increases in the residuals associated with coal extraction. Mining wastes increase substantially, particularly from surface mining.

	Mining Wastes $[10^3$ t] 1975	1985	2000	% Increase 1975-2000
National Total	46,000	86,000	131,000	228
Underground [% Total]	75	59	57	116
Surface [% Total]	25	41	43	390

Major Regional Impacts

Mining Wastes in 2000

Region	Amount $[10^3$ t]	% Increase 1975-2000
3 Underground	40,100	63
Surface	13,300	359
4 Underground	23,400	200
Surface	21,600	484
5 Underground	6,500	209
Surface	8,100	161
6 Underground	85	1,317
Surface	3,000	1,150
8 Underground	4,900	2,684
Surface	6,300	794

- Bulk of total (underground and surface) mining wastes occurs in Regions 3 and 4.
- Underground wastes from eastern mines (Regions 3, 4, and 5) must be compacted and stabilized for surface disposal.
- Rapid increase of strip mining wastes in semi-arid Regions 6 and 8 poses reclamation problems.

*Annual production in 10^{15} Btu according to Pre-NEP and NEP scenarios.

<table>
<tr>
<td><u>Extraction</u>
(cont'd)</td>
<td></td>
<td><u>Acid Mine Drainage</u>
Primarily an eastern problem associated with underground mining. Poorly sealed abandoned mines allow rain water to leak into mine caverns where it can leach pyritic material into groundwater or backwash through the mine mouth and contaminate surface waters. Sulfate releases are an indicator of acid mine drainage.</td>
<td>Sulfate releases associated with eastern underground mining
<table>
<tr><th></th><th colspan="3">[10^3 t]</th><th></th></tr>
<tr><th>Region</th><th>1975</th><th>1985</th><th>2000</th><th>% Increase 1975-2000</th></tr>
<tr><td>3</td><td>720</td><td>836</td><td>1000</td><td>38</td></tr>
<tr><td>4</td><td>40</td><td>45</td><td>94</td><td>135</td></tr>
<tr><td>5</td><td>21</td><td>29</td><td>45</td><td>114</td></tr>
</table>
- State laws governing mine closure regulation vary.
- Region 3 faces serious problems from long-abandoned mines. States in each region must develop improved mine sealing techniques.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><u>Subsidence</u>
Subsidence is a problem associated with eastern underground mining. The weight of overburden and geological stress on unsupported sections of mine ceilings causes surface area to sink. The potential for subsidence exists whenever underground mining occurs, therefore temporary land use demand for deep mining is an indicator of subsidence potential. Improved geological testing and longwall mining will reduce subsidence potential, as will deeper mines.</td>
<td>Annual temporary land use associated with eastern underground mining
<table>
<tr><th></th><th colspan="3">[10^3 acres]</th><th></th></tr>
<tr><th>Region</th><th>1975</th><th>1985</th><th>2000</th><th>% Increase 1975-2000</th></tr>
<tr><td>3</td><td>65</td><td>79</td><td>96</td><td>47</td></tr>
<tr><td>4</td><td>34</td><td>37</td><td>82</td><td>141</td></tr>
<tr><td>5</td><td>19</td><td>27</td><td>42</td><td>121</td></tr>
</table>
- Rates of increase in Region 4 and 5 are substantial.
- Region 4 nearly equals Region 3, the historical leader in underground mining, in annual temporary land use by 2000.</td>
</tr>
</table>

Table 1. (cont'd)

<table>
<tr><th rowspan="2">Energy Activity</th><th rowspan="2">Year</th><th colspan="2">Quads</th><th rowspan="2">Major Environmental Factors</th><th rowspan="2">Major Regional Impacts</th></tr>
<tr><th>Pre-NEP</th><th>NEP</th></tr>
<tr><td>Extraction
(cont'd)</td><td></td><td></td><td></td><td>Occupational Health and Safety
Underground mining continues to be a hazardous occupation throughout the study period. There is also occupational risk associated with strip mining, but it is only one quarter as dangerous per Btu recovered as deep mining.</td><td>Occupational deaths and person-days lost from underground mining (2000)
<table>
<tr><th>Region</th><th>Deaths</th><th>% Increase 1975-2000</th><th>Person-Days Lost [10³]</th><th>% Increase 1975-2000</th></tr>
<tr><td>3</td><td>84</td><td>47</td><td>396</td><td>46</td></tr>
<tr><td>4</td><td>67</td><td>123</td><td>317</td><td>140</td></tr>
<tr><td>5</td><td>37</td><td>118</td><td>175</td><td>121</td></tr>
<tr><td>National</td><td>226</td><td>113</td><td>1071</td><td>114</td></tr>
</table>
- Region 3 has the largest number of mining deaths and person-days lost throughout the study period. Because the region's coal activity is already well developed, the rate of increase of these incidents is small compared with other regions shown and with national totals.
Occupational deaths and person-days lost from surface mining (2000)
<table>
<tr><th>Region</th><th>Deaths</th><th>% Increase 1975-2000</th><th>Person-Days Lost [10³]</th><th>% Increase 1975-2000</th></tr>
<tr><td>4</td><td>23</td><td>155</td><td>61</td><td>144</td></tr>
<tr><td>6</td><td>23</td><td>1050</td><td>64</td><td>1180</td></tr>
<tr><td>8</td><td>40</td><td>900</td><td>106</td><td>783</td></tr>
<tr><td>National</td><td>117</td><td>265</td><td>314</td><td>265</td></tr>
</table>
- Region 6 experiences large increases in occupational mishaps due to coal mining increases of the same magnitude.</td></tr>
</table>

<table>
<tr>
<td><u>Beneficiation</u>
1975
1985
2000</td>
<td>
3.1
10.1
15.2</td>
<td>
3.1
14.1
22.5</td>
<td><u>Wet Cleaning</u>
Suspended solids in process water and in runoff from refuse piles constitute the major environmental problem associated with beneficiation. Coal fines in process water represent not only residual release but energy loss as well. Increased fines reclamation is anticipated during the study period and will drastically reduce suspended solid discharge. If EPA regulations requiring closed cycle are modified, water residuals may change significantly.</td>
<td>Suspended solid releases from coal beneficiation
<table>
<tr><th></th><th colspan="3">[10³ t]</th><th></th></tr>
<tr><th>Category</th><th>1975</th><th>1985</th><th>2000</th><th>% Increase 1975-2000</th></tr>
<tr><td>Gross</td><td>33,062</td><td>105,000</td><td>167,000</td><td>406</td></tr>
<tr><td>Net</td><td>7,559</td><td>1.2</td><td>1.9</td><td>-100</td></tr>
<tr><td>% Captured</td><td>77</td><td>100</td><td>100</td><td></td></tr>
</table>
- Suspended solids are drastically reduced even by 1985, based on assumptions.
- Coal fines reclamation reduces need for additional mining to meet energy requirements and indirectly reduces residuals associated with extraction.</td>
</tr>
</table>

Table 1. (cont'd)

<table>
<tr><th rowspan="2">Energy Activity</th><th rowspan="2">Year</th><th colspan="2">Quads</th><th rowspan="2">Major Environmental Factors</th><th rowspan="2">Major Regional Impacts</th></tr>
<tr><th>Pre-NEP</th><th>NEP</th></tr>
<tr><td>Transportation</td><td></td><td></td><td></td><td rowspan="18">Train Transportation

The transportation of coal via railroad systems presents problems in both particulate emissions and occupational and public safety.

Particulate emissions are associated with the loading and unloading of coal at mines and destination points, and the blowing of coal fines from hopper cars during transit. Emissions are generally higher from conventional trains than unit trains.</td><td rowspan="18">Particulates from coal transport by rail--2000
<table><tr><th>Region</th><th>Emission Total [10^3 t]</th><th>% From Unit Train</th><th>% Increase (Total) 1975-2000</th></tr><tr><td>3</td><td>121</td><td>23</td><td>426</td></tr><tr><td>4</td><td>170</td><td>28</td><td>154</td></tr><tr><td>5</td><td>230</td><td>27</td><td>119</td></tr><tr><td>7</td><td>88</td><td>14</td><td>132</td></tr><tr><td>8</td><td>51</td><td>62</td><td>168</td></tr></table>
- The above regions account for 98% of all particulate emissions from trains nationally
- Region 5, which has significant particulate emissions from other sources, receives the greatest share of train transport particulates.
- The largest increase is in Region 3.
- The greatest share from unit trains is in Region 8 (more than double other regions).</td></tr>
<tr><td>Unit Train</td><td>1975</td><td>3.3</td><td>3.3</td></tr>
<tr><td>Conv. Train</td><td></td><td>6.6</td><td>6.6</td></tr>
<tr><td>Barge</td><td></td><td>1.9</td><td>1.9</td></tr>
<tr><td>Other</td><td></td><td>3.1</td><td>3.1</td></tr>
<tr><td></td><td></td><td>14.9</td><td>14.9</td></tr>
<tr><td>Pipeline</td><td>1985</td><td>0.7</td><td>0.8</td></tr>
<tr><td>Unit Train</td><td></td><td>5.6</td><td>6.4</td></tr>
<tr><td>Conv. Train</td><td></td><td>9.6</td><td>11.1</td></tr>
<tr><td>Barge</td><td></td><td>3.4</td><td>4.0</td></tr>
<tr><td>Other</td><td></td><td>4.4</td><td>5.1</td></tr>
<tr><td></td><td></td><td>23.7</td><td>27.4</td></tr>
<tr><td>Pipeline</td><td>2000</td><td>3.9</td><td>4.5</td></tr>
<tr><td>Unit Train</td><td></td><td>8.9</td><td>10.2</td></tr>
<tr><td>Conv. Train</td><td></td><td>12.0</td><td>13.9</td></tr>
<tr><td>Barge</td><td></td><td>5.3</td><td>6.1</td></tr>
<tr><td>Other</td><td></td><td>5.3</td><td>6.1</td></tr>
<tr><td></td><td></td><td>35.4</td><td>40.8</td></tr>
</table>

Transportation
(cont'd)

Train Transportation (cont'd)

Rail transportation of coal is associated with substantial public and occupational safety risk, primarily from accidents at rail crossings.

Deaths and person-days lost from coal transportation by rail (2000)

Region	Deaths	% Increase 1975-2000	Person-Days Lost [10^3]	% Increase 1975-2000
3	254	112	248	110
4	382	181	373	180
5	449	124	438	125
7	156	152	152	153
8	106	186	104	189
National	1358	141	1324	141

- Approximately 40% of national totals for deaths and man-days lost are associated with unit trains by 2000 (up from 31% in 1975).
- Region 5 has large rail volume, accounting for the numerous deaths and days lost.

Slurry Pipeline

Slurry pipeline will begin to transport a slurry of pulverized coal and water from Colorado and Wyoming to Arkansas and Texas by 1985. Pipeline water requirements represent one of many competitors (from other energy sectors and nonenergy sectors) for the limited water resources of western coal regions.

Region 8 water use for slurry pipeline

Year	10^3 Acre-Feet	% of Regional Water Use for Energy
1985	25	9
2000	137	16

- Regional water use for other energy activities increases at a faster rate than for slurry pipelines.

- Increasing amounts of sludges, spent sorbents, and ashes from new and conventional coal combustion technologies may present a solid waste disposal problem; further, these wastes may cause a significant potential leachate problem. In 2000, noncombustible solid wastes from coal and industrial boilers increase to 2.7 times the 1975 level; sludges increase to 8.5 times the 1975 level, primarily due to the introduction of scrubbers for industrial boilers. Many of these facilities will be in urbanized areas where land-fill property is expensive and scarce. The South Atlantic and Midwest Regions (Regions 4 and 5) together produce nearly half of all coal combustion solid wastes and sludges.

Table 2 summarizes the major environmental factors and regional impacts associated with coal combustion.

COAL LIQUEFACTION AND GASIFICATION CONTRIBUTIONS TO ENVIRONMENTAL IMPACTS

According to the NEP scenario, approximately 3.8 quads of energy will be provided as liquefied and gasified coal in the year 2000. This is a 50% larger output than is projected without the NEP. In addition to the indirect environmental effects of extracting the coal for these processes, coal conversion to gaseous and liquid fuels has the following significant environmental impacts:

- Water use for coal conversion processes is much greater than that required for conventional combustion. Water is a major process feedstock and is also required for cooling. In the North Central Region (Region 8), coal gasification is responsible for over half of the region's energy-related water consumption in 2000.

- Coal gasification will cause substantial increases in residual releases to water. Gasification in the North Central Region (Region 8) causes substantial increases in nutrients, oils and greases, and biological oxygen demand in surface water. Gasification in the South Atlantic and Southwest Regions (Regions 4 and 6) is projected to cause substantial increases in dissolved solid releases, particularly dissolved cyanide.

- Net air residuals (criteria pollutants) for most conversion processes are lower than coal combustion since only one fifth of the coal is actually consumed in the process and other emissions are captured. SO_x emissions may be significant in proposed areas of gasification development.

- Ashes and chars from gasification and liquefaction may pose solid waste disposal problems. The presence and

Table 2. Coal combustion.

Energy Activity	Year	Quads Pre-NEP	Quads NEP	Major Environmental Factors	Major Regional Impacts
Advanced Coal Combustion				Fluidized Bed Combustion	
	2000	1.0	1.3	Electric utilities fired by fluidized bed boilers are not expected to make a significant energy contribution before 2000. Because fluidized bed boilers have reduced SO_2 and NO_x emissions and higher fuel efficiencies compared to conventional boilers, widespread introduction to this technology beyond 2000, is expected to be accompanied by substantial environmental improvement per unit compared with conventional coal combustion.	No significant regional dependent impacts are expected from fluidized bed combustion.
Conventional Coal Combustion				Air Residuals	
Electric Utilities	1975	9.2	9.2	Even with BACT, SO_x and NO_x residuals increase, as do particulates. Coal combustion causes 12% national growth in SO_x and 58% in NO_x by 2000. SO_x emissions from coal combustion in 2000 are 23.3 Mt, a 23% increase over 1975. Without BACT, these emissions would be 27.3 Mt in 2000. Improved BACT will be required to reduce SO_x, NO_x particulates.	Large increases in SO_x and particulates in Regions 4, 6, and 7; no significant decrease in Region 5 or Pennsylvania and New York.
	1985	16.0	16.5		
	2000	22.5	20.6		
Industrial Boilers	1975	2.0	2.0		
	1985	3.2	6.0		
	2000	7.1	13.1		
Total	1975	11.2	11.2		
	1985	19.2	22.5		
	2000	29.6	33.7		

Table 2. (cont'd)

<table>
<tr><th rowspan="2">Energy Activity</th><th rowspan="2">Year</th><th colspan="2">Quads</th><th rowspan="2">Major Environmental Factors</th><th rowspan="2">Major Regional Impacts</th></tr>
<tr><th>Pre-NEP</th><th>NEP</th></tr>
<tr><td><u>Conventional Coal Combustion</u>
(cont'd)</td><td></td><td></td><td></td><td><u>Solid Waste</u>
In 2000, noncombustible solid wastes (NCSW) from coal and industrial boilers increase to 2.7 times the 1975 level. Sludges increase to 8.5 times the 1975 levels.
Coal Combustion
Solid Waste [10^3 t]
<table>
<tr><th></th><th>1975</th><th>1985</th><th>2000</th></tr>
<tr><td>Electric Utilities</td><td></td><td></td><td></td></tr>
<tr><td>NCSW</td><td>42,219</td><td>72,947</td><td>85,842</td></tr>
<tr><td>Sludges</td><td>6,204</td><td>23,889</td><td>21,715</td></tr>
<tr><td>Industrial Boilers</td><td></td><td></td><td></td></tr>
<tr><td>NCSW</td><td>5,646</td><td>18,987</td><td>43,518</td></tr>
<tr><td>Sludges</td><td>0</td><td>5,778</td><td>97,180</td></tr>
</table>
</td><td>Regions 4 and 5 together produce nearly half of coal combustion solid wastes and sludges.</td></tr>
</table>

> amount of hazardous trace materials in these chars may make their disposal a more difficult problem than disposal of conventional combustion wastes.

Table 3 summarizes the major environmental factors and regional impacts associated with coal liquefaction and high and low energy gasification.

CONSTRAINTS TO ACHIEVING THE PROJECTED INCREASE IN COAL MINING AND USE

The General Accounting Office in a very recent study has said, "The environmental issue is paramount. We cannot use 1 billion tons of coal per year without harming our environment - at least not with current technology."* Installing the best available control technology will necessitate scrubbers and desulfurization techniques for essentially all coal burning industrial and utility plants. The General Accounting Office estimates that the cumulative additional capital costs for controlling emissions will be 19×10^9 \$ and 26×10^9 \$ in 1985 and 2000 respectively. Annual operating costs would be 1.3 and 2.3×10^9 \$ per year respectively. Even with these planned controlled facilities there will be vigorous opposition to the use of coal in many sections of the country. If the coal utilization goals are to be met, the provisions of the National Energy Plan for stimulating increased use of coal by converting existing facilities and building new coal-fired facilities will have to be vigorously implemented.

If these provisions of the NEP are successful there will be additional environmental problems to be solved. The Bureau of Mines estimates that between now and 1985 surface mining will disrupt over 150 square miles of land per year. The recent Surface Mining Control and Reclamation Act prohibits such mining in certain areas, such as steep slopes, and requires that surface mined land be restored as nearly as practicable to its original contour. Underground mining results in land subsidence in certain cases and in acid drainage in other cases. The Bureau of Mines estimates that total surface and underground mining reclamation costs would be about 1.2×10^9 \$ in 1985 and 1.9×10^9 \$ in 2000, almost as much as the annual cost of operating emission control scrubbers. Furthermore, enormous quantities of sludge from air pollution control devices will have to be disposed of. By 1985 the amount of sludge generated per year could be about the same as the total municipal solid waste produced in the USA per year. The costs and the enormous physical bulk handling of material will act as severe constraints on achieving the coal mining production and use anticipated.

**US Coal Development - Promises, Uncertainties*, EMD-77-43, GAO, Washington, D.C., September 1977.

Table 3. Coal liquefaction and gasification.

<table>
<tr><th rowspan="2">Energy Activity</th><th rowspan="2">Year</th><th colspan="2">Quads</th><th rowspan="2">Major Environmental Factors</th><th rowspan="2">Major Regional Impacts</th></tr>
<tr><th>Pre-NEP</th><th>NEP</th></tr>
<tr><td>Coal Liquefaction</td><td></td><td></td><td></td><td rowspan="3">Coal liquefaction does not make a major energy contribution during the study period and is not expected to have significant environmental impact before 2000.</td><td rowspan="3">All coal liquefaction during the study period is located in Region 8.</td></tr>
<tr><td></td><td>1985</td><td>0</td><td>0</td></tr>
<tr><td></td><td>2000</td><td>0</td><td>0.1</td></tr>
<tr><td>Coal Gasification</td><td></td><td></td><td></td><td rowspan="6">High Energy Gasification
The two most significant environmental problems associated with high energy gasification are the disposal of noncombustible solid wastes and process and cooling water requirements.</td><td rowspan="6">High Energy Gasification Water Requirements 2000
<table>
<tr><th>Region</th><th>Total Water Use [10^3 acre-feet]</th><th>% Increase 1975-2000</th><th>% of Regional Water Use for Energy</th></tr>
<tr><td>4</td><td>81</td><td>1925</td><td>4</td></tr>
<tr><td>6</td><td>103</td><td>1040</td><td>8</td></tr>
<tr><td>8</td><td>429</td><td>210</td><td>50</td></tr>
</table>
- All high energy gasification is in Regions 4, 6, and 8.
- Water requirements for high energy gasification in Region 8 is 2.5 times that of Regions 4 and 6 combined.
- Water requirement for high energy gasification in Region 8 is one quarter of all water use requirements for energy in the region.</td></tr>
<tr><td></td><td>1985</td><td></td><td></td></tr>
<tr><td>High Energy</td><td></td><td>0</td><td>0.7</td></tr>
<tr><td>Low Energy</td><td></td><td>0.1</td><td>0.6</td></tr>
<tr><td>High Energy</td><td>2000</td><td>1.4</td><td>2.7</td></tr>
<tr><td>Low Energy</td><td></td><td>1.0</td><td>1.1</td></tr>
</table>

Table 3. (cont'd)

<table>
<tr><th rowspan="2">Energy Activity</th><th rowspan="2">Year</th><th colspan="2">Quads</th><th rowspan="2">Major Environmental Factors</th><th rowspan="2">Major Regional Impacts</th></tr>
<tr><th>Pre-NEP</th><th>NEP</th></tr>
<tr><td>Coal Gasification (cont'd)</td><td></td><td></td><td></td><td>High Energy Gasification (cont'd)</td><td>Noncombustible Solid Waste from High Energy Gasification 2000
<table><tr><th>Region</th><th>Amount [10^3 t]</th><th>% Increase 1975-2000</th></tr><tr><td>4</td><td>1900</td><td>1800</td></tr><tr><td>6</td><td>3000</td><td>1011</td></tr><tr><td>8</td><td>7600</td><td>204</td></tr></table>
- The Region 8 total, although 1.5 times greater than that of Region 4 and 6 combined, is only 2% of the waste total from oil shale also in Region 8.</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Low Energy Gasification
Low energy gasification, because it is an adjunct to mine mouth electricity generation and industrial processes, is more dispersed over the coal producing regions than high energy gasification. The major environmental problems associated with the low energy process are also noncombustible waste disposal and water demand. Although low energy gasification generates about the same amount of solid wastes and requires more process water on a unit energy basis than its high energy counterpart, total residuals from it are lower because of its smaller energy contribution.</td><td>Water Requirements and Noncombustible Solid Waste from Low Energy Gasification 2000
<table><tr><th></th><th>TOTAL WATER USE</th><th>SOLID WASTE</th></tr><tr><th>Region</th><th>Amount [10^3 acre-feet]</th><th>Amount [10^3 t]</th></tr><tr><td>3</td><td>41</td><td>580</td></tr><tr><td>4</td><td>64</td><td>1,200</td></tr><tr><td>5</td><td>89</td><td>1,100</td></tr><tr><td>6</td><td>30</td><td>16,900</td></tr><tr><td>8</td><td>72</td><td>4,560</td></tr></table>
These regions account for approximately 95% of all low energy gasification.</td></tr>
</table>

When these constraints are overcome, then to achieve the coal production levels the USA will have to open as many as 800 new coal mines, recruit and train 300,000 to 500,000 new miners, manufacture enormous quantities of mining equipment, obtain 25 to 50 × 10^9 $ in capital and overcome labor and management problems that might result in extensive strikes. To transport the coal to the point of use railroads will carry over two thirds of the coal production. The railroads will require extensive upgrading as well as adding as many as 200,000, 100 t hopper cars, 10,000 locomotives and improved system control equipment.

On top of these pollution, financial, and equipment problems there are social problems to be overcome. Much of the increased mining will be in depressed areas of Appalachia and sparsely populated areas of the west. The people brought to these communities by coal development projects may well outnumber the original residents. They will bring their own social, political, and moral values and may change the character of the communities. The newcomers will need additional public facilities and services immediately, but the revenues to pay for them will not be available until the mines, power plants and new citizens begin paying taxes. To meet this time lag communities will need advanced financing. On a nationwide basis these costs might run as high as 4 × 10^9 $ by 1985 and 10 × 10^9 $ between 1985 and 2000. There are provisions in the Act to provide some of these funds. However, the states and communities will have to plan very well to meet the problems and obtain all of the funds necessary.

Finally, there is the role of research, development, and demonstration to produce new technology to improve coal production, coal utilization, and pollution control. Although technology cannot solve all of the financial and social problems, it can lead to lower costs and cleaner products and hence markedly improve the capability of the USA to meet its goals through the use of coal. The Department of Energy has a vigorous coal mining and utilization research and development effort under way. Transferring the new technology from the Federal R&D program to wide-scale use by the coal mining and utilization industries is currently of major concern and will continue to be of concern throughout the balance of the century.

Although reaching the goals will be extremely difficult, there appears to be little choice for the USA beyond further reliance on imports of oil from the members of the Organization of Petroleum Exporting Countries. Developing a secure energy source from US domestic coal reserves to decrease oil imports from insecure sources will certainly remain a number one priority in any national energy program.

AN INTEGRATED APPROACH TO COAL-BASED ENERGY TECHNOLOGY ASSESSMENT IN THE USA AND THE INTERNATIONAL IMPLICATIONS

K. Chen, A.N. Christakis, R.S. Davidson,
R.P. Hansen, and K. Kawamura

INTRODUCTION

Traditionally, environmental research programs in the USA have been concerned primarily with the physical impact of new energy plants and technology. In December 1973, Dr. Dixie Lee Ray, then Chairman of the US Atomic Energy Commission, reported to President Nixon on the *Nation's Energy Future* [1]. This report stimulated a broader-based look at the effects of energy technology and provided the impetus for a government interagency program on energy and the environment. As a result, two interagency panels, dealing with control technology development and environment effects research, developed the program suggested in the Ray report in greater detail [2].

From the reports of these panels, often referred to as the Gage report and the King-Muir report, the Office of Management and Budget established an interagency task force on the Health and Environmental Effects of Energy Use. This task force was to (a) examine ongoing federal research in the energy/environmental field and (b) recommend an allocation of research funds for a more effective research program.

A major conclusion of the energy/environment task force was that the social and economic consequences of alternative energy and environmental policies had to be considered along with the more traditional health and environment impacts. The King-Muir report recommended the formation of a research program to identify "environmentally, socially, and economically acceptable (energy development) alternatives" [3]. From this recommendation, the Environmental Protection Agency (EPA) launched their Integrated Assessment (IA) program, which we are going to discuss in this paper.

Concurrent with these events, coal was emerging as a primary future energy source in the USA. Coal remains as a vast natural resource in the USA and, with the increasing shortage and rising prices of oil and natural gas, the USA will rely heavily on coal's contribution to her energy supply. The present US Administration has emphasized coal and conservation as the cornerstones of the US natural energy strategy.

Although coal has been used extensively in the past, it is clear that the enormous scale and the complex form of coal utilization in the future will bear little resemblance to that in earlier US history. The broad environmental and socioeconomic effects of unprecedented coal extraction, processing, transportation, conversion, and the end-use activities must be assessed now before the national energy and environmental policies can be appropriately modified. EPA has a major responsibility for conducting this assessment on sectoral, regional, and national levels and coal-based technology has become an important part of their IA program.

This paper will briefly describe that program; identify several sectoral and regional coal assessment projects already in progress under it; discuss the approach to be used in the national coal-technology assessment project that just started; and consider the international implications of coal technology development.

EPA'S INTEGRATED ASSESSMENT PROGRAM

Traditional EPA environmental research programs have followed the same trend noted in our introduction. They have been "waste stream" oriented, confining the environmental analysis to direct effects of pollutant emissions and discharges from industrial facilities. Adequate attention frequently has not been given to "nonpollutant" effects such as noise, land use, employment, community services, and esthetics. The Gage report reoriented this program by calling for a series of "environmental assessments" designed to go much further in utilizing chemical and biological analysis, as well as existing health/ecological effects data, to assess the impacts of industrial discharges on air, water, and land. The report also recommended that limited attention be given to nonpollutant effects, i.e. social and economic. These environmental assessments are now under way for high- and low-energy gasification, liquefaction, fluidized-bed combustion, coal cleaning, and fuel cells.

The Integrated Assessment (IA) based on the King-Muir recommendations take a further step forward by analyzing social and economic consequences not only of energy development but also of alternative policy options and implementation strategies. This means that legal, institutional, and political aspects of the problem will be examined. In addition to the effects of waste streams on all media, matters to be considered include: employment, capital costs, "boom-town" effects, community services, scenic and recreation resources, wildlife habitat, mined-land reclamation, and environmental laws and regulations. The policy analysis component of integrated assessments is particularly challenging.

Technology assessment (TA) provides the methodological framework for the IA program. Thus, we are really talking about integrated technology assessment (ITA). As defined by Coates [4]:

> "Technology assessment is a class of policy studies directed to examining the broadest social implications of the introduction of a new technology or the expansion or extension of an existing technology. It is intended to provide the decision-maker with useful advice and guidance on policies, programs, plans and alternative actions."

The components of the EPA/ITA programs and their status are:

- ITA of Electric Utility Energy Systems being conducted by Teknekron, Inc., Berkeley, California. This sectoral assessment effort will soon issue an interim report [5].
- A TA of Western Energy Resource Development being under way as part of the University of Oklahoma's Science and Public Policy Program, Norman, Oklahoma, assisted by the Radian Corporation, Austin, Texas. The first year's Progress Report on this regional assessment program was issued mid-year 1977 [6].
- A TA of the Development of Large-Scale Energy Facilities in the Ohio River Basin known as the Ohio River Basin Energy Study (ORBES) Program. This regional assessment program is being conducted by a consortium of mid-west universities which includes the Universities of Illinois, Indiana, Kentucky, Louisville, Pittsburgh, Ohio State, and Purdue. It has just completed the first year's effort [7].
- A TA of Energy Development in Appalachia, another regional assessment program initiated mid-1977 by Battelle-Columbus Laboratories, Columbus, Ohio.
- A plan for a National Technology Assessment of Coal-Based Energy Technologies, developed by Battelle-University of Michigan. The study was initiated in late 1977.

The ITA program comprised 3.1% of the total funding for the Interagency Environment Program for fiscal year 1976. About two thirds of the ITA program is supervised and contracted by EPA but is coordinated with the US Departments of Energy, Agriculture, and Housing and Urban Development, the Tennessee Valley Authority, and the Appalachian Regional Commission. Most of the activities in the program relate to coal development.

AN INTEGRATED METHODOLOGY FOR NATIONAL COAL ITA

For the fifth project listed above, the year 2030 has been chosen as the time horizon, when coal will almost definitely have replaced oil and natural gas as the major fossil fuel in the USA. The project will synthesize relevant inputs from the four sectoral and regional ITA projects at the national level and will consider national coal energy and environmental policy options.

To assure comprehensibility, ITA involves an analysis of technological choices and their potential impacts. Technological choices and societal reactions to technological impacts are dependent on social values and institutions which may change significantly over the next 50 years. Thus, as illustrated in Figure 1, our technology assessment is embedded in alternative futures, i.e. hypothetical scenarios of future society. The procedure by which we show the relationship of "choice space" to "impact space", actually by which we assess impact, is called mapping and may involve both qualitative and quantitative analysis.

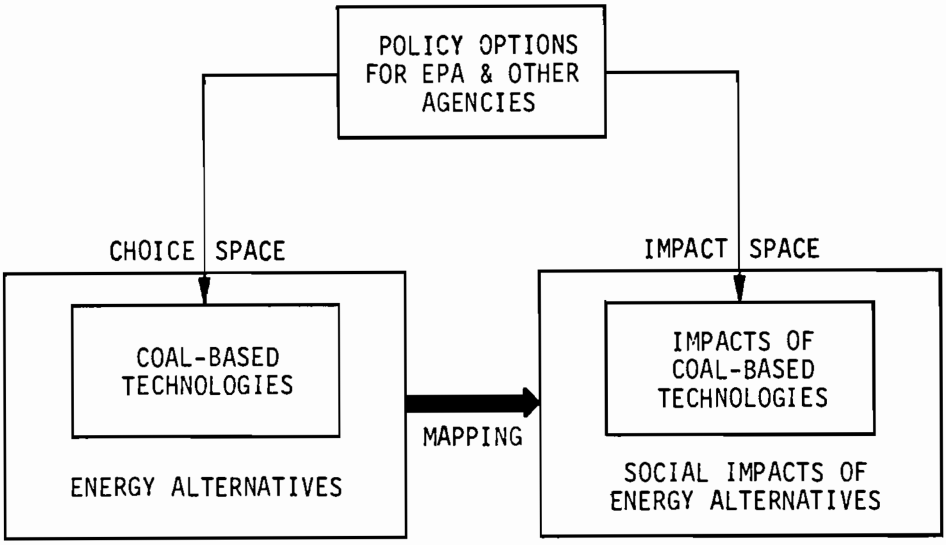

Figure 1. Embedding the integrated technology assessment in alternative futures (to 2030).

The development of an integrated methodology for the assessment of coal-based energy technologies will start by investigating four principal dimensions of the choice space. These are:

- Resource dimension: coal, extending from extraction (source) to end use (sink);
- Technology dimension: alternative configurations of existing or forecast technological options, including combinations of "capital intensive" and "labor intensive" trajectories;
- Temporal dimension: choices to be made between short-term (present) and long-term (future) benefits and costs, including considerations of inter-generational equity [8];
- Spatial or "geographic" dimension: complex trade-offs between local, regional, national, and international perspectives.

During the past 70 years, capital intensive (hard) technologies, short-term benefits, and local interests have been emphasized at the expense of long-term and global concerns. One of the primary objectives of the integrated technology assessment of coal-based energy technologies is to explore these more far-reaching concerns--the international, less capital- and energy-intensive technologies, and long-range future issues--through the use of scenarios. In this manner, we intend to explore the consequences of policy choices that do not necessarily correspond to the extrapolation of perceived historical trends.

In the resource utilization dimension, resource is visualized as a "resource system" that extends from "source" to end product or "sink". The resource system can be subdivided into the procurement subsystem, the transformation subsystem, and the delivery subsystem. Each subsystem requires supplementary inputs that might come from other resources and relevant factors; also, each subsystem generates supplementary outputs. For coal, the delivery subsystem might include trains, slurry pipelines, or a combination of the two. Depending on the choice of the "mix" for the delivery subsystem, different assumptions must be made about the supplementary inputs from other resources. In conducting the integrated TA, the dominant interactions within the coal resource system will be identified and examined through the application of existing "net energy" models.

The technology dimension includes the whole spectrum--low technology, moderate technology, and high technology. Seven significant attributes will be considered: energy efficiency, capital-use efficiency, productivity, quality of goods, environmental soundness, worker satisfaction, and labor intensity. Alternative technological mixes are assigned different ratings along each one of the seven attributes. For example, low technologies are rated as "very high" in terms of energy efficiency and labor intensity, while high technologies are rated as "medium" in energy efficiency and "medium/low in labor intensity" [9]. By means of this kind of rating, the TA team can conceptualize technological trajectories based on configurations of low-technology and high-technology choices.

The next dimension of the choice-situation space is the temporal dimension; that is, to what extent can one develop and apply a long-range planning methodology that can take into account the long-term consequences of the choices. One of the major points that will be stressed in our approach is that the classical concept of discounting is questionable if applied to nonrenewable resources and also if applied across generations. Insofar as long-range societal decisions are concerned, discounting is applicable in two instances:

- If the decision will improve the welfare of future generations;

- If future generations will be substantially better off than the present generation so that transferring resources from the future to the present improves the equality of welfare.

The fourth dimension of the choice-situation space is the spatial dimension, which focuses on the integration and coordination of local, regional, and national issues. It is very important to integrate all the findings of these studies in a coherent way. Meaningful interactions between the ongoing regional IAs with the national-level ITA, as well as interactions and communications across different geographical (spatial) levels, can be established through the adoption of a hierarchical system model.

The second space to be organized and explored in the conduct of the TA is the "impact assessment space". This multidimensional space will include not only the physical and ecological components, but also the social, political, economic, and legal components as well.

Ideally, one would like to have qualitative measures for each of these components and be able to aggregate all the impacts and derive the overall value of each alternative configuration identified in the choice space. However, such an aggregated numerical measure of value is not feasible since many kinds of impacts cannot be quantified. Nevertheless, for purposes of conceptual clarity and graphic representation, it has been assumed that for each component, an *acceptable/feasible* region can be delineated in the impact space. That is, it is assumed that certain physical, ecological, social, political, and economic limitations should preclude the study of infeasible alternatives. Good judgment about the political acceptability should preclude the adoption of an obviously unacceptable alternative. It should be clear, however, that within the acceptable/feasible region, difficult choices will need to be investigated by the study team. This will involve the participation of interested parties.

ESSENTIAL LINKS IN THE INTEGRATED APPROACH

Although an integrated technology assessment is by definition comprehensive, in practice, it is not feasible nor desirable for an ITA project to be all-encompassing. In designing the national coal ITA project, we have given special attention to the following kinds of essential links in the integrated approach:

- Substantive,

- Methodological,

- Process,

- Temporal,

- Spatial.

These five kinds of links are themselves linked to one another and should not be treated separately. The following discussion points out how these essential links are considered in the integrated approach.

Temporally, for a very long time frame, such as that projected for the coal ITA (to the year 2030), a strictly "exploratory forecasting" approach, based on mathematical extrapolation of historical trends, would not be credible by itself. A "normative forecasting" approach [10] is also needed. Such an approach emphasizes the use of alternative assumptions about dominant "alternative futures", including social value patterns; a process "openness" based upon the need for extensive involvement of interested parties; and a decision analysis framework that explores the way in which the major interested parties view trade-offs between the impacts identified.

Figure 2 is an overall "road map" of the principal procedures to meet these needs. Three important points are illustrated by this diagram. First, the technological choices are dependent on the alternative future scenarios hypothesized. Second, an analytical procedure is needed that allows both qualitative and quantitative analysis. And third, the value-oriented social decision analysis [11] provides an iterative link to the whole process.

Initially, we will conceptualize and delineate two sharply contrasting scenarios. These scenarios will be based on:

- A clear understanding of the energy situation, scientific, technical, and institutional "reality";
- Interpretations of relevant survey data;
- A review of the appropriate futures research literature; and
- An interactive process involving interested parties.

Later in the project, we will produce more plausible scenarios, somewhat between the two contrasting extremes, based on a clear understanding of the important societal dynamics over the next 50 years.

Within the framework of each alternative scenario, the mapping from technological choices to their impacts will be carried out both qualitatively and quantitatively. An interdisciplinary team including ecologists, economists, engineers, lawyers, physicists, and political scientists will handle the mapping. Involvement of interested parties will make the mapping both more comprehensive and more credible. Computer models such as the EPA's TA Modeling Project (TAMP) model [12] and the Battelle Energy Residuals Model [13] will be used to assist in quantitative mapping. If necessary, the computer models will be modified so that their underlying (often hidden) assumptions will be consistent with the alternative futures, i.e. the structural changes in society forecast by each of the alternative futures must be represented by the computerized mathematical models.

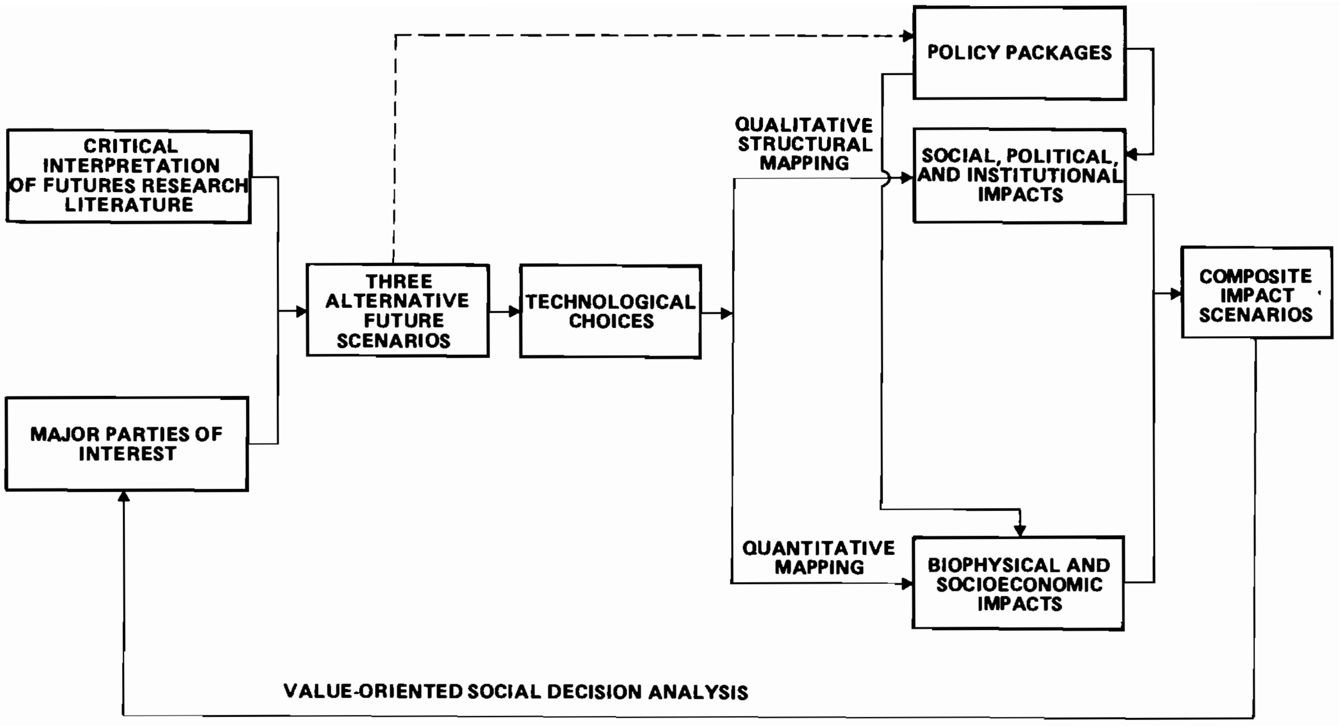

Figure 2. A "road map" for linking the methods in various tasks.

It will be important throughout the procedure outlined in Figure 2 to integrate qualitative and quantitative assessments. This integration requires the linking of various models; for example, certain residuals projected by TAMP may be translated into biophysical impacts through environmental quality index functions [14]. Qualitative and quantitative impacts will be combined by generating composite impact scenarios in which the impacts are transformed into a prose form substantiated by quantitative indicators. The impact description, one for each alternative future in combination with a specific policy package, will include inputs of interested parties through value-oriented social decision analysis (feedback path at the bottom of Figure 2). From this, we will modify the choice of alternative futures to be addressed in the next iteration. Several iterations are deliberately planned for the 2½ year national coal ITA project.

Spatially the national coal ITA project will, of necessity, link to regional and site-specific levels on the one hand, and international levels on the other hand. The ongoing regional coal ITA projects will generate a large amount of information useful in the national coal ITA project. The exact aggregation and disaggregation of impacts, however, will be oriented toward national policy decisions. Thus, the level of aggregation and disaggregation must be flexible and must make sense to policy makers or those who influence policy in the USA. For example, when policy makers are concerned about who is to gain and who is to lose in a typical "boom town", the "site-specific" impacts must be determined on a local level. On the other hand, when policy makers are concerned about the impact on the global climate, for example, how much coal and other fossil fuel consumption is too much, CO_2 impacts must be aggregated to the national level and international considerations must be included.

The overall conceptual framework to be used in this study for interrelating the choice space to the impact space was illustrated in Figure 1. As shown in that figure, the scenarios provide the most all-encompassing context for the ITA. In fact, the scenarios embrace: the choice of energy alternatives and coal-based technologies corresponding to the "choice space", and the social impacts of energy alternatives and the impacts of coal-based technologies corresponding to the "impact space". The indicated "mappings" between the choice space and the impact space can be performed through the use of quantitative models, opinions of interested parties, and expert judgment. For example, TAMP developed by EPA could be useful in performing a portion of these mappings.

Alternative societal futures, similar to those described by Lovins [15], establish an interesting framework for the conduct of the TA. The study team will use such diverse societal futures to study in-depth alternative choices in terms of trajectories of coal-based energy technologies and their impacts. The policy options for EPA and other agencies within the context of the alternative societal futures will be identified and assessed.

INTERNATIONAL IMPLICATIONS

In general, technology and its impacts do not respect national boundaries. This is especially true in the case of coal-based energy technology. For example, many of the coal conversion technologies (e.g. liquefaction and gasification) now being used or under further development in the USA were originally developed in Germany. International transfer of coal technology will expand, either through intergovernmental cooperation or through transnational enterprises.

Energy systems are clearly global. The extraction, processing, transportation, and end use of petroleum have involved many countries in an interdependent fashion. Oil pricing and import-export policies have played a significant role in international relationships: balance of payments, transfer of wealth, rate of techno-economic development, political power, and international alliance. With global oil production peaking and declining during the next 10 to 25 years, it is likely that coal will replace oil as an important factor in the international energy situation. The fact that China, the USSR, and the USA account for nearly 60% of world output of coal, approximately in proportion to their known reserves and economic reserves of coal [16], indicates a future world geopolitical balance or imbalance between large and small countries. In the long run, the relative economic development and social/environmental consequences in many countries and the international trade pattern may be affected by the availability of coal and coal-based technology.

Carbon dioxide resulting from large-scale fossil fuel utilization could have far-reaching impacts. These could include the "greenhouse effect" of increased CO_2 in the global atmosphere with consequent melting of the polar ice cap and inundation of coastal zones around the world [17]. The implications of national and international policy on CO_2 could have many ramifications. When and if the CO_2 content in the global atmosphere approaches the danger level, would all countries acknowledge the danger to the same extent? Would land-locked countries care about the danger to countries whose coastal cities are threatened by the melting of the polar ice cap? If such a hazard materialized, would coal-rich countries unilaterally refrain from increasing use of coal without other countries doing the same?

The effect of coal consumption on the global climate could become a typical case of the "tragedy of the commons" [18], in which the pursuit of near-term interests by individual countries leads to long-term peril for all. However, this kind of warning is usually not heeded by those who are in dire need for subsistence, or who feel they must maintain their living standards or catch up with the materially advanced countries. Even the most advanced countries may feel that they must maintain the lead in economic and technological development. Countries with little coal and other energy resources would press for nuclear power. A strong pro-breeder reactor argument current in the USA is that other countries will proceed with breeder reactor development and deployment even if the USA halted its own development in this area. Thus, the US national coal and environmental policies in the future cannot be considered in isolation from those of other countries.

In the context of the national coal ITA project, all of the above international considerations must be included. In fact, they may command a larger proportion of the total effort than we initially anticipated. To maintain a proper international perspective, effective "two-way" communications with the international community is imperative for the coal ITA throughout the project. The integrated approach has sufficient openness and flexibility to incorporate changes as a result of what will be learned from the international community as well as domestic interested parties. That is why a two-way communication with the international community is sought now as the national coal ITA project has recently commenced. Through the International Institute for Applied Systems Analysis (IIASA) and other organizations and channels, continuing communication with the international community throughout the project will be possible.

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LARGE-SCALE COAL USE IN THE USSR FUEL/ENERGY COMPLEX

V.A. Shelest

The USSR fuel/energy complex--one of the most intricate complexes in the national economy--is a single system of fuel and power resource extraction and production, transport, distribution, and use. It has multiple ties with the other branches of the national economy, which determine the pattern of the economy as a whole and the development rate, structure, and distribution of the fuel/energy complex.

Conversely, the development level of the fuel/energy complex, the degree to which it meets the requirements of the national economy, and the economic indicators of extraction, transport, and consumption of fuel and power resources all have a decisive influence on the development of the national economy.

The present stage of world economic development is characterized by comparatively high energy consumption. Energy consumption (in conventional fuel) has grown from 4700 Mt in 1960 to 7600 Mt in 1970 and 8900 Mt in 1975 (Table 1)--an average annual growth rate of 4.3% (1961-1965, 4.2%; 1966-1970, 5.5%; and 1971-1975, 3.2%). World energy consumption will presumably increase by 2.5 times by the end of the twentieth century.

Table 1. World energy consumption [Mt].

Source: [1]

Type of resource	1950	1960	1965	1970	1975
Coal	1544	2223	2166	2285	2506
Oil	680	1400	1988	3058	3560
Natural gas	256	622	952	1405	1700
Peat	18	20	20	22	22
Wood and substitutes	167	200	305	314	320
Hydraulic, geothermal, and nuclear energy	187	265	367	496	747
Total	2852	4730	5808	7580	8855

The structure of energy consumption has changed drastically. From 1950 to 1973 the share of oil in the world fuel/energy balance increased from 23.8% to 42.6%, and that of gas from 9% to 20%. The low oil prices that obtained in the world market until 1973 gave rise to irrational oil use by a number of industries in some countries (for example, electric power stations and industrial and municipal heating systems), and inhibited capital investment in the exploration of oil resources. Thus a number of industrially developed countries faced a shortage of proved oil and gas deposits. The situation of the last decade led to a considerable rise in the price of many fuels, primarily oil and gas, and affected the whole pattern of expenditures in energy-producing and energy-consuming industries.

Along with the elaboration of measures for greater economy and increased efficiency of fuel and energy consumption, the development of nuclear power engineering, and the invention of new energy sources, further development of the world fuel/energy economy presupposes large-scale use of coal beyond its substitution for oil and gas in certain branches of industry. The possibilities of extensive efficient use of coal to a large degree depend on technological developments that will make its mining, transport, and use economic, on devising and putting into operation the comprehensive processing of coal, and on setting up major energy bases and power-engineering complexes near coal mines.

The fuel/energy complex of the USSR now faces these tasks. It is one of the main production complexes that form the pattern of the national economy. It has a continuously growing role in stimulating scientific and technological progress, raising labor productivity, improving the location of the productive forces, and contributing to the development of the economies of the Republics and economic regions of the country.

Significant results have been achieved in developing the fuel/energy complex. In 1975 the volume of primary fuel and energy resources (discounting exports) increased sixfold as compared with 1940, reaching about 1700 Mt of conventional fuel (Table 2).

The characteristics of the development of fuel and energy resource consumption are: a sharp increase in per capita consumption (from 1.46 t of conventional fuel in 1946 to 7.2 t in 1975); the enlargement of the share of the converted types of energy; an increase in electric energy consumption per unit of gross national income coupled with a decrease in total energy and fuel consumption per unit, the same relation holding for major industrial products; a growth in the power and electric energy potential and hence in labor productivity; and increased provision of fuel to the utilities.

The pattern of the fuel/energy balance of the national economy has greatly changed due to the increased share of oil, gas, and coal from opencast mining. The rates of extraction of the main power and fuel resources are shown in Table 3.

Table 2. Fuel/energy balance of the USSR [Mt].

Source: [2, p. 112]

	1913	1940	1965	1970	1975
Resources - total	64.4	283.8	1121.5	1399.8	1850.7
Production (extraction) of fuel	48.2	237.9	966.6	1221.8	1590.3
Hydroelectric energy	0.0	0.6	10.0	15.3	15.5
Imports	8.0	3.1	9.1	14.1	35.1
Other receipts	2.4	10.2	35.5	36.5	41.0
Remainder at beginning of year	5.8	32.0	100.3	112.1	168.8
Distribution - total	64.4	283.8	1121.5	1399.8	1850.7
Expended	57.6	249.7	897.8	1117.9	1436.1
Production of electric energy and fuel	2.0	44.7	335.0	452.5	569.7
Production and technical needs	55.6	205.0	562.8	665.4	866.4
Export	1.2	1.1	116.7	167.0	237.7
Remainder at end of year	5.6	33.0	107.0	114.9	176.9

Table 3. Energy resource extraction rates.

Source: [2, p. 204]

	1940	1950	1960	1970	1975
Oil [Mt]	31.1	37.9	147.9	352.6	482.0
Gas [10^9 m^3]	3.2	3.8	45.3	198.0	289.0
Coal [Mt] - Total	165.9	261.1	509.6	624.1	701.0
Share of opencast mining	6.3	27.1	102.6	166.6	208.0
Peat [Mt]	33.2	36.0	53.6	57.5	78.3
Electric power [10^9 kWh]	48.6	91.2	292.3	740.9	1038.6
Share of hydraulic energy	5.7	12.7	50.9	124.4	143.0

The coal industry is of major economic importance to stable and efficient development of the fuel/energy complex in the USSR. Its development is accompanied by a continuous absolute growth in the volume of coal extraction--from 578 Mt in 1965 to 624 Mt in 1970 and 712 Mt in 1976. The share of coal in the fuel/energy balance is 34%. The USSR has led the world in coal extraction since 1958, and the rate of extraction is growing faster than in the world as a whole.

In recent years comprehensive measures have been taken in the USSR for development of the coal industry in keeping with the requirements of the national economy. There is an increase in the rate of construction and remodeling of mines, pits, and concentration plants; and extensive work has been carried out on the technical reequipment of plants, modernization of technology, concentration and comprehensive mechanization of production, and improvements in industrial management. Over the past 15 years, the rate of the most economic extraction method--open-pit mining, which accounts for 32% by weight of all coal extracted--has grown by 2.3 times (as against 1.4 times for total coal extraction). The technical and economic indices of the coal industry have also improved: the average monthly labor productivity has risen by 1.3 times for the five-year period 1970-1975.

Coal is widely used in the national economy, about one third going to electric power plants. Nearly 60% of the electric energy from coal-fired load power stations comes from regional ones. The share of coal in the fuel balance of the electric power plants of the eastern regions is particularly large: coal is virtually the only fuel used in the regional power systems of Siberia.

Large quantities of coking coals meet the needs of the iron and steel industry. Lump coke is used in machine building (for casting), the nonferrous industry (production of nickel, copper, and lead), and the chemical industry, and for building materials. Limited quantities of lump coke go to the utilities. Coal is a technological raw material for the production of a number of goods of the chemical industry: fertilizers, dyes, pharmaceuticals. It is also widely used for everyday communal needs.

The USSR coal industry faces great tasks and must solve major scientific and technical problems in the long term. These arise from the changing conditions of energy provision of the national economy: the growth in specific cost of production (extraction and transport) of oil and natural gas that accompanies the transfer of extraction to the northern regions of West Siberia, far from the main consumption centers; the increase in the value of oil, oil products, and gas due to changes in their prices on the world market; the growing role of the ecological aspects of fuel/energy complex development, and so forth. In these circumstances the main guidelines for further development of the USSR fuel/energy complex could be the following: rapid development of nuclear power engineering for the production of electric and thermal energy; large-scale use of cheap coal as a fuel, based on new large deposits where coal can be mined by the efficient open-cut method; speedy development of gas and oil extraction; comprehensive use of hydro-energy resources; and maximum substitution of hydroelectric power for more expensive sources of energy. Today, as well as in the future, coal remains one of the main elements of the fuel/energy complex of the USSR and its most significant reserve.

The main fuel coal utilization will continue to be at thermal power plants. The share of coal in the overall volume of fossil fuel will rise steadily. Large power plants and power engineering complexes are being built on the basis of coal deposits. The ferrous metal industry (production of coke) will remain the biggest consumer of coal. Coal use in the national economy will expand due to the introduction of power-technological methods of coal processing with simultaneous manufacturing of high-energy solid, liquid, and gaseous fuels and of products for further chemical processing, and to the use by the nonferrous and the building materials industry of reject coal and power station and boiler ash.

Coal plays an enormous role in the fuel/energy balance of the USSR because of its considerable reserves, great number of fields and deposits, and comparative ease of access and exploitation. The overall geological coal deposits in the USSR account for 6.8×10^6 Mt, of which in present conditions 5.7×10^6 Mt are accessible and 0.425×10^6 Mt are economic [3, p. 112]. This makes it quite safe to plan for the development of coal mining to correspond to the requirements of the national economy.

Technological progress in the coal industry will concentrate on the development of open-cut coal mining with powerful extraction and transport equipment and the use of equipment of large unit capacities and great reliability; extensive use of continuous-flow production with conveyor and other types of nonstop transport; maximum reduction of labor-intensive auxiliary processes; solving the problems of dust, gas, spontaneous blowout of gas and coal, rock outburst, high temperatures, and noise; and protection of the environment from the harmful effects of production activity. Progress in open-cut mining will be made through wider use of rotary bucket excavators, which provide the needed grades of coal with high efficiency of production; increased non-transport extraction; the use of continuous-flow techniques in hard-rock mining with the application of the conveyor and combined systems of transport; and comprehensive mechanization and automation of technological processes and whole plants. The basis of coal extraction technology will consist in destroying coal layers and rock while preserving the working space during the period needed, and transporting coal and rock by various means. The space-technological pattern of the future coal mine will not visibly differ from the present one, but the technological level and exploitation parameters of equipment will improve considerably.

Development of the coal industry presupposes an improved pattern and location of coal extraction and the building of large new mines and quarries at the deposits with the most suitable mining and geological conditions. It also presupposes the closing down of technically and economically inefficient mines whose reconstruction is impractical. The old coal fields of the European part of the USSR must be reconstructed and enlarged to compensate for those that have to be closed. New capacities will be put into operation in the Donetsk, Moscow region, Lvov-Volzhsk, Dnieper, and Pechora coal basins.

The greater part of the coal resources is concentrated in the eastern regions. It is here that the deposits most suitable for extraction by the economic open-cut technique are situated. The following coal basins have the greatest possibilities: Kansk-Achinsk, Kuznetsk, Irkutsk, and South Yakutsk in Siberia, and Maikyuben and Turgai in Kazakhstan. A considerable number of proved deposits are already earmarked as the sites of coal mines more powerful than present ones.

Further development of the coal industry will be connected with more complex mining and geological conditions in the main coal basins, with the necessary reconstruction and technical re-equipment of mines, and with major building projects for new basins and deposits with the specific conditions of Siberia, Kazakhstan, and other regions of the Asian part of the USSR. Providing the coal industry with all the necessary equipment will be a major task.

In accordance with the plan established, coal extraction in the USSR will grow by 1980 to 850 Mt: 233 Mt in the Donetsk basin, 158 Mt in the Kuznetsk basin, 74 Mt in the Ekibastuz basin, and 42 Mt in the Kansk-Achinsk basin.

The Kansk-Achinsk basin has lignite geological resources (0.6×10^6 Mt), which are mainly flat-lying and gently dipping. The thickness of strata fluctuates by deposits: 2 to 24 m at Abakan; 10 to 21 m at Nazarovsky; 20 to 50 m at Irsha-Borodinsky; 40 to 50 m at Uryupsky; 8 to 70 m at Beryozovsky; and 30 to 96 m at Itatsky. The depth is from 5 to 30 m [3, p. 222]. The distance between deposits of the western and eastern parts of the basin is 600 to 800 km.

A major task is the speedy development of the Kansk-Achinsk resources. The potential of this coal field is much larger than that of other deposits. Studies of the basin show the extent of the separate deposits: in the western part, Itatsky with 362 Mt (12 quarries), Beryozovsky and Uryupsky with 280 Mt (8 quarries), Nazarovsky with 10 to 16 Mt (1 quarry), Bogotolsky with 68 Mt (6 quarries); in the eastern part, Abakan with 290 Mt (14 quarries); Irsha-Borodinsky with 65 Mt [3, p. 223]. The scales of exploitation of these deposits are determined by the requirements of Siberia (mainly by the whole Angara-Yenisei region) and by the necessity to eliminate the fuel/energy deficit of the European part of the USSR.

The first main step in utilization of the Kansk-Achinsk coal is its burning in thermal power stations close to the extraction sites. A cluster of thermal power stations is to be built in the basin whose unit capacity for ecological reasons should not exceed 7 to 8 × 10^6 kW. At the power stations first put into operation, energy blocks of 800,000 kW unit capacity can be built. The possibility of transition to energy blocks of greater unit capacity is now being studied.

On the basis of coal pits and thermal power stations, large energy-intensive enterprises can be opened in the Kansk-Achinsk basin.

In building the Kansk-Achinsk complex, particular attention is devoted to sanitary-hygienic protection of the air. The coal of the basin is characterized by a very low ash content and small quantities of sulfur; but possible future large-scale burning of coal demands extensive environmental protection measures.

An important means of involving Kansk-Achinsk coals more widely in the fuel/energy complex of the country is preliminary comprehensive processing of the coal into high-quality fuels for different uses and into valuable raw materials for industry and agriculture. The following directions of thermal "enriching" of Kansk-Achinsk coal are of interest: energy and technological processing by high-speed pyrolysis, with the production of pulverized semicoke and tar; thermal processing by gas, with the production of so-called thermocoal (part of the liberated gas would provide fuel for the process); the autoclave method of processing lump coal by steam for raising the combustion heat and assuring the safety of lumps during transport and storage. The main and most efficient method is the energy-technological one. Research into all these methods is now being carried out.

A major role in the development of the USSR coal industry is played by the large Kuznetsk coal basin, whose geological reserves account for 0.725 × 10^6 Mt, in the Kemerovo region. The basin is famous for the size of the overall and proved resources of high-quality coals and the accessibility for industrial mining. Further mine construction in the basin will be oriented, in the main, toward coking coals; fuel coals should be mined primarily in quarries, and open-cut mining used in new regions--Erunakovsky, Leninsky, and others.

A large fuel/energy complex of interregional importance can be set up in northern Kazakhstan on the basis of the Ekibastuz coal deposit and the Maikyuben and Turgai lignite basins. The Ekibastuz deposit is characterized by three seams merged into one of 140 to 170 m thickness. The coal of the Kamenny high-ash deposit is a very good fuel. The resources and mining and geological conditions potentially allow future extraction up to 150 Mt annually--and including coal extracted from the nearby Maikyuben basin, up to 170 Mt. Major thermal power stations for providing energy to the regions of Kazakhstan and the Urals, and for energy transmission to the central areas of the European USSR, can be built on the basis of the Ekibastuz and Maikyuben deposits.

In the future, the Turgai lignite basin can be of interest. It is characterized by very complex hydrogeological conditions. In the foreseeable future it could yield up to 100 to 120 Mt of lignite annually. The project of prime importance here could be the Orlovsky mine (25 Mt per year).

An important reserve for the foreseeable future is the Tunguska anthracite basin (the largest in terms of overall geological reserves), which is not yet sufficiently developed.

The transfer of the coal industry to the eastern regions of the country causes great problems in organizing the transport of large quantities of coal (raw or processed) over long distances (3000 to 4000 km) from Siberia and Kazakhstan to the European USSR or the Urals. A task of prime importance is the further development of rail transport by strengthening the existing lines (Siberia to the European USSR), converting the Central Siberian railway into a super-railway line with heavier trains, or building a modern specialized coal transport line. Both the strengthening of the existing railway lines and the building of a new line will demand development of the present rail framework of the European part of the country for transporting fuel to the major consumers. Kuznetsk coal could be transported by rail without special enrichment, but lignite (for instance, from Kansk-Achinsk) only after concentration (semicoke dust or lump semicoke).

One of the most efficient uses of the fuel coals of Siberia, the European USSR, and the Urals is the transmission of electric energy. It is common knowledge that the capacity of power transmission lines grows with increasing voltage: 1000 kV a.c. transmission lines can carry 4500 MW over a distance of 1000 to 1500 km), and a 1200 kV a.c. line 6000 MW. Other possibilities for increasing carrying capacity are opening up with the use of d.c. transmission lines. The capacity of the 1500 kV (± 750 kV) d.c. lines is 6000 MW, and that of the 2200 kV lines (± 1100 kV) 13,500 MW. In the future a very powerful 2500 kV d.c. line with a capacity of 40,000 MW can be built [3, p. 274]. East-west d.c. lines will have some evident advantages: they will establish independent ties between the European and Asian parts of the unified power grid; provide the possibility of redistributing current between parallel electric lines; and ensure the stability and independent work of different power systems. The economic efficiency of the long-distance d.c. lines is determined by the low cost extraction of the Siberian and Kazakhstan fuel coals.

Accelerated development of natural resources on the basis of power production is one of the main prerequisites for a speedy economic advance of the nation. Thus comprehensive investigation of this problem and a long-term scientific and technological program are major and urgent tasks.

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MINE PLANNING IN THE USSR

V.F. Krylov

The USSR possesses vast hard and brown coal resources. Proved coal reserves alone (categories A + B + C_1)* are estimated at more than 270×10^9 t, and probable reserves (C_2) in excess of 140×10^9 t. 66×10^9 t of these reserves are coking coals. The percentage distribution of coal reserves by regions is as follows:

Total proved reserves (categories A + B + C_1)	
The European part of the USSR (primarily the Donetsk and Moscow regions and the Pechora basins)	27%
The eastern part of the USSR	73%
Brown coal reserves (categories A + B + C_1)	
The European part of the USSR	9.2%
The eastern part of the USSR	90.8%
Hard coal reserves (categories A + B + C_1)	
The European part of the USSR	38.2%
The eastern part of the USSR	61.8%

The coking coal reserves of the European and the eastern regions are 34 and 66% respectively. A new potential source of coking coal supply is the South Yakutsk basin, where 2.5×10^9 t, or 3.8%, of the total coking coal reserves (categories A + B + C_1) are concentrated.

Proved coal reserves workable by opencast mining methods amount to 111.5×10^9 t, of which brown coals account for 75% and hard coals for 25%. Virtually all the coal reserves suitable for opencast mining--98% of the total--are located in the eastern regions: 33.7% in West Siberia, 45.3% in East Siberia, 4.1% in the Far East, 9.2% in Kazakhstan, and 1.1% in Central Asia.

The coal basins and deposits of the USSR are characterized by a great diversity of seam bedding, number of seams, and seam thickness and depth of occurrence, as well as by variable coal properties, tectonic structure, and hydrology. The development of some deposits is complicated by weak adjoining strata and adverse hydrological conditions (the Dnieper and Moscow region basins, Far East brown coal deposits), high natural methane

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*For details of coal reserve classification, see Modelevsky et al., this volume.

content (the Karaganda, Donetsk, Kuznetsk, Pechora, and Suchan basins), low specific coal reserves per unit area and low thickness of seams (the Donetsk basin), complexity of tectonic structure (the Suchan basin), and other factors.

Coals in the USSR also differ in quality, depending on the petrographic structure and the degree of metamorphism. Of the USSR total reserves, steam coals account for 78%, the share of brown coal and anthracite being 37.4 and 3.0% respectively. The remaining 22% are coking coals, three fifths of which are coals of "Zh", "K", and "OS" grades.

Proved coal reserves would provide for an economically efficient source of heat. In the future, hard and brown coals will be used for energy, for ferrous and nonferrous metal and rare element production, in the brickmaking and cement industries, and as a raw material for products for nonenergy-producing use--adsorbents, soot, graphite carbon materials, specially processed anthracite, and coal powder.

The technical and economic study of fuel consumption for the period up to 1990 indicates that the USSR energy industry and coking plants will remain the primary users of coal. Steam coals will be consumed by thermal power stations, expanded or newly built, with generating units of 500, 800, and 1200 MW capacities, and by industrial and local/central boiler plants, the public/domestic sector, agriculture, and so forth. On account of the anticipated considerable growth in the thermal power station share over the next 15 to 20 years, steam coal demand is expected to increase. Practically the whole of the increase in steam coal supply is intended to meet power station requirements.

In the long term, the coal basins in the eastern part of the country--the Kuznetsk, Kansk-Achinsk, and Ekibastuz basins--will be of growing importance as a source of fuel for power stations. A marked growth in coal demand for industrial boiler plants is expected over 1975. Heat for the public/domestic sector will be provided through direct combustion of fuel in public/domestic facilities, as well as by central thermal power stations and large boiler plants. Direct fuel consumption in the public/domestic sector is expected to continue primarily in rural areas and small towns.

Some of the coal produced in the USSR will be used for carbonization. Its consumers are ferrous metallurgy (blast furnaces, ore agglomeration, lime and dolomite kilns, the ferroalloy industry), machine manufacturing (casting), nonferrous metallurgy, and the chemical industry.

In view of the resources of some coal grades and their geology, the increase in gas and weakly caking coal consumption for metallurgical coke production in the long-term future should be accompanied by a reduction in the use of coking and fat coals.

According to experts, meeting the needs of the national economy for coal fuel will require a twofold increase in coal output during the next 15 to 20 years. This increase is to be achieved through the operation of existing underground and opencast mines, coupled with reconstruction and development of new mines, mainly in the eastern regions of the country. Here high-output opencast mines are planned to be put on stream as a fuel source for large industrial and energy complexes in West and East Siberia. Such projects for the integrated development of new areas and basins is a qualitatively new phase in development planning.

The Fifteenth Congress of the Communist Party of the Soviet Union decreed that a large interregional fuel/energy complex is to be constructed, based on the unique deposits of the Kansk-Achinsk coal basin (KATEK). Basin development plans include reconstruction of opencast mines so as to expand their capacity, construction of new large opencast operations, coal preparation and conversion plants, and infrastructure, provision of building and maintenance services, and realization of housing projects.

In the Ekibastuz and Maikyuben basins in Kazakhstan, the Ekibastuz fuel/energy complex is planned, where large opencast coal mines with a total annual capacity in excess of 100 Mt will be developed. The South Yakutsk fuel/energy complex with the dedicated Neryungry opencast mine is scheduled for construction in the South Yakutsk basin, whose coking coals will serve as a reliable source of supply for the Far East metallurgical industry.

Acceleration of fuel/energy complex development rates is considered a problem of primary importance to all branches of the national economy. Its solution will substantially affect the fuel and energy consumption pattern of the country.

Notwithstanding the high rate of opencast mining development, increased production efficiency in the coal industry as a whole depends critically on improved underground mining technology. The structure and performance of coal mining enterprises are greatly influenced by the diverse geological conditions throughout the country, which require a wide range of engineering approaches to solve the problems of working coal deposits. The near future will be marked by more complicated geological and mining conditions due to increased working depths and mine gas content, and decreased average seam thickness. These unfavorable conditions will be a major factor determining progress in underground mining technology. Consequently the efforts of scientists, designers, and planners are concentrated on solving such problems as development and introduction of high-performance techniques and of methods of working deep, thin, and steeply pitching thick seams, which are mainly found in the Donetsk and Kuznetsk basins. Improved mining technology will provide the following gains:

- Reduction of roadway construction and maintenance work;

- Complete mechanization and automation of production processes, with removal of workers from the coal face;

- Adequate quality of coal won;

- Adequate surface protection.

The opening up of mines at depths exceeding 600 m will be done mainly by vertical shafts, whereas at shallower depths inclined shafts will be favored, providing for continuous flow of coal to the surface by means of conveyors.

At most new and reconstructed mines, takes extending long distances to the strike will be opened up in separate blocks. The changeover to the progressive opening up and development of mines will reduce the length of workings driven per 1000 of output and the extent of workings maintained. In flat seams, main-entry development will be prevalent, allowing for single-level opening up of mine takes. In inclined seams, panel development schemes are widely used. Just as at present, the horizon system of mining will be used for working steeply inclined and steeply pitching seams.

Longwalling with preliminary construction of entries up to the border of the panel will be practiced for working seams under most geological conditions. The mode of winning the thick and steeply pitching seams of the Kuznetsk basin by multislice longwalling with goaf stowing is expected to become popular.

In the USSR various types of complexes are commercially available for working seams 0.7 to 5.0 m thick and dipping up to 35°, as are complexes for steeply pitching seams ranging in thickness from 0.65 to 2.2 m. At present such techniques account for more than 60% of coal production from flat seams and almost 7% of that from steeply pitching seams. In the near future, complexes and aggregates for the entire range of geological conditions are to be developed and introduced.

At deposits with disturbed geology, where conventional coal-winning techniques have proved inefficient, extensive use of underground hydraulic mining is envisaged. The capacity of existing hydromines will be increased, and reconstructed mines will change over to hydraulic mining or hydraulic transport systems. Implementation of a long-term program will ensure the development of hydraulic mines with an annual capacity of 4 to 6 Mt in the Donbass (thin seams) and of 9 to 12 Mt in the Kuzbass.

Extensive experience in hydraulic coal mining, coupled with project feasibility studies based on an analysis of geological conditions, make it possible to forecast the rate of increase in hydraulic coal mining for the next 15 to 20 years.

The Ministry of the Coal Industry of the USSR pursues a persistent policy directed toward planning high capacity coal mines. This can be illustrated by a number of underground mines with the following annual output: in the Kuzbass, the V.I. Lenin mine (12 Mt) and the Raspadskaya mine (7.5 Mt); in the Donbass, the Dolzhanskaya-Kapitalnaya mine (2.2 Mt), the Krasnoarmeyskaya-Kapitalnaya mine (4 Mt), and the Zhdanovskaya-Kapitalnaya mine (3.6 Mt). The present annual output of the Bogatyr opencast mine amounts to 30 Mt, while the projected capacity is 50 Mt per year.

Modernization of existing coal mines usually provides for output expansion attained by merging small, low-capacity, and unprofitable enterprises. In most cases, level development work at operational underground mines allows for expanded outputs. This policy trend--along with the application of revolutionary new modes of opening up, development, and mining operations, and a sustained improvement in the arrangement and appearance of the underground coal mine--has resulted in sharply increased daily coal face output and high productivity per worker, amounting to 200 per month or more (Raspadskaya, Dolzhanskaya-Kapitalnaya, and Zhdanovskaya-Kapitalnaya underground mines). The planning concepts realized in the Zhdanovskaya-Kapitalnaya N1 and Krasnoarmeyskaya-Zapadnaya N1 underground mines have resulted in a fundamentally new type of mine surface layout, based on separate zoning of industrial/administrative buildings and providing for maximum compactness within each zone. Industrial and administrative buildings are grouped into one or two blocks, as against three or more blocks in the past. This accounts for a sharp decrease in labor consumption during construction, a reduced intra- and intershop communication and transport network, and maximum continuity of operations. New solutions of surface layout problems, mechanization of ancillary operations, and centralization of warehouse facilities, maintenance, and other auxiliary services have resulted in the improvements described.

The operation of underground and opencast mines and preparation plants has an adverse environmental impact: disturbed land due to mining activities, water stream pollution by mine drainage and coal preparation plant slime waters, and emission to the atmosphere of dust and gases from boiler plants and drying sections of coal preparation plants; waste spoil fires and coal lost during transport are also sources of air pollution. Thus, the coal industry of the USSR faces the need to work out a program for further conservation of mineral resources. The program should provide for accelerated rates of developing and introducing new high-productivity methods of coal mining and preparation, and expansion of R&D work on the most urgent problems concerning the conservation of mineral resources.

In the USSR mine planning for the coal industry is carried out by 17 planning institutes with 5 affiliates situated in the main coal-producing basins of the country, and by the planning branches of 2 research institutes and 7 planning offices of the coal Production Units. The 14 main planning institutes are combined into the All-Union organization "Soyuzshakhtoproyekt".

Planning institutes offer services to the coal basins near them and are responsible for all planning operations dealing with the development of new coal enterprises and reconstruction of those in operation--underground and opencast mines, preparation plants, maintenance shops, coal machinery plants, transport facilities, energy and water supply systems, and so forth.

Planning offices are responsible for servicing the coal mines of Production Units and designing schemes for opening up new levels, and for the development of new mine takes, mechanization and automation of certain links of production processes, and similar tasks.

Both types of organization deal with all facets of the coal industry via specialized departments--mining, electromechanical, construction, sanitary engineering, exploration, geological survey, transport.

Specialization of the main planning institutes is under way, with the aim of increasing their effectiveness. In the western, eastern, and northern regions of the country, specialized planning institutes are responsible for designing coal preparation plants. Institutes for planning machinery and repair plants, and auto repair plants, are located in the western and eastern regions, as are planning institutes for construction/assembly plants.

The network of coal industry planning organizations also comprises a Central Research and Planning Institute, the leading establishment dealing with the following matters: the upgrading planning technology, working out scientific principles for planning, development, and improved planning standards, and module and experimental planning for complete mechanization and automation of all stages of planning and construction. The Institute also coordinates work on the development of standard layout and design patterns for the surface buildings of the coal industry.

To enable them to furnish the estimates and design data needed in connection with the program for creating additional and reconstructing existing coal mines, the planning organizations should be expanded. The planning system structure and optimum quantitative parameters are the subject of a "scheme for and distribution of coal industry planning organizations for the period up to 1990", which outlines the possibilities for further development of all operational planning establishments.

The most essential capital investments to be made during the period considered are in the coal basins of the eastern and northern regions. This in turn will stimulate the development of planning organizations in these regions. Thus, an affiliate of one of the planning institutes, "Sibgiproshakht", has been set up in the center of the South Yakutsk fuel/energy complex; and an establishment of a similar affiliate in the Kansk-Achinsk basin is being considered. But on the whole, the scheme for geographical distribution of planning organizations is not expected to undergo essential changes before 1990.

In connection with the need for specialists for planning establishments, it was stated that the growth in the scope of planning should exceed that in the number of planners. This could be achieved by measures aimed at productivity growth: improving working conditions through construction of new buildings for planning institutes and expansion of existing ones; mechanizing calculation, graphic, and reproduction operations; upgrading the organization of planning activities and planning technology; designing module projects; developing standard engineering patterns and standard specifications, and the like.

In recent years planning technology has undergone substantial change, markedly affecting the quality of projects. These changes were brought about by wide application of economic and mathematical simulation techniques and multiversion planning, based on computerized technical and economic feasibility studies of projects, and by changeover to computer techniques for most engineering and economic estimates.

Within the coal industry automated planning system (SAPR-coal), more than 50 sets of software (algorithms and programs) for computerized planning have been developed (mine hoisting, underground transport, coal preparation flow sheets, etc.). This trend is considered to have great potential and is to be further developed. Thus, most planning organizations will be furnished with third-generation computers in the near future.

At the same time a three-dimensional planning method will be further developed. Work is under way on elaborating standard engineering patterns and technical and economic parameters for separate parts of projects, and on improving the information service for planning.

The progressive trends in USSR coal mine planning that have been described ensure a sustained improvement in the quality of projects, thus facilitating the expansion of coal output.

GENERAL AND INTERNATIONAL ASPECTS

THE ROLE OF COAL IN THE EVOLUTION OF THE GLOBAL ENERGY SYSTEM: A REFERENCE CASE

W. Sassin and W. Häfele

INTRODUCTION

The energy community has changed its attitude toward coal in the last few years: coal has attracted new attention. This is not the result of a spectacular breakthrough in modern coal technologies; rather, it is the combined effect of supply constraints for cheap crude oil and an unexpected opposition to nuclear energy, which has led to a marked downward revision of many national nuclear programs.

The improved situation of coal is not a sufficient basis, however, for judging the future importance of this traditional energy source. Detailed national case studies leave no doubt that there is a significant potential for increased coal use; but many of the side-effects attributed to nuclear energy will also appear with an energy strategy favoring coal. Furthermore, with coal it would be difficult to quickly meet the challenge of the fast-growing energy supply/demand gap [1,2] that with high probability will develop in the next twenty years. Figure 1 displays some results of the Workshop on Alternative Energy Systems which has analyzed the global energy prospects until the year 2000 [3]. In many cases considered there, supply begins to lag behind demand because of possible limitations on the production capacities assumed for OPEC oil. High limits for the OPEC supply would postpone an imbalance between demand and supply, but at the price of a dramatically fast widening of the supply gap.

The severe energy problems of mankind that are hidden behind the few curves of Figure 1 demand a careful assessment of the long-term future of all energy sources. Initial difficulties accompanying a revival of coal are not of prime concern in this context; in view of the large resources of coal, such an analysis is an important element of a solution, and we will try to outline the basic role coal could play in the evolution of the global energy system.

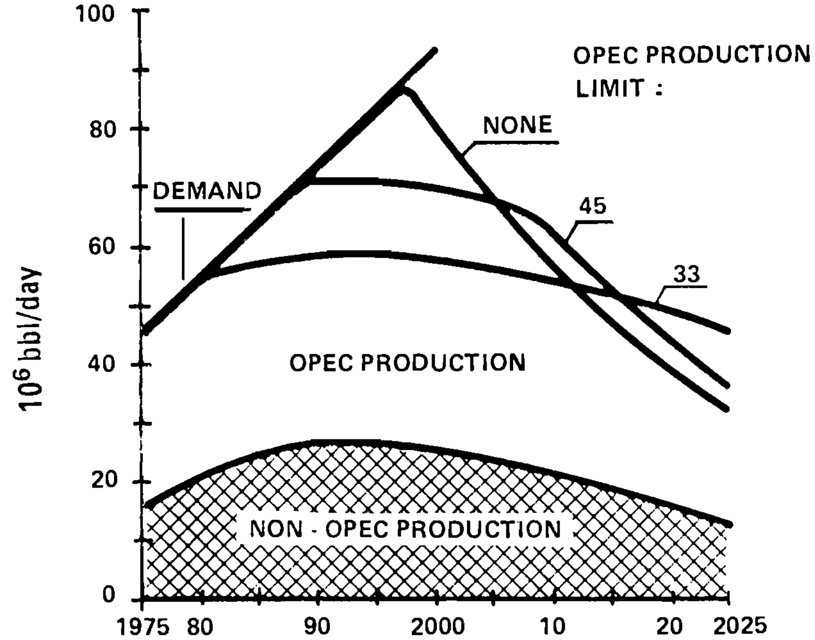


Figure 1. Oil production in the world outside CMEA and China.

Assumptions: High economic growth rate, rising energy price, vigorous government response, coal as the principal replacement fuel, and gross additions to oil reserves 20 x 10^9 bbl/year.

A GLOBAL ENERGY DEMAND SCENARIO

The yardstick for evaluating an energy source is the expected energy demand. Extremely long periods were necessary in the past to switch from one basic primary energy source to another. We must therefore choose an appropriate time horizon for our analysis. Figure 2 summarizes the history of coal and its competitors. The market shares F of each primary energy form are given in a special logarithmic plot, in which a straight line represents a logistic (S-shaped) curve. The regular pattern of new energy forms supplanting old ones is quite remarkable. It was only slightly disturbed by drastic economic and technological changes such as those between 1914 and 1945.

Globally, roughly 100 years were obviously needed for a new source to gain 50% of the market. A transient advantage, even over one or two decades, of one competitor might therefore not be sufficient to change the secular trends.

The need for much more energy is not a transient requirement, however. Three reasons contribute to a continued growth of global energy demand for 50 years and more: the increase in global population, the development of developing countries, and

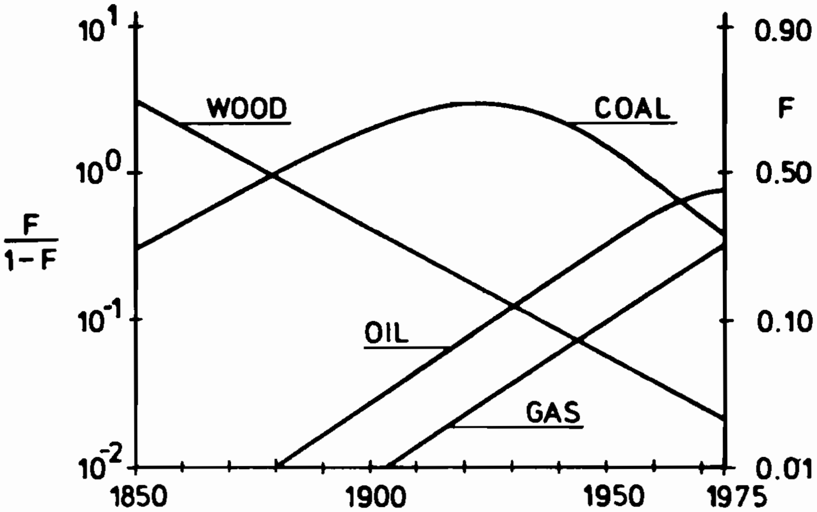
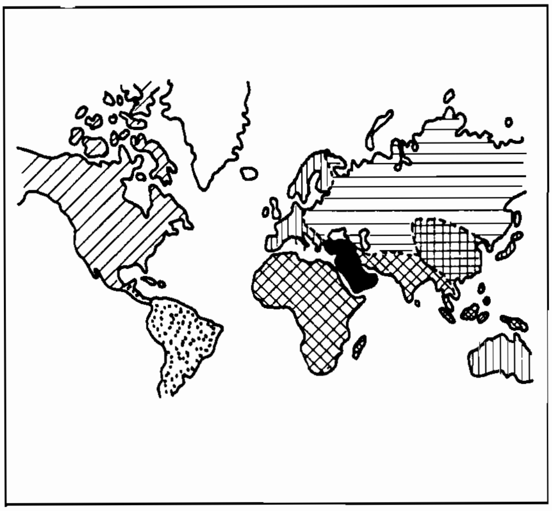


Figure 2. Energy market penetrations: world.
F, market share.

the continuing industrialization of developed nations. In view of these long-term processes we will focus on the next 50-year period. Figure 3 lists world energy demand projections (minimum



Region		Pop. 10^6	kW/cap	TW
I	▨	310	16.5	5.0
II	▤	460	11.6	5.3
III	▥	780	10.5	8.2
IV	░	720	3.3	2.4
V	▩	3700	1.4	5.2
VI	■	300	4.8	1.4
VII	▦	1800	4.6	8.3
				~ 35

Figure 3. Reference demand scenario, world, 2030.
Population: 8 x 10^9; energy: 35 TW, or 4.4 kW/cap.

estimates) for the year 2030 [4]. A comparison of the per capita consumption specified for various regions with consumption today shows that a global energy demand of 35 TW is an extremely conservative figure for 2030. An increase by a factor of 4 over the present consumption level of 7.5 TW reduces roughly to a doubling of the average per capita consumption of a global citizen over 50 years. Much higher demand estimates can easily be obtained and indeed are implied in the request of developing nations for a new economic order to expedite their general development [5]. The scenario of Figure 3 should not be considered the most likely nor a particularly attractive development; it was designed to put energy supply possibilities in perspective with a still conceivable minimum demand. The scenario excludes catastrophic situations in major parts of the world which might certainly translate into even lower global energy demand figures.

COAL, A LONG-TERM FOSSIL PRIMARY ENERGY OPTION?

With the reference demand scenario as a background, we will first address the question whether coal can regain the position of main primary energy source. Figure 4 contains the results of a recent survey, presented at the World Energy Conference, of global coal resources and reserves [6]. The geological resources

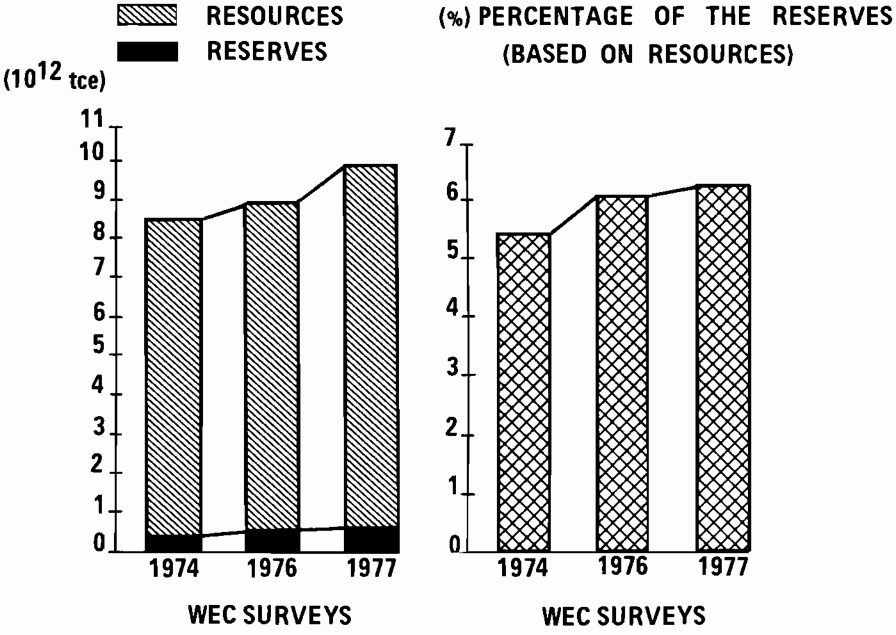


Figure 4. Recent additions to coal resources/reserves.

of 10 × 10^{12} t of hard coal equivalent are indeed very large*, dwarfing present estimates of conventional oil and gas resources, which are smaller by at least a factor of 10. The economically recoverable reserves of coal, 6.5% of the resources in Figure 4, are of the same order of magnitude as the ultimately recoverable amounts of oil and natural gas up to a price level of $20/bbl.

We have tried to quantify the resource requirements for a global coal option. Figure 5 summarizes the results of some straightforward calculations. Coal now meets 2.5 TW or roughly 30% of the global energy needs. Fifty years ago coal held a much larger share: more than 80% (Figure 2). In line with past trends, considerable time would be needed to promote coal back into the position of main primary energy source. We have fixed a figure of 80% of the total demand to be reached sometime in the future. This is somewhat artificial, but helps to bring out the salient points.

As we were strongly in favor of coal in this example, we assumed that a coal revival would begin at once, neglecting the enormous R&D efforts still to be made before a responsible decision toward this end could be made.

With a market penetration speed equal to that of oil in the past, and after correction for the conversion losses incurred in

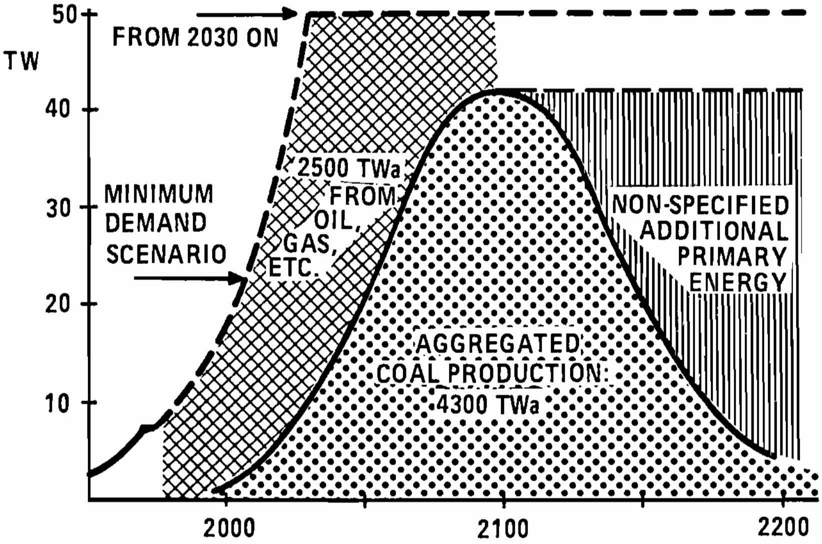


Figure 5. A global primary energy option based on coal?

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*10^9 tce = 0.93 TWa ≈ 1 TWa.

providing oil equivalent primary energy, roughly 100 years were needed to phase in coal. Allowance for these losses increases minimum primary energy demand to 50 TW in 2030 (see Figure 3). In view of the dramatic rise in coal production displayed in Figure 5, two additional assumptions appeared necessary. First, coal resources are large but not unlimited. A zero growth of global energy demand was therefore fixed from 2030 onward, limiting primary energy consumption to 50 TW. That is, the minimum demand of Figure 3 (an oil equivalent supply of 35 TW) would never be exceeded. The coal production curve in Figure 5 reaches 80% of the total demand in 2080; 40 TW, or slightly more than 40,000 mtce per year of coal, would go to the global economy by then. Our second additional assumption (Figure 5) is that after the year 2100, an unspecified nonfossil primary energy source would take over the market share of coal with the same speed with which coal came in.

The results of this hypothetical undertaking are prohibitive: 4300 TWa, or roughly 45% of the geological resources of coal, would have to be produced cumulatively. Taking recovery factors into account, practically the total resource base of coal would be consumed in this scenario. Some 2500 TWa would have to come from other sources, mainly from oil and gas until 2100. They make up for the difference between a coal supply according to Figure 5 and the total supply of energy necessary to meet the requirements of the minimum energy demand scenario.

Of the many difficulties of a global coal option, the CO_2 dilemma should be briefly discussed. Combustion of coal leads to CO_2. Once given to the atmosphere this gas can be regarded as a permanent waste heat source. CO_2 changes the infrared radiation balance of the upper layers of the troposphere. The climatic consequence of a certain increase in atmospheric CO_2 content cannot be accurately predicted today. Expert opinion tends to expect a significant increase in mean temperature of the polar regions if the pre-industrial CO_2 level doubled [7]. Figure 6 relates possible energy production based on coal to arbitrary upper limits for the increase in atmospheric CO_2 content. A detailed analysis would have to account for the actual split between coal and hydrocarbons. A first-order correction is already included in the model illustrated in Figure 6 [8]. Therefore the total fossil energy consumption, given in terawatts in Figure 6, appears to be lower at the beginning of the upward curve than the real figures to be found in energy statistics, because the contribution of hydrocarbons is still large in the early years.

If we consider a tripling of atmospheric CO_2 content as a tolerable upper limit, the coal scenario of Figure 5 would have to be drastically revised between 2050 and 2100. Lower CO_2

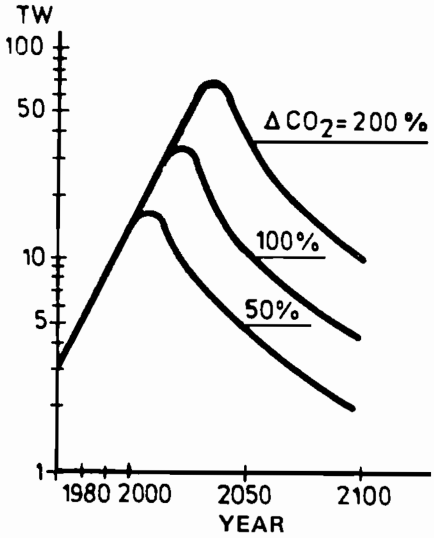

Figure 6. Necessary control of fossil energy consumption, if supplied in the form of coal, to stay below certain CO_2 levels in the troposphere.

Source: [8]

limits must be envisaged, however. Even if we allow for the installation of fossil fuel cycle centers, which would dump CO_2 directly into the deep sea [9], only a fraction of the CO_2 emissions to the atmosphere can be avoided.

Both the analysis of the resource question and the treatment of the CO_2 problem given here are only rough. But when taken together with other considerations, some of which will be touched upon later in connection with a more modest role of coal, one must expect that in the long run coal cannot supply the bulk of man's energy needs--it is not a global primary energy option for a world with eight billion people.

COAL, THE MAIN PARTNER FOR NONFOSSIL PRIMARY ENERGY SOURCES

The exercise we have just performed for coal throws some light on the enormous requirements any primary energy source will have to satisfy. Given a 35 TW minimum demand, only two sources do not suffer from severe resource constraints: nuclear and solar energy. Nuclear energy comprises fission and fusion and in both cases depends on the breeding principle. Solar energy in this context is to be understood as a hard technology, using the energy available in large desert regions [10]. In the extreme position to which we promoted coal, nuclear or solar energy would no doubt also face extreme environmental problems, though proper siting can most probably deal with these [11,12]. Nuclear and solar energy do have one distinct disadvantage, however. They cannot directly provide a material energy carrier that could be easily stored, shipped over global distances, and finally distributed in small quantities to the end user at reasonable cost--all properties that are inherent to fossil energy, especially oil. This limits the economic use of nuclear and solar energy today. Commercial nuclear energy therefore has concentrated from the outset on the production of electricity, and it is interesting that coal, under strong competition from oil, has maintained its position only in the electricity sector, leaving metallurgical applications aside (see Figure 7). The necessary replacement of oil as our main primary energy source will create a gap in the supply of secondary energy. The production of hydrogen by splitting the water molecule with energy derived from nuclear and solar heat appears as the ultimate solution. The difficulties of a hydrogen society suggested many years ago by C. Marchetti have since become evident. Hydrogen production still awaits a breakthrough in thermochemical engineering [13]. Furthermore, hydrogen is a gas and would easily replace natural gas in its own market, which is tied to the existence of pipelines and distribution grids. The largest single market for secondary energy, that for liquid fuels, will suffer most from a shortage of oil. Direct replacement of oil by nuclear and solar energy is therefore badly needed, and it appears possible that coal can meet the interim energy demand.

For various reasons, methanol (CH_3OH) is the prime candidate for a synthetic liquid secondary energy carrier [14]. Coal would have to provide the carbon for methanol synthesis. Because

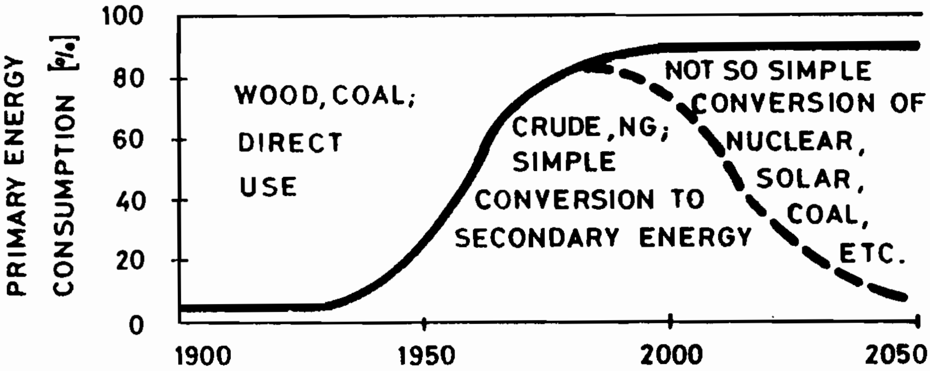

Figure 7. A widening gap between primary and secondary energy.

of the energy value of a CH_3OH molecule, which is twice that of a single C atom, coal would essentially act as a lost storage material for the H atoms carried in the CH_3OH molecule. If the necessary energy to synthesize methanol is taken from other sources, e.g. nuclear reactors or solar concentrating devices, 1 t of hard coal could provide roughly 2 tce methanol. In view of both the resource limitations of coal and the CO_2 constraints, such an efficient use of the C atom appears mandatory.

Figure 8 shows a nuclear system combined with a chemical reactor, capable of producing very large amounts of methanol. Efforts to step up the nuclear supply fast enough to meet the demand for liquid fuels in our reference demand scenario are quantified elsewhere [4,15]. The limited cheap uranium resources enforce early introduction of breeders, which is less necessary if nuclear energy is considered merely an input for electricity production. The box "chemical reactor" in Figure 8 comprises all processes to convert coal into methanol. We have based our calculations on a two-step system. First coal is oxidized in a molten iron bath using pure oxygen from an electrolysis unit to produce CO + ½ H_2. Another ½ H_2 can be produced by chemical reactions from the 30 kcal released at 1400 °C. Second, the deficiency of hydrogen is compensated by enriching the synthesis gas with H_2 from the electrolysis unit before methanol is produced catalytically at low temperatures and high pressure [16]. This concept is not demonstrated experimentally, but the major elements of it do exist in large-scale units. Other combinations

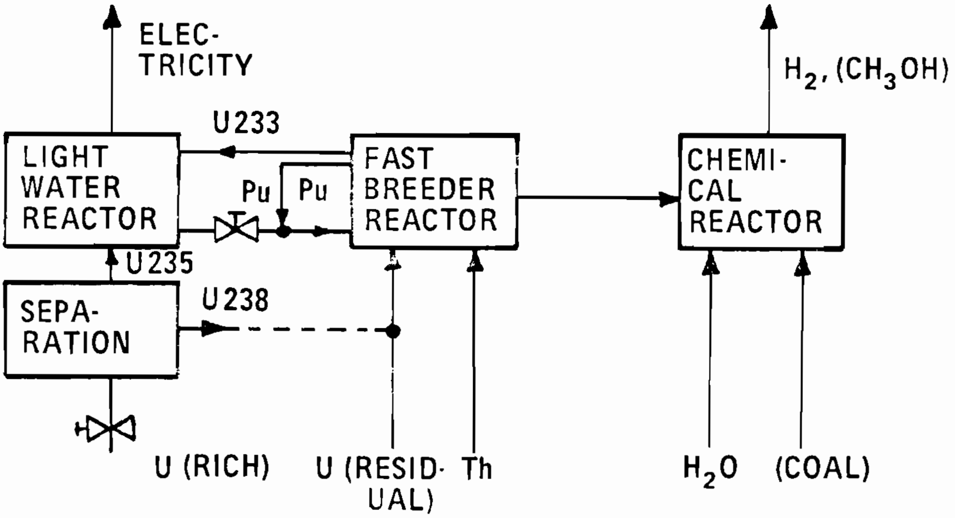

Figure 8. Transformation of fuel resources and capital into an endowment. Maximum yield: continuous 3 TW(e) + 10 TW(meth) from 2030 onward related endowment: 10 x 10^6 t U (RICH) + 17 x 10^{12} $.

of processes are also conceivable. The choice of reference technologies is therefore not crucial for our further arguments.

We will assume from now on that coal, now used as a primary energy source, will gradually concentrate on its role as a feed material for producing synthetic liquid secondary energy. After recalculating the necessary amounts of coal for this more realistic supply scenario, we will then analyze some constraints likely to determine the future deployment of coal.

A GLOBAL COAL DEMAND SCENARIO

Present annual coal production amounts to 2.6×10^9 tce or 2.4 TW. Coal thus supplies roughly one third of the global energy needs (cf. Figure 2). Medium-term studies indicate that coal can essentially maintain a 30% share of the primary energy balance if it substitutes for nuclear energy in the electricity sector and for natural gas in the heat supply sector. Only a small indirect replacement of oil is likely in the case of heavy fuel oil [1,2,17]. Prime uses of coal will ultimately be confined to steel production and the chemical industry. Figure 9 exemplifies this trend for the FRG.

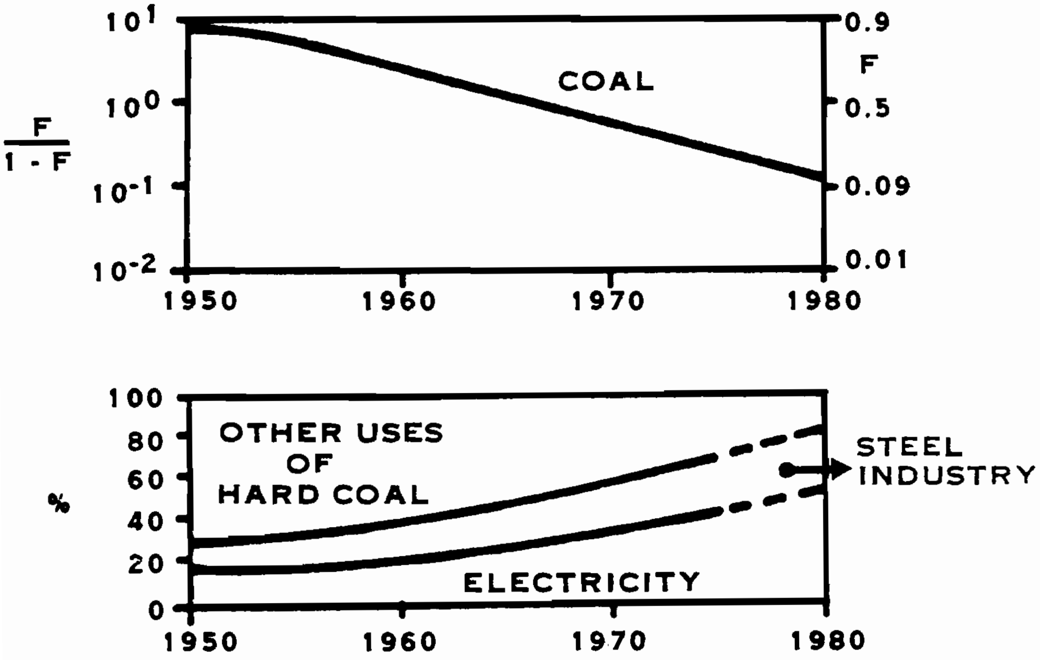

Figure 9. Market shares (F) of coal in the FRG.

Contrary to the technological direction selected in [1] and [2] for a fast revival of coal up to 2000, we assume that methanol production after 2000 will quickly absorb the available coal. To determine the possible development of synthetic methanol as a function of time, one can again use the market penetration concept (Figure 2). It turns out that the limiting constraints are to be expected from the maximum possible growth rates of the nuclear part, not from those of coal. Yet "new coal"--comprising first electricity, gas, and industrial heat production and later synthetic methanol--would again have to enter the global market with the speed of crude oil or natural gas in the past. This is certainly an ambitious goal. If we fix a target of 17 out of 35 TW to be supplied in 2030 in the form of liquids --the fraction that crude oil now supplies--then 15 TW of methanol would require a coal input of approximately 7.5 TW. Another 2 TW of liquid demand would still have to come from crude oil. Adding 3 TW for steel production and another 3 TW for chemical or other prime applications like intermediate heat demand for medium-size consumers, a total of 13.5 TW of coal consumption in 2030 is conceivable. It is important to recall here that dramatically large amounts of oil and gas reserves are needed to fill the gap between any coal demand scenario and the global reference demand scenario of Figure 3 (cf. Figure 5).

CONSTRAINTS FOR A GLOBAL COAL SUPPLY SCENARIO

How feasible is our coal demand scenario? A basic check is to compare the required coal production level with the coal reserves needed. We proceeded similarly when we analyzed the possibility of a primary energy supply based on up to 80% coal. Again we assume that a substitute for methanol, the main product derived from coal, could enter the market at some time beyond 2030 and phase out coal at the same speed at which it came in. The results of these calculations are given in Figure 10. Curve (a) shows the start of a substitute for methanol, say hydrogen in 2035. Because of the gradual penetration of this substitute, the maximum coal production of curve (a) occurs 10 years later. Curve (b) fixes the same penetration event around 2045, leading to maximum coal production shortly after 2050. The coal production levels necessary for a primary coal option (Figure 5) are shown as curve (c). Despite all efforts to concentrate coal use in our coal demand scenario to areas where a minimum input has the maximum effect, a large part of the total coal resources would be needed. Curve (a) leads to a cumulated requirement of 1200 TWa of reserves, curve (b) to 2400 TWa, or roughly 25% of the present stated geological coal resources.

The figure published at the World Energy Conference for economically recoverable coal reserves is 600 TWa; 1200 TWa were stated as possible with a further significant increase in coal prices [6]. Curves (a) and (b) in their initial part are also compatible with the anticipated maximum coal production. Figure 11 is taken from the same source [7], and by and large supports our coal demand scenario up to the year 2020.

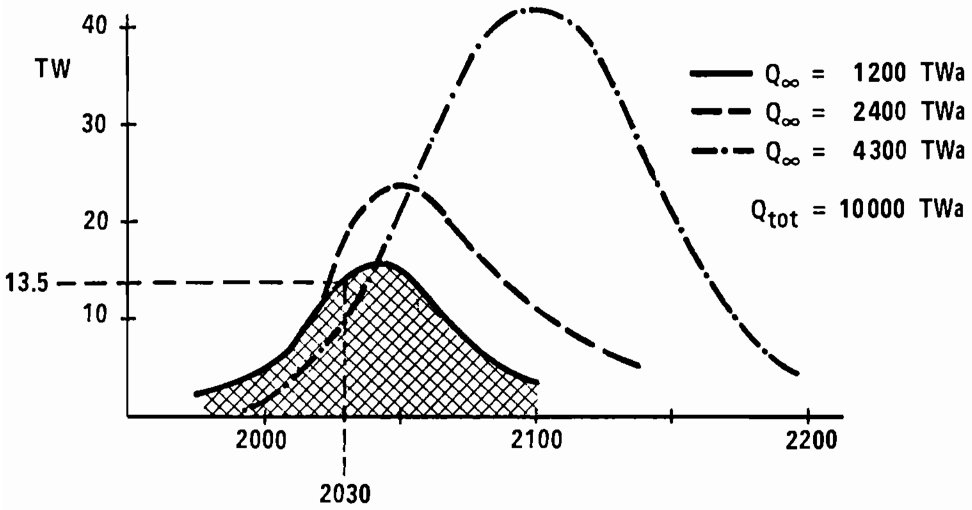

Figure 10. Coal demand scenario: coal production and reserve requirements.

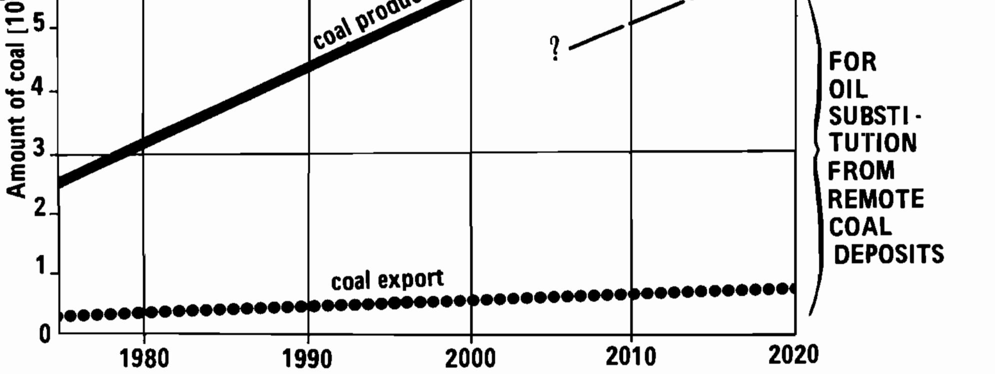

Figure 11. WEC 1977: Maximum coal supply.

Careful analysis reveals a number of inconsistencies, however, between our global approach and the long-term national estimates for an extension of the coal supply. Figure 11 gives the expected amounts of coal that could be exported according to present national plans. The coal exports of the three main coal-producing countries--the USSR, the USA, and China, which dispose of roughly 90% of world coal resources--amount to 255 × 10^6 tce in 2020, and would not have changed dramatically one decade later. According to our reference scenario, the aggregate energy demand of these three countries is nearly 18 TW, or 50% of the total, 35 TW, in 2030. It is certainly an oversimplification to allocate resources in proportion to the aggregate demand estimated for each region, but it helps to establish the size of the supply problems. Thus, the world outside these three countries, assuming that they have 10% of 10,000 TWa, i.e. 1000 TWa, geological resources of coal, would have to produce as much as 600 TWa of coal, if we follow the example of curve (a) in Figure 10. If we fix the percentage of ultimately recoverable reserves at the still acceptable high level of 30% of these geological resources, we can hope that 300 TWa could be produced outside the USSR, the USA, and China. A minimum demand for coal exports from these three countries can then be estimated within the limits of our exercise: 3.6×10^9 tce per year in 2030, which is approximately 14 times the export capacity envisaged at the World Energy Conference.

An equally important inconsistency between our coal demand scenario and actual planning results from Figure 11. The low estimates for coal exports indicate that the large coal-producing countries envisage using a significant share of their coal production more traditionally: partly for electricity production, and partly for gasification, taking the necessary conversion energy also from coal and thus not implementing the most resource-efficient strategy. Our own findings in the medium-term studies, based on economic considerations, support these applications [1,2]. The consequence of such a strategy, maintained well beyond 2000, would be negative, however. Coal would be converted into secondary energy forms with only very low efficiencies. Moreover, the demand for oil could be reduced only comparatively slowly, as other secondary energy forms depend on the buildup of costly distribution grids, which happens only slowly. Thus the pressure on oil as a source of liquid fuels would increase; and this in turn would favor not so efficient early use of coal, mentioned above, in other sectors not depending on liquid secondary energy. Thus coal would directly compete with nuclear energy and delay its penetration even in the electricity sector. In fact that seems to be what is happening today.

As the purpose of this analysis is to describe a global use of coal that is in some sense optimum, we will not adapt our coal demand scenario to the constraints that are obviously imposed by adding up the results of national or regional optimizations. Figure 11 shows the main uses of coal in our scenario. We further assume that coal exports up to 3.5 TW in 2030 will not be blocked by alternative planning in the main coal-producing countries. Still the question remains whether such exports are economically feasible.

The buildup of coal mining capacity and long-distance coal transport systems is time-consuming and capital-intensive. Sizeable efforts are needed, especially for deep mining, which translate into high coal costs. It is impossible to estimate a future price level for coal that would increase the demand for imports to or even beyond 3.5 TW. Yet clearly the coal price cannot exceed a certain fraction of the oil price if methanol is to replace light fuel oil and gasoline in large quantities.

Future increases in oil price will also allow for higher coal prices. A comparison of energy prices and their economic value, measured by the GNP produced from that energy, points to a major obstacle to extension of the international energy trade. A country that had imported 100% of its energy needs in 1970 when oil was $3/bbl could have compensated this trade flow by exporting 3% of its GNP. At a reference price of $20/bbl ($15 to 20/boe are typical for synthetic fuels derived from cheap coal only), that country would find it very difficult to maintain its balance of payments: it would have to export more than 20% of its GNP. The situation is even worse if methanol from a combined nuclear and coal plant (cf. Figure 8) must be envisaged. The present terms of international economic cooperation thus seem to exclude on-site liquefaction of cheap coal for large-scale export, which would quite elegantly solve the transport problem and which suggests itself for the deployment of coal basins far from the large consumer centers.

An outline of the relationship between mining costs and transport modes of coal and methanol, and their related costs for a fixed distance of 1000 km, is shown in Figure 12. The data were taken from various sources [18,19,20] and repeat the well-known fact that liquids can easily be transported over continental distances, whereas solids require sea routes. In line with our national case studies [1,2] and with cost estimates for a nuclear methanol plant [16], a coal price of $\$1.5/10^6$ Btu delivered to the consumer is an upper limit for a broad revival of coal, for both the medium- and the long-term applications in our coal demand scenario. We have chosen the coal slurry pipeline as the cheapest mode of transport for the very large amounts of coal involved. Even if pipelines of 30×10^6 tce transport capacity per year are combined with the cheap coal from large surface mines, a surface transport distance of 1000 km is the upper limit for coal supplied to a world market.

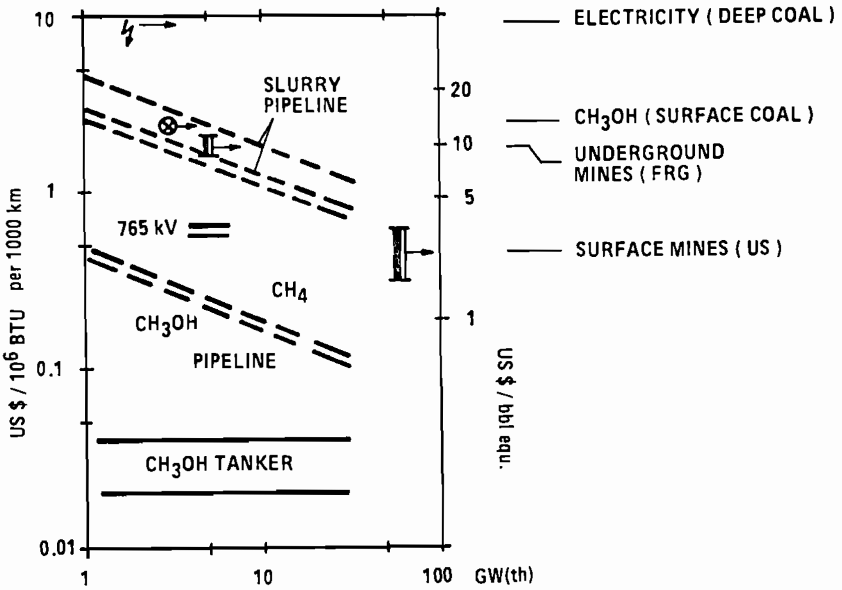

Figure 12. Mining, transportation, and conversion costs of coal.

SYNTHESIS AND CONCLUSIONS

Coal transport, as far as we can see at present, constitutes the main technical constraint for long-term intensive use of coal. Some maps displaying the location of the main coal basins (Figures 13, 14, and 15) show immediately that only a small fraction of world coal resources is situated within 1000 km of navigable coastal waters. Only these resources can be classified in a global coal supply scenario as potentially accessible. It remains to be seen what quantities will emerge from a more detailed investigation of the transport that is planned at IIASA. The limitations, just discussed, to stepping up the coal supply apply mainly to the fraction of coal that must be exported by the main coal countries in our scenario. If we take into account the waste heat disposal problem and the enormous capital requirements for conversion of coal into methanol, large energy centers in an oceanic environment offer many advantages. They could be organized as joint ventures, the coal-producing nations bringing in coal and the energy-importing nations supplying most of the capital for building conversion plants, including nuclear reactors. Methanol would then flow back to the coal suppliers. Such joint ventures might be particularly beneficial to developing regions with severe capital constraints. This concept would maximize the output of secondary energy or, expressed differently,

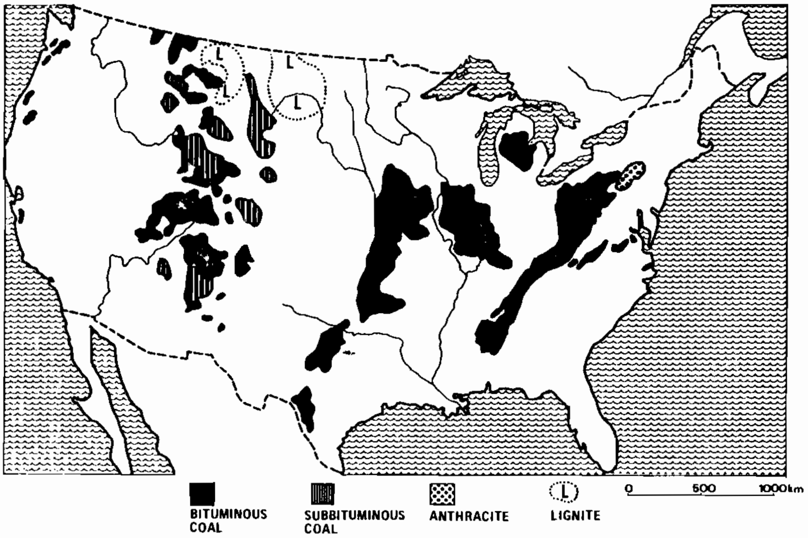

Figure 13. Location of coal resources in the USA.

Source: [21]

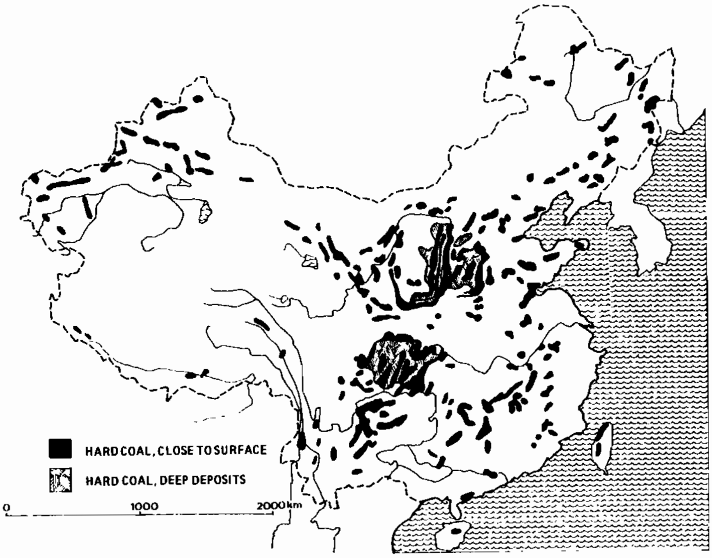

Figure 14. Location of coal resources in the People's Republic of China.

Source: [21]

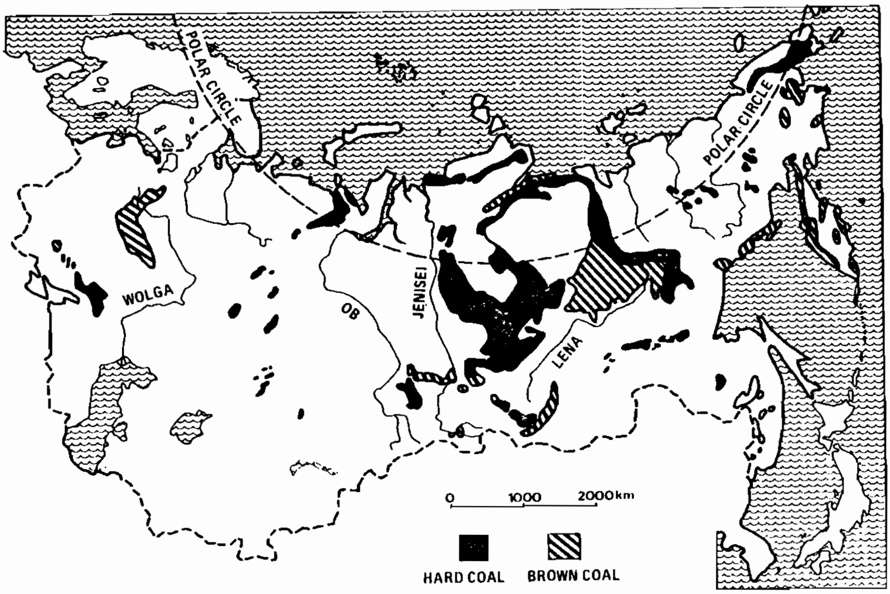

Figure 15. Location of coal resources in the USSR.

Source: [21]

minimize the requirements for coal; yet it increases transport requirements. Some part of the coal requirements of the coal countries would also have to come from deposits less than 1000 km from the coast.

In our as yet preliminary analysis of the possible long-term role of coal in a global context, we arrive at the following conclusions.

First, it is highly unrealistic to interpret the large global coal resources as sufficient for a long-term primary energy option. Coal is not a real competitor or alternative to other primary energy sources. *Second*, coal offers the strategic link for transition from a fossil-based global energy system to one that must rely also on nuclear and solar energy. *Third*, even assuming the most efficient use of coal as a feed material for synthetic liquids, the required coal supply exceeds present maximum production estimates for the next 50 years. This scenario would obviously place an extreme burden on the coal resources accessible with present mining and transport technologies, even if we allow for substantial improvements within our time horizon.

For a still broader justification of the natural role of coal described here, coal must be seen in conjunction with the potential of other primary energy sources, as was recently done at the World Energy Conference, where the 35 TW supply scenario was developed [4]. That scenario corresponds to our more detailed one described above. From the more general reasoning of the global supply scenario, it becomes clear to us that any decision on the deployment of coal in the next few years will have far-reaching and profound consequences for man's ability to master the energy problems of the globe.

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COAL DEMAND AND SUPPLY IN 1985: AN APPRAISAL OF THE NEW COAL POLICIES IN THE ECE REGION

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INTRODUCTION

A host of motivations has induced governments of the Economic Commission for Europe (ECE) region (covering North America and Europe, including the USSR) to reformulate their coal policies after 1973/1974. As a result, coal production and demand are likely to grow annually till 1985 by about 2.7% for the ECE region as a whole. Although this is an acceleration of three to four times in comparison with the 1960s and the early 1970s, it will not suffice to provide for substitution for oil, natural gas, and nuclear power, either in the overall energy balance or as regards the raw material basis for electricity generation. It is true that coal resources and technologies would seem able to sustain a further acceleration. But because of worsening geological conditions, growing distances between new mines and industrial/metropolitan areas, lead times, manpower, and productivity constraints such further acceleration could be reached only in the longer term and would presuppose a further (likely) improvement of coal's competitiveness, the broad application of new technologies, an intensification of international trade and scientific and technological cooperation.

These were the major findings of a secretariat analysis** of an exchange of information on new coal policies that ECE governments undertook between December 1974 and July 1977 in the Working Party on Coal Trade, a subsidiary organ of the ECE Coal Committee. This exchange had been launched in response to the so-called oil crisis of 1973/1974, but it rapidly became evident that other motivations as well had prompted a reassessment of the role of coal. Certainly, further adaptations will become necessary in the future. It should, therefore, be clearly understood that the findings reflect an appraisal of coal's future at a given moment; while they certainly remain essentially valid in the short and medium term, they are subject to periodic review.

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*The paper whilst based on the findings of a secretariat study, represents the views of the author. Paper presented by U.P. Chestnoi.

**A revised version entitled *Coal 1985 and Beyond - The Perspectives of the Coal Industry in the ECE Region* can be obtained from Pergamon Press, Oxford, UK.

MOTIVATION FOR A NEW POLICY FOR COAL

No doubt the "oil crisis" of 1973/1974 with the quadrupling of crude oil prices had been a major cause for the formulation of new energy policies after 1973/1974 in the majority of ECE countries. It demonstrated the vulnerability of the energy economies, of balancès of payment, of employment and growth targets to substantial price increases and supply disruptions, and prompted a reconsideration of the role that imported oil and other energy sources were to play in future energy balances.

But while the oil crisis was a most powerful motivation, it was not the only one; doubts had developed about the availability of nuclear power, its competitiveness, safety, and resource base. Considerable delays had occurred in the commissioning of nuclear fission plants as a result of increasingly stringent safety regulations and public resistance. Construction and raw material costs had increased under the impact of inflation, new regulations, unsatisfactory progress in standardization of equipment and low profitability of exploitation. The margin of competitive advantage was reduced and in certain cases even disappeared; the coming on the market of breeder and nuclear reactors on an industrial scale was again postponed and intermediate technologies--high temperature reactors--became necessary to reduce the strain on uranium resources which otherwise were likely to disappear before the end of the century. These were matters of considerable concern to governments. While some governments strengthened their involvement in nuclear programs to overcome these difficulties and to become less dependent on oil, others began to reconsider their nuclear programs and reduced them drastically. For these countries the balancing of energy supply and demand in 1985 and 2000 were additional problems to those caused by the oil crisis.

Doubts had also developed with respect to the way in which the Earth's energy resources were put to use. The perception of the finite character of conventional forms of energy and of their present wastage gained ground not only in environmental circles but also in governments. It appeared unacceptable to a growing number of countries to perpetuate energy demand/supply systems which "lost" 85% of the energy content of their energy resources on the way from extraction to final use [1].

Whereas these motivations prompted a reappraisal of energy and coal policies after 1973/1974, two reasons were lacking that had dominated energy and coal policies in many western European countries during the 1960s: employment and regional development policies. The tightness of the labour markets during the years immediately preceding and following the oil crisis had rendered such policies less urgent. Also, another reason--earning foreign currency through coal exports--quite powerful in the past, seemed of less importance during the formulation of the new coal policy after 1973/1974. Less easily available investment funds and a desire to export high-value products based on coal (electricity, synthetics), rather than coal, seemed to be the basis of this somewhat more hesitant attitude.

These changes in emphasis and the new reasons were so important that they necessitated and, indeed, prompted the formulation of an altogether new coal policy in the ECE region during 1974 and 1975. However, born out of a crisis and drafted in a situation of uncertainty these policies have a strong short- and medium-term connotation. They would be subject to further change, as the future of the world energy economy becomes clearer and as constraints affecting coal mining and use are lifted. The following analysis will, therefore, not only describe and assess the policies formulated in 1974 or 1975, but also indicate the margin of manoeuvre that governments have or could gain in future with respect to coal, and that may be the basis of a further adaptation of their coal policy.

MAJOR FACTORS DETERMINING THE FUTURE OF COAL

It appeared from the exchange of views that government planners in the field of coal considered the following factors as essential for coal's future:

- Competitiveness,
- The resource base,
- Availability of manpower and labour productivity,
- Managerial and technological progress,
- Capital availability,
- Environmental constraints,
- Institutional factors,
- Lead times.

To what extent were these factors considered to limit future production growth?

Competitiveness

The actual competitive position of coal has improved since 1973/1974. A substantial competitive advantage over oil was gained in the power station market, particularly in the UK and the USA. Submarginal coal fields or seams have become visable under the impact of the fourfold increase in crude oil prices; losses (and hence the burden on public budgets) were reduced. However, since 1974 a considerable portion of the competitive edge gained over oil as a result of the oil price increases has been lost. Higher coal prices had been introduced in the centrally planned economies of the ECE region, to induce industrial consumers to greater economy. In the market economies, the substantial rise in coal prices was motivated partly by increased labour costs (accounting for up to 50% of production costs) and inflation and partly by the desire to reduce loss and government assistance. Coal's competitive advantage was further reduced by the greater ability of the oil industry to optimize its operation over a range of countries and limit price increases in particular markets in line with expected competition from coal. These various interactions are best illustrated by the developments in the FRG, a country in which world market changes are rather easily felt: in this country crude oil prices went up by 309% during 1970 to 1976, while the price of heavy fuel oil which competes with coal in the power generation market, went up by only 145%; the price of indigenous coal rose by 92 to 95% in the same period*. In general, the short-term price formation on the ECE energy market resulted in a smaller improvement of coal's competitive position than expected immediately after the fourfold increase in crude oil prices in 1973 to 1974.

No statements were made with regard to the long-term competitiveness of coal. Indeed, it appeared out of order to speculate about future price relationships. However, attempts seem justified and have indeed been made to evaluate the long-term relationships of production costs of coal relative to competing forms of energy, particularly nuclear power, oil, and natural gas. The assumption underlying such considerations is that in the long run the relative physical scarcities of the various forms of energy become the decisive factor for their extraction costs and hence total costs, and that these relationships could not be ignored continuously during price formation. Taking into account that the economically recoverable reserves are much bigger in the case of coal than in the case of oil, natural gas, and uranium, this school of thinking concludes that the production costs of coal will fall relative to those of oil, natural gas, and uranium. It would depend on the importance of production costs in total costs and of the relation between total costs and market prices when, and to what extent, coal becomes cheaper than its competitors.

An attempt to quantify this argument has been undertaken in a United Nations report entitled *The Future of the World Economy* prepared under the direction of Professor W. Leontief (ST/ESA/44, New York 1977). This study, the particularities of which have to be well understood to assess its conclusions correctly, relates the cost-based prices of coal, oil, and natural gas to the general price level of the economy and concludes that relative to this general price level, cost "prices" for coal will slightly fall, oil "prices" will increase approximately threefold, and natural gas "prices" will increase approximately sixfold between 1970 and the year 2000. It may be added that the cost relation between nuclear power and coal is also expected to develop in favour of coal. Thus, to the extent that physical scarcities affect earlier or later production costs, and that production costs affect earlier or later prices, the

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**Handelsblatt*, 21 December 1976.

acceleration of coal supplies will exercise a generally moderating influence on price increases for energy. This moderating influence will gain momentum in the 1980s, but its full impact will only be felt from the late 1980s onwards.

The Resource Base

However incomplete and uncertain our knowledge of the structure, location, volume, and properties of coal reserves* may be, all the regions and major coal-producing countries of the ECE area are endowed with huge reserves of economically recoverable coal. These reserves would last 230 years at the 1973 production level and 75 years at a production growing at the rates established after 1973/1974. Even at double these growth rates the reserves would prove sufficient to cover demand for 30 to 60 years in the major coal-producing countries of the ECE region.

One factor that will play a growing and limiting role already in the medium term is the growing distance between coal producing and consuming areas. It can be estimated that between 1973 and 1985, 76% of the net increase in coal production will be in "distant" coal basins.

The economically recoverable reserves of high energy coal, coking coal, and low sulphur coal (less than 1% sulphur content by weight) do not seem to constitute a limiting factor for coal supply growth. For the ECE as a whole, 70% of the economically recoverable reserves are above 5700 kcal/kg. Approximately 20% are said to be of coking quality. Hard coals with less than 1% sulphur content represent about 10% of the reserves in western Europe and 15% of the reserves in North America; low sulphur brown coal/lignite holds an even bigger share: more than 33% of the reserves in western Europe and more than 90% in North America are low sulphur.

But problems may arise in smaller countries or those having a less favourable geological spread. Out of the 22 ECE countries having coal reserves considered economically recoverable, only 16 possess high energy (hard) coal reserves and only 12 possess coal reserves of coking quality (the bulk of which--95%--is located in four countries: the FRG, Poland, the USA, and the USSR). As regards low sulphur coals, they seem to be lacking only in Yugoslavia, Portugal, and Norway.

An encouragingly high proportion of coal reserves is suitable for opencast mining: in western and eastern Europe 80% and more of the economically recoverable reserves of brown coal/lignite are suitable for opencast mining; in North America the

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*Sources used: World Energy Conference, *Survey of Energy Resources 1974*, New York, 1974, p. 50-60 and 307-321, as well as information directly supplied by governments.

percentage is lower, 30% or so. As concerns hard coal reserves, 24% in North America and 1% in western Europe are suitable for opencast mining; the western European ratio may also be representative for eastern Europe, except in the USSR where huge reserves of hard coal are suitable for opencast mining.

In conclusion and with due regard to the reservations made, economically recoverable coal reserves in the ECE area and its major subregions proved sufficient to sustain an accelerated growth of coal demand which could even go beyond the rate of increase currently envisaged in the ECE region.

Availability of Manpower and Labour Productivity

Owing to demographic and social factors, the coal industry will have to compete for new labour in a much tighter labour market. All other factors remaining equal, the growth of active population could sustain a rate of coal production of only 0.7% in the coal-producing countries of western Europe during 1970 to 1985, of 0.8% in eastern Europe, excluding the USSR, of 1.2% in the USSR and of 1.3% in North America. A higher coal production growth would require greater internal and external mobility, and/or a shift of occupational patterns in favour of coal.

Under European conditions, these prerequisites are not likely to be fulfilled: internal mobility is very limited; migration seems subject to increasingly restricted policy, even in boom periods; the recruitment of young labour (15 to 19 years) may pose in some countries problems due to demographic factors and an increased length of education. It is therefore not surprising that European governments generally expect no increase in employment in the coal industry. On the contrary, western European coal producers expect continued absolute decreases in the number of men employed and east European coal producers consider a stagnation more realistic than an expansion. Under North American conditions, the recruitment of new labour seems less critical. The projected growth of active population is higher than in Europe and the mobility of labour is traditionally high. The increase in the labour force in the US coal mines, corresponding to an expansion of coal production to around 940 mtce would be 36,000 men; problems could arise locally and temporarily if production were to double in comparison with the currently envisaged tonnage, in which case 177,000 men would have to be added to the labour force by 1985.

In view of the poor prospects for employment growth, most European coal-producing countries have to raise labour productivity to raise coal production. During 1960 to 1975, output per man-year underground increased at an average rate of 3.7% in western Europe, 3.3% in the USSR and 2.7% in eastern Europe, excluding the USSR. Since the early 1970s, productivity growth rates have become erratic and tended to slow down. The level of underground productivity reached in 1973 was fairly similar: 706 per man-year underground in western Europe, 674 in eastern

Europe, excluding the USSR, and 600 tons in the USSR. In the US, productivity trends were different from Europe. As a result of labour disputes and new safety and health regulations, productivity fell during 1967 to 1975 on the average by 4.9% annually. The level recorded in 1973 was still high in comparison with European standards: around 2600 t per man-year underground.

No evaluation of the results of productivity-raising measures were ventured, but it could be concluded from employment and production plans that during 1973 to 1985, the potential for annual productivity gains in underground mining would be around 3.5% in western Europe, 3.3% in eastern Europe, including the USSR and 3.1% in the United States, if production and employment grow at the expected rates.

Managerial and Technological Progress

Since the improvement of labour productivity will be largely the result of technical progress (and managerial improvements), the growth rates mentioned provide a rough indicator for the benefits expected to be derived from the numerous measures currently envisaged by industry and supported by governments. These include:

- a switch to opencast, in situ gasification, hydraulic and chemical mining;
- a refinement of existing technologies through complex mechanization, automation and remote control;
- the adaptation of mining management and operations, in particular the concentration of workings, and the combination of operations, for example in "coalplexes";
- the greater efficiency of coal extraction through the exploitation of thin seams, inclined seams, seams beyond 2 m thickness, safety pillars, and through the replacement of room-and-pillar working by short- and longwall mining;
- the orientation of R and D towards new mining methods such as in situ gasification, solvent extraction, continuous haulage, greater attention paid to mining at greater depth or off shore, application of new technologies to mining such as interface sensing devices.

The potential of these measures will not be fully tapped by 1985, which therefore provide for further productivity gains in the long term.

Capital Needs and Resources

Coal mining and preparation are capital-intensive activities, and investments per ton of output grow under the impact of deteriorating geological conditions, substitution of capital for labour, growing sophistication of equipment, higher degree of mechanization and automation, and escalating construction costs. The capital necessary for supporting the anticipated growth of coal production between 1973 and 1985 has been estimated at around 20×10^9 US$ of 1975 value for North America and 13×10^9 units of account for the European Community.* No figures are available for eastern Europe and the USSR, but they have been estimated at nearly 17×10^9 US$ [2]. This would bring the total in ECE capital needs for coal expansion up to 50×10^9 US$ or 71 $ per ton of new capacity.

These impressive absolute figures appear less in relative terms: investments in coal production and preparation during 1975 to 1985 would amount to only 0.1% of total energy investments in Canada, 3% in the USA and 5% in the European Community, compared with 19% for oil and 28% for nuclear power [2].* Some countries, particularly the USA, Canada, Poland, Romania, and the USSR have the possibility of reducing the financial burden by increasing the share of coal production from opencast mining, for which investments per ton may be only half those for underground mining. This ratio is derived from a comparison of two model mines in the USA, a deep mine with an annual production of 10^6 s. tons from a 1.83 m thick seam at a depth of approximately 215 m, and a strip mine with an annual production of 10^6 s. tons, from a 1.83 m thick seam and a 10:1 overburden ratio.*

The fact that coal requires less capital per ton produced than any other fossil form of energy within the ECE region, renders financing problems less stringent. Accordingly, no major concerns have been expressed by those governments who addressed this issue, although the extraordinary capital needs of the energy economy as a whole, including transport and conversion of coal, may have a side effect on the coal industry's capability of attracting the necessary capital. In countries with capital markets, the share of funds supplied by public authorities may therefore tend to rise. However, such an increase would not seem to reflect a shortage of capital, but the desire, on the part of governments, to control any rise of the

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*For the USA, Federal Energy Administration, *National Energy Outlook*, p. 306 (17.7×10^9 US$ at 1975 value); for Canada: Ministry of Energy, Mines and Resources, *An Energy Strategy for Canada - Policies for Self Reliance - Summary*; Ottawa, 1976, P. 18 (2.3×10^9 Canadian $ at 1975 value); for the European Community: see [2].

price of coal or of the influx of foreign ownership. This being stated, it is also obvious that investment funds are not plentiful and that priorities have been established in favour of investments serving domestic needs. A rise of coal production in response to foreign demand would increasingly require a financial commitment on the part of the importer.

Environmental Constraints

The activities of the coal industry, in spite of considerable progress in the control of subsidence, noise, and dust can still pose important environmental problems, particularly through the release of heat, carbon monoxide and dioxide, nitrogen oxide, and sulphur dioxide from coal-fired power stations, the release of toxic effluents from coking plants and mines, and the destruction of the flora and fauna of opencast mining.

The means at the disposal of the coal industry to reduce the environmental consequences of its activities are generally considered compatible with the needs [3]. They comprise new technology (fluidized bed combustion and desulphurization, hydrogenation, in situ gasification, improved preparation techniques, recultivation) and operational changes (preferential production of low sulphur coals, use of waste heat for district heating, etc). Constraints may appear locally as the result of specifically stringent air/water/reclamation standards, or temporarily as a result of the time needed to adapt to production and conversion techniques. More serious problems may appear in arid areas if coal slurry pipelines are envisaged for the long-distance transport of coal, and in the long term, if the combustion of coal (as the combustion of any other fossil fuel) prejudices the carbon dioxide balance of the globe.

The proportionate increase in coal production costs can be substantial, depending on local conditions, the characteristic of the deposit, the properties of the coal and the technologies applied [4]. For example, the recultivation of excavated areas in the UK has been estimated to account for 4% of production costs, and for up to 8% of production costs in the USA depending mainly on seam thickness. The cost of environmental control in coal gasification and liquefaction is estimated at about 10 to 20% of total gasification/liquefaction costs. The reduction of the sulphur content of high-sulphur coals for deep mines, by 40 to 60% is estimated to cost around 5 to 6% of total production costs of high-cost western European coal and around 15% of total production costs of comparatively cheaper US deep-mined coal. Flue gas desulphurization with efficiencies of up to 90 per cent are estimated to cost about 15 to 20% of production costs in western Europe and up to 50% of production costs for high-sulphur US coal [5].

These impressive figures should not obscure the fact that the economically recoverable reserves of low sulphur coal constitute a notable share of the coal resources of the ECE region and that accordingly the financial burden of environmental protection on the coal industry as a whole is much lower; for the FRG environmental protection required 1.5 to 1.8% of total production costs and 2.2% of total investment costs of the hard coal industry in 1974, shares that will increase to 3.1 to 4.3% and 1.6 to 3.2% during 1975 to 1979 [6]. Thus, it may be concluded that generally environmental considerations are not a limiting factor to coal expansion--physically, technically, or financially.

Institutional Factors, Lead Times, and Other Factors

In their reports governments have made no allusions to possible constraints resulting from the organization of the coal mining industry in their respective countries. This may be interpreted as meaning that generally no major problems are expected to result from institutional factors. However, the expansion of the industry is not insensitive to ownership patterns and organizational structures: large new mines that could draw maximum benefit from economies of scale, are not likely to be opened if reserves are owned and exploited by a great number of companies, or if coal mining companies are integrated into other industries such as electric utilities or steelworks.

A major limiting factor is the lead time required to increase capacity. The short-term flexibility of production under normal economic and operational conditions is limited to a few percentage points. The opening of new mines requires at best four to seven years, and the planning and building of coal-fired power stations five years, but longer lead times must be anticipated for high-capacity installations, openings in remote or densely populated areas or if difficult geological and climatic conditions prevail.

There are further determinants of future coal production that need at least to be mentioned: land-leading policies; the ability of manufacturers to supply the required underground and surface mining equipment, preparation and conversion technologies and transport equipment; an appropriate expansion of rail and water transportation fleets, including ocean transport; the standardization of equipment; the facilitation of international trade, particularly harmonization of regulations applicable to equipment use. None of these factors has been singled out as limiting the expansion of coal production, but it is also evident that an active intergovernmental cooperation with regard to the last-mentioned areas could have only a beneficial effect on expansion programs.

ANTICIPATED CHANGES OF DEMAND/SUPPLY TRENDS AND PATTERNS

In the preceding chapter, the major factors determining coal demand and supply in the ECE in the medium term have been assessed. What will be their combined effect on coal consumption, production, and trade?

Overall Growth Rate of Coal Demand in the ECE as a Whole

According to government plans and programs, coal demand will rise from 1738 mtce in 1973 to 2370-2410 mtce in 1985 in the ECE region as a whole, i.e. 38% or 630-670 mtce more than in 1973. The average annual growth rate of coal demand during the twelve-year period 1973-1985, is 2.7%, compared with 0.9% during the preceding twelve-year period 1961-1973. Thus, coal demand growth is expected to increase threefold. The expected long-term growth rate of 2.7% has never been achieved in the ECE region since 1950; the maximum hitherto achieved was 1.5% (during 1954 to 1966).

Regional Growth Rate of Coal Demand

All coal-consuming regions of the ECE area will increase coal demand and will accelerate demand growth. Western Europe, which presently shows a continued high reliance on imports of oil will reverse the decline in coal consumption. A substantial acceleration is anticipated in the USA (which under "business as usual" conditions would rely on foreign oil to an extent of 23% of its total energy demand in 1985). An acceleration of the ECE region which reflects the expectation that the present comfortable position of this group of countries with regard to hydrocarbons might fade away as a result of the continued high rate of economic growth and growing costs and difficulties of tapping new reserves.

Change of Sectoral Supply Patterns

Changes in the pattern of supply are in line with past experience: a relatively and absolutely considerable increase in the coal supply will take place in the power station sector; the amount required by the iron and steel and coking industries will continue to grow in absolute terms, but its share in the total coal supply remains practically unchanged; small absolute but important relative losses will affect the remainder of the market mainly accounted for by households, small consumers and in the USA by coal gasification and liquefaction plants. The trend towards concentrating the coal supply in two consuming sectors continues: 84% of all supplies in 1985 will be earmarked for use by the electric power and iron and steel industries, compared with 77% in 1973 and 57% in 1967.

Supply Strategies

The coal supply strategies chosen by the three major ECE regions are quite different. One might have expected that an increase in production would be the most important avenue for meeting increased demand. This is true for the ECE region as a whole where the increasing coal production (660-690 mtce) will be bigger than the increase in coal demand (630-670 mtce). This will be true also for North America and eastern Europe where production growth will cover all the internal coal demand increase as well as new foreign requirements. But for western Europe, the most important parameter for procuring the required new coal supplies of about 40 to 45 mtce, will not be production, but imports which increase by 36 to 41 Mt. These different supply strategies are important indicators of the medium-term competitiveness of coal in western Europe, eastern Europe and North America, the first ranging at the lower end, the latter at the higher end.

Overall Growth Rate of Coal Production in the ECE as a Whole

In 1985 production of hard coal and brown coal in the ECE region will be higher by about 40% than in 1973 and reach 2405 to 2440 mtce. The net increase in coal production is about 660 to 690 mtce. The annual growth rate of coal production during the twelve-year period 1973 to 1985 is 2.8% and compares with 0.8% in the preceding twelve years. Thus, coal production growth is expected to accelerate three to four times. The anticipated medium-term growth rate of 2.8% has never been achieved in the ECE region after the Second World War.

Production Growth by Type of Coal

In the ECE region as a whole, production of hard coal and brown coal (on an energy content basis) will grow at practically the same rate of 38%. This balanced growth pattern is due to the extraordinary development of hard coal production in the eastern parts of the USSR and to the steep increase in brown coal/lignite mining in southern Europe, the Balkans and North America. Production of hard coal will grow by about 550 Mt and production of brown coal/lignite by 125 mtce or 260 Mt in the ECE region as a whole. The share of brown coal/lignite will remain at 19%. Eastern Europe will remain the most important producer of brown coal/lignite (1973: 79% of ECE total; 1985: 65%), but brown coal/lignite mining is expected to undergo a fast absolute and relative growth in North America (1973: 2% of ECE total; 1985: 17%).

Production Growth by Mining Techniques

The share of opencast mined coal in total production will grow from 37% in 1973 to 48% in 1985, i.e. almost half of the 1985 production will be by surface mining. Out of the new coal production of about 660 to 690 mtce, 75% will be by opencast mining--an extraordinary challence to equipment manufactures. All ECE regions will expand surface mining. In southern Europe, almost all the increases in coal production will come from such mines.

Regional Production Growth

All ECE regions anticipate a growth of coal production. In all regions the growth rate lies above that suggested before the oil crisis. But the rate anticipated for the various ECE regions is quite different:

> +0.01% for western Europe for 1973 to 1985 compared with -3.1% for 1961 to 1973;
>
> +2.4% for eastern Europe, including the USSR, compared with 2%;
>
> +4.5% for North America, compared with 3%.

Overall Growth of Exports from, Imports to, and Intraregional Trade within the ECE

By 1985, coal imports by ECE countries and coal exports from ECE countries will grow by between 40 and 56 mtce. The region will remain a net exporter of coal of between 20 and 45 Mt. North America will increase net exports by between 30 and 40 Mt, and eastern Europe by between 5 and 15 Mt, whilst western Europe will increase net imports by 45 to 50 Mt. Intra-ECE coal trade will certainly grow substantially, but figures supplied do not allow one to quantify the increase.

Coal's Role in the Energy Balance of the ECE

In 1973, the share of coal in total primary energy supplies of the ECE region was 28%. Without a change in coal policies, the share of coal would have fallen to 18% in 1985, in western Europe even to 10%.

However, governments have changed their policies as a result of which coal will play a greater role than anticipated before the oil crisis. The extent of coal's additional contribution depends not only on the tonnage of coal produced and supplied, but also on the future rate of growth of energy demand: if energy demand continues to grow at the 1961 to 1973 rate, which was 4.9% for the ECE region as a whole, coal's share in the total ECE balance in 1985 would be 22%. If energy demand grows at a reduced rate resulting from a slowdown of economic growth and greater energy economy and efficiency, the share of coal in 1985 would be 26% in 1985 compared with 28% in 1973. Only in North America would coal's future share be higher than the present one.

Thus, the new coal demand policies as they took shape after 1973/1974, substantially contribute to the diversification of energy supplies in all ECE regions if compared with pre-crisis policies. However, they are not sufficiently vigorous to maintain the level of diversification that actually existed in 1973 in western and eastern Europe. Maintaining the 1973 level of

28% would either require a further acceleration of coal demand or a further slowdown of energy demand or a combination of both. Unless such a further review of coal policies take place, oil supplies, particularly, would have to be increased, not only in absolute terms, but would also have to take over market shares from coal in western and eastern Europe.

Coal's Role in the Electric Power Market

As a result of the new coal policies, supplies of coal to power stations will increase between 1973 and 1985 in western Europe by 55 mtce, in eastern Europe by 215 to 240 mtce, in North America by 286 mtce, and in the ECE region by 556 to 581 mtce. This increase is not sufficient to maintain the share of coal as an input for power generation: the growth rates of coal supplies to power stations however big and impressive they may be from the point of view of the coal industry, lie below the growth rate of electricity demand in eastern Europe, western Europe and the ECE region as a whole; only in North America might the share of coal, as an input for power generation, increase and hence contribute to the diversification of the supply base. Thus the concentration of coal supplies to power stations does not provide a potential for substitution for oil, nuclear power, natural gas, or other energy supplies in Europe, and provides only a marginal improvement in the USA.

CONSEQUENCES FOR LONG-TERM POLICIES

The conclusion that emerges from the above analysis that the new coal policies enhance coal's role relative to pre-crisis plans but not in comparison with the 1973 situation, raises the question whether the constraints on coal expansion mentioned could not be overcome in the long term. Apart from pointing to the potential of coal gasification/liquefaction, governments have not addressed this issue. But others suggested that the scarcity of hydrocarbons relative to coal will inevitably, particularly after 1985, improve coal's competitiveness. Also new technologies and management techniques seem to carry promise of relieving constraints on labour productivity, without requiring too big a contribution from the capital markets. It would seem to be the essential role of international cooperation to assess the potential of new opportunities and to shorten lead times, through exchange of experience, joint R and D, trade promotion, standardization, investment sharing, joint infrastructure projects such as long-distance transmission lines, coal slurry pipelines, coal loading/unloading facilities, unit trains, etc. The prospects for successful cooperation are bright: the similarity of problems and approaches is striking. Whilst coal policies had been in the past an example of variety and even divergence, they have appeared after 1973/1974 as an example of similarity and convergence.

Table 1. Solid fuel balances in the ECE region 1973 and 1985.

	WESTERN EUROPE[b)]					EASTERN EUROPE[c)]					NORTH AMERICA					ECE TOTAL				
	mtce		pattern		annual growth 1973-1985 %	mtce		pattern		annual growth 1973-1985 %	mtce		pattern		annual growth 1973-1985 %	mtce		pattern		annual growth 1973-1985 %
	1973	1985	1973	1985		1973	1985*	1973	1985		1973	1985	1973	1985		1973	1985	1973	1985	
I. BALANCES[a)]																				
1. Production	346	350	87	79	±0	850	1115-1150	104	104	+2.4	552	940	105	109	+4.5	1748	2405-2440	101	101	+2.8
+2. Imports	79	110-120	13	21	+3.4	43	48-54	-4	-4	+1.4	16	15*-20*	-5	-9	+0.7	138	178-194	-1	-1	+2.5
-3. Exports	34	25			-2.5	77	93-98			+1.8	61	95*-100*			+4.0	172	213-223			+2.0
-4. Additions to stocks (+ = withdrawals)	8	...			...	-1	...			...	17	...			...	24	...			...
=5. Total inland deliveries of which to	400	440-445	100	100	+0.9	815	1070-1105	100	100	+2.4	524	860*	100	100	+4.2	1738	2370-2410	100	100	+2.7
(a) power stations	195	250	48	56	+2.1	450*	665-690	55	62	+3.5	369	655	70	76	+4.9	1014	1570-1595	58	66	+3.8
(b) iron and steel works coke ovens	110	115	28	26	+0.4	115*	180-190	14	17	+4.0	98	120	18	14	+1.7	323	415-425	19	18	+2.2
(c) others	95	75-80	24	18	-1.7	250*	225	31	21	-1.0	57	85	12	10	+3.4	402	385-390	23	16	-0.2
II. INDICATORS																				
1. Share of coal in energy supplies			26	20				46	36				19	22				28	26	
2. Share of hard coal production			81	78				69	74				99	93				81	81	
3. Share of underground prod.			82	69				62	59				51	38				63	52	
4. Share of regional coal prod. in total ECE coal prod.			20	15				49	47				32	39				100	100	

a) Hard coal, brown coal, lignite converted into tons of coal equivalent according to UN Statistical Series J "World Energy Supplies"

b) Incl. Turkey.

c) Incl. USSR.

* = Secretariat estimates.

... = Not available.

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PROSPECTS FOR COAL

P. Kelly

It is a great pleasure for me to be here today. I am very honoured to have been invited to take part in this Conference and, most particularly, to have this opportunity to re-examine the role of coal resources in the light of our work at the International Energy Agency. It has become increasingly apparent to us that, if we are to make a successful transition from present oil-based economies, coal must be utilized more extensively as an energy resource in the medium term.

Though estimates of economically exploitable reserves vary widely, one fact stands out clearly: coal is our most abundant fossil fuel and there is no doubt that coal resources are available to meet the energy requirements of the world for several hundred years. The World Energy Conference put total reserves at over 10×10^{12} tce, economically recoverable reserves at 640×10^{9} tce and 1976 world production was about 2.7×10^{9} tce.

Until around 1920, coal covered almost the total world energy demand but today it accounts for only about 32 per cent of total primary energy. By the early 1950s, oil and natural gas had competitively outstripped coal as primary energy sources and this trend has continued. The statistical picture is clear: world energy demand grew by around 6-7 per cent per year between 1950 and 1975 while coal production increased by only 2.2 per cent during the same period.

The reasons for this shift in demand patterns are manifold:

- Oil *was* cheaper. Production costs, investment requirements for the development of production capacity and transport costs were lower.

- The flow of oil is comparable to the flow of a fully convertible currency; oil was available wherever it found its market. For the consumer this meant a high flexibility with regard to the choice of supply sources, which is not the case with regard to coal.

- Oil is easier, cleaner, and cheaper to handle without large space requirements for stocks and without large manpower requirements for handling.

- The use of oil means a lesser burden on the environment in both production and consumption. This advantage enabled industries to move into densely populated areas close to the necessary work-force.

- Compared with coal, oil production, transportation and processing are much less labour intensive. Thus oil does not create, in times of economic recessions or temporary decreases in demand, insoluble problems of far above average unemployment in specific regions.

Obviously oil offers a number of important advantages over coal as an energy resource and these factors have not altered during the past quarter century. Nevertheless, price factors and the perception today of the all-too-finite limits of oil supplies make it clear that coal can no longer be considered a fuel of the past but very much a fuel of the future.

Before examining future prospects for coal resources, I think it will be instructive to examine the present energy market situation.

Over the long term, oil will no longer be available in sufficient quantities to meet the world energy demand. It is idle to speculate or to question whether oil reserves will last for the next 30 or 50 years--the fact is that the oil resources of the world will be depleted in the foreseeable future and that we have to look for substitutes. The more time we have for this transition the easier and less costly it will be.

The inevitable depletion of world oil resources has a great impact on the present situation as far as the development of costs for marginal oil supplies is concerned. The average size of newly discovered reservoirs is decreasing and exploration has to be carried out in more and more physically difficult environments such as the North-Slope, the North Sea, and Alaska. The production of Alaskan oil, for example, costs 50 to 60 times more than oil produced in Saudi Arabia and the investment requirements for 1 bbl/day capacity in Alaska are 15 times higher than in the Middle East. It is easy to see, therefore, that economic considerations will force us, long before the definite depletion of the world oil resources, to search for cheaper types of energy as substitutes for increasingly expensive oil. The growing transference of wealth from oil consuming to oil producing countries initiated by abrupt price increases on the world oil market since 1973 will speed up this process in the oil consuming countries.

The increasing geographical, technical, and financial difficulties of finding and developing new oil fields and the associated transport systems have led to prolonged lead times and reduced or less successful exploration activity so that, since the end of the sixties, oil demand is growing at a quicker rate than discovered and developed reserves. Thus, despite present adequate world oil reserves, we might well run into an oil shortage simply because these reserves cannot be developed and made available to consumers in time. Indeed, if present trends continue, this situation might very well be upon us within the next decade. The World Energy Outlook published by the Organisation for Economic Co-operation and Development (OECD) in early 1977 forecasts that world demand for OPEC oil in 1985 will be about 40×10^6 bbl/day, whereas the production capacity of OPEC would be around 45×10^6 bbl/day. These figures as they stand may not seem too alarming but two aspects should be considered.

The demand forecast of 40×10^6 bbl/day is very optimistic. It is based on the assumption that developing countries will not increase their OPEC oil imports but develop their own energy resources to meet their increasing energy needs. This would require a huge effort and it seems more realistic to assume that in total the OPEC oil imports of developing countries will increase by $2\text{-}4 \times 10^6$ bbl/day by 1985. Another assumption of the OECD forecast has already been rendered obsolete by more recent studies. The forecast is based on a nuclear contribution (in OECD countries) of 464 mtoe in 1985. Realistically, we should expect something like 100-150 mtoe less than that figure which would increase demand for OPEC oil by another $2\text{-}3 \times 10^6$ bbl/day. In other words, there is a real risk that demand for OPEC oil might actually increase to $44\text{-}47 \times 10^6$ bbl/day and exceed the physical production capacity of OPEC.

Furthermore, there are uncertainties as to whether the oil exporting countries have the technical ability to use their production capacities fully and as to whether it is in their national political and economic interests to make full use of this potential. The forecast assumes, for example, a production potential of 15×10^6 bbl/day for Saudi Arabia, the full use of which would result in a per capita income, at today's oil prices, of about US$ 25 daily or US$ 9000 per year for 8 million Saudis. It is obvious that such an inflow of money raises very serious questions for the country.

To sum up, let me stress that we must recognize that we have to shift long-term energy demand away from oil since resources are being depleted and costs of marginal production are already increasing rapidly. The problems we face in the medium term, however, are even more serious. Demand for oil by the middle of the next decade might very well have already overtaken production capacity not because world oil resources are depleted but because we have failed to develop them in time.

What then, are our options for coping with the energy problem?

First of all we must learn to regard conservation as an energy resource in its own right. To strike a balance between energy demand and supply we must make meaningful efforts to cut waste. Measures which might be implemented now, such as pricing energy at world market levels, improved automotive and other transportation efficiency standards, monitoring of industry conservation, as well as building insulation standards and construction codes, provide substantial scope for increased energy savings. For the OECD countries we estimate the maximum conservation potential to be about 4×10^6 bbl/day in 1985. Other measures of a more structural nature in the transportation, industry and residential/commercial sectors will take more time and effort but could enhance even further the long-term prospects for achieving high energy savings.

We must take steps to accelerate development of oil and gas resources. The potential for this accelerated development in OECD countries is estimated at 4.5 mtoe by 1985. A note of caution is necessary here to stress that while such action will contribute to the solution of our medium term problems, it will obviously not facilitate the transition from oil to other fuels.

A related resource is liquefied natural gas. World gas resources are quite considerable but sources usually are located far away from consumer markets. Some gas can be transported by pipeline but in most cases liquefaction and transport by ship will be necessary. This requires highly capital intensive infrastructures such as liquefaction plants, ships, re-gasification plants and special pipelines and, because of long lead times on such construction, we cannot expect to have infrastructure in place by 1985 that has not already entered the planning stage.

Another option open to us is the development of non-conventional energy sources. Such non-conventional sources as solar energy, oil shale and tar sands, geothermal energy, wind energy, wave energy, and biomass conversion will not very likely contribute significantly to energy production in the next decades but might, nevertheless, be of some significance towards the end of this century. Even then, we should not expect them to be a main source of energy.

Finally, we come to nuclear power which could play a substantial part in the future. At the present time, however, development in this sector is lagging badly. Some 20 years after the first large nuclear plant came on stream, the Western industrialized countries are still discussing whether nuclear power is really needed and whether the risks of nuclear power are acceptable. In point of fact, nuclear power development efforts have in the past concentrated on reactor safety with less attention being paid to the question of handling and disposal of spent fuels and radioactive waste. On the other hand, there has been no co-ordinated public information policy on the part of governments and utilities with the result that the public is now shocked by the prospect of a world that will soon have not tens, but hundreds of nuclear power plants. A third issue in this context is the question of secure supplies of nuclear fuel which has become clouded by problems concerning reprocessing and non-proliferation.

Given the present state of nuclear power development and considering the long lead times for the construction of nuclear power plants, we cannot expect that nuclear power will substantially increase its contribution to the total energy supply by 1985. We can only concentrate our efforts to ensure that present nuclear programs are implemented without further delay.

Broadly speaking, these are all the key options we have available to cope with the energy problem. Still I am convinced that these alternatives are not sufficient--the main contribution, in the medium term at least, must be made by the increased utilization of coal.

Many discussions of energy policy implicitly convey the impression that coal is a fuel of the past. On the contrary, the need to expand production of energy sources other than oil combined with the enormous resource base of world coal reserves indicate that a new and enhanced role can and should be developed for coal. Coal resources can be counted in centuries rather than in decades. Nevertheless, at the present time, coal is far less flexible as a fuel and cannot readily be used to "balance" shortfalls of energy in other sectors. Indeed, demand essentially limits coal supply so that future changes in supply are dependent on long-term measures affecting demand.

Electric power generation and the iron and steel industry together account for three quarters of coal consumption in the member countries of the International Energy Agency, and prospects for a substantial increase of coal consumption in other sectors are limited. There is the possibility, however, that successful technological advances in the fluidized bed combustion process could stimulate industrial demand.

Expansion of coal production on a substantial scale is intimately linked to the growth of electricity demand and electric power generation facilities. The basic thrust of a new coal policy should be to ensure that as much as possible of new electrical generating capacity be provided by coal-fired plants. In addition, policy measures should aim to encourage wherever possible substitution of coal for heavy fuel oil in existing electric power facilities. Much of the increase in oil consumption forecast over the next decade is due to the commissioning of oil-fired power stations ordered before 1973/1974. It is difficult to change the picture for 1980 due to the long lead times required for construction in the electricity industry in general and, unless major decisions are made soon involving a large scale reorientation of policy over the long term, the scope for changing the 1985 outlook will diminish as well.

The range of uncertainties concerning electricity demand and possible alternative fuels for generating electricity are substantial. Given some of the limitations facing the development of nuclear and hydro power, unforeseen increases in the growth of electricity demand will have to be met by conventional thermal power stations. An underestimate of the growth rate of electricity demand could be dangerous in that it would very likely stimulate a further increase in oil imports, since unexpected demand could only be met by oil.

In order to reduce the uncertainty faced by electrical utility planners and, at the same time, enhance the role of coal, clear-cut concerted policy measures should be taken by all industrialized countries. These may prove in the short run to be inconvenient for electrical utility managers, who find that oil may be easier to handle and to use. They may also prove unwelcome to some oil companies who seek ready markets for the heavy fraction of the barrel rather than change refinery industry structures so as to produce a greater proportion of lighter distillates. But in the long run it will be more secure and economical to embark on these structural changes in order to enhance the contribution of coal and reduce dependence on oil imports. It has been estimated that, by 1985, such measures could reduce the use of oil and gas in power stations in countries by about 3×10^6 bbl/day which would be equivalent to 200 Mt of coal a year.

Side by side with these efforts to meet electricity demand for increased coal production, policy measures will also be necessary to create secure long-term conditions for an expanded world coal trade. The potential is immense but a substantial increase in trade will require favourable conditions for both producers and consumers. Currently, the landed price of imported coal in western Europe is competitive with that of oil even when the additional costs of burning coal are considered. It may be, however, that under long-term contractual arrangements coal consumers in western Europe and Japan could obtain more favourable prices. If a large trade in steam coal is to be developed, the construction of unloading facilities might raise difficulties in certain cases. Support and co-ordination between national administrations for installations designed to serve a wide region might be required.

A stronger policy in favour of coal utilization would also remove uncertainties facing coal producers. Greater confidence thus created in the long-term prospects of the coal industry would also work to reduce such constraints as shortage of equipment in some countries and shortage of skilled manpower in others. Many hesitations and doubts concerning environmental constraints would be eliminated if the industrialized countries were to take joint action to harmonize environmental regulations affecting coal; such hesitations and doubts in one country are liable to affect coal prospects in another. International cooperation can enable us to press on with the speedy development of these technologies as well as the use of coal feedstocks for the chemical industry.

What do these recommendations for a stronger coal policy mean for coal producers? An internationally agreed strategy to encourage greater coal utilization can help to resolve individual national policy issues by removing uncertainties and laying a solid basis for large scale coal development. This would benefit producer countries such as the USSR, Poland, the USA, and Canada by opening expanded and secure markets in Japan and western Europe. Internationally agreed support measures would safeguard existing investments in the coal industry and stimulate increased capital investment. Consuming countries would benefit through availability of secure energy supplies.

The case for a strong coal policy which should form an integral contribution to greater international cooperation on energy rests not only on energy grounds but also on the broader economic and political well-being of the world.

I should now like to turn to the specific actions that could be taken by my own organization, the International Energy Agency (IEA).

Firstly, IEA countries have already recognized that an enhanced role for coal must play a prime role in the task of reducing dependence on excessive oil imports. As part of its long-term cooperation program the IEA has established a minimum safeguard price below which imported oil will not be sold in their domestic economies. This will have the effect of guaranteeing against the so-called downside risk and is designed to provide long-term security for investments in alternative sources of energy including coal.

In the energy R & D area, five implementing agreements relating to coal have already been concluded among certain IEA countries. These provide for cooperative activities in some key areas of coal development:

- A coal technical information service to collect and disseminate scientific and technical data on coal research and development;
- An economic assessment service for coal to assist in the formulation of new research projects and the evaluation of existing technologies;
- A world coal resources and reserves data bank service;
- A mining technology clearing house service to collect and disseminate information on research on deep and surface coal mining;
- A project on the fluidized combustion of coal to design, construct, and operate an experimental fluidized bed combustion rig.

But much important work remains to be done.

The IEA is but an instrument to be used to implement the political commitments jointly undertaken by the participating countries. Although I cannot claim to be an unbiased observer, I think it can be justly claimed that the IEA, which was born out of the chaos of the oil crisis, has registered an impressive record of concrete international energy cooperation measures. The IEA is currently engaged in a major exercise designed to elaborate in detail collective and individual objectives to reduce dependence on oil. Stimulation of member countries to more intensive use of coal in electricity generation will be an important component of this effort.

I would put forward the following list of measures for implementation by IEA member countries:

- A commitment to develop the use of coal for electricity production under appropriate economic conditions. This would oblige countries with coal resources to encourage production, use, and export of coal. Other countries would be obliged to import and use more coal to meet their electrical generation needs.

- A commitment to curtail or eliminate the construction of new oil-fired power stations once stations now ordered have been completed. It would be made clear to utilities that a shortfall in nuclear generation capacity in the mid 1980s would not be covered by new oil- or gas-fired stations.

- A recognition of the need to remove uncertainty caused by different national regulations affecting the mining and the use of coal. This would involve a possible exchange of experience on relevant regulations with a view to establishing a common code or set of guidelines to ease the acceptance of coal.

- An agreement to accelerate the development of technologies capable of easing the environmental problem of coal production and use. Land reclamation techniques, for instance, and improving scrubbers in respect to their effectiveness, reliability, and cost.

- Creation of a climate of confidence between sellers and buyers in the government bodies charged with responsibility for international coal trade. This would mean easing import and export restrictions with due regard to the need to safeguard indigenous coal production.

- A commitment to foster the growth of coal trade through negotiation of long-term contracts; purchasers' financial participation in coal mining, including "joint ventures"; "joint venture" participation in coal transport; and equipping ports for exporting and importing coal.

- A regular assessment by governments of coal trade prospects including expected availability of coal for export, of infrastructure problems relating to transport, etc.

- Incentives for using more coal in power plants and for building coal-fired stations in appropriate sites by means of fiscal measures or financial support. Some incentives could not only cover the construction of new coal-fired power plants but also in certain cases additional costs of burning more coal in existing plants, modernization and adaptation of plants for coal burning.

- Assistance to developing countries to develop their coal resources, transport infrastructures and use of coal. This would lessen developing countries' dependence on imported oil and contribute to a viable coal trade infrastructure.

- Support for further R & D efforts into fluidized bed combustion, coal mining techniques and transport, and coal conversion techniques--gasification and liquefaction.

Finally, each country should be encouraged to develop targets for reduced oil consumption in the electricity sector by 1985 and corresponding targets for coal consumption.

The energy challenge facing the world today is no easy task. I have attempted to illustrate the kind of actions that could enhance the contribution of coal resources. I have deliberately placed these actions in an international context for I believe firmly that it is only in such a context that stronger energy policies can be ultimately successful. The consequences of not working cooperatively will in the end prove to be self-defeating for all countries, energy-rich or not. On the other hand, parallel cooperative efforts can reinforce domestic energy aims all round and bring wider benefits in the form of enhanced economic and political relationships.

APPENDIX. INTERNATIONAL ENERGY AGENCY RESEARCH AND DEVELOPMENT PROJECTS RELATED TO COAL (AS OF 1 SEPTEMBER 1977)

Background

A number of IEA countries have the potential to significantly increase the proportion of energy supplied from coal resources. The principal medium- and long-term opportunities for expanded coal use are in electricity and heat generation, and in producing gaseous and liquid fuel substitutes. Existing technologies for coal mining, combustion, gasification, and liquefaction involve economic and environmental uncertainties. Consequently, coal-producing countries have embarked on large R & D programs directed at the development of technologies that will improve techniques for direct combustion of coal and for converting it to easily transportable liquids or gases.

To date, five IEA "Implementing Agreements" on cooperative R & D projects on coal have been signed, all of which are operated on behalf of the participants by a subsidiary company of the UK National Coal Board. Other cooperative IEA projects are now being considered in the fields of gasification and liquefaction.

Data Bank of World Coal Reserves and Resources

The objective of this project is to build a comprehensive computerized data analysis and retrieval facility that will generate assessments of world coal resources and reserves, with the capability for continuous updating and revision. In particular, analytical assessments will be made of coal reserves and their sequential exploitation that take into account new data, changing economic factors, and new techniques.

Mining Technology Clearing House Service

The basic aim of the Mining Technology Clearing House Service is to collect, collate, and disseminate information on research and development in all aspects of coal mining (both surface and underground) and coal preparation technologies, including the improvement of operational efficiency and safety, and health; research into the physics and chemistry of coal; and demonstration of new methods and equipment. As it develops, the Service will cover all relevant R & D and will arrange contacts between experts in particular disciplines, and assist in the formulation of new cooperative projects.

Coal Technical Information Service

The purpose of this international service will be the selective dissemination of information relating to all aspects of coal technology that can assist in promoting greater utilization of coal in meeting future energy needs.

The Service will first survey and report on existing coal science and technology information services, and on the basis of this survey, will then establish any new facilities or services required for a central storage and retrieval system, and an active register of all ongoing research in coal science and technology. The Service aims to deal with enquiries ranging from simple specific questions to comprehensive briefs.

Economic Assessment Service for Coal

The Service will assist the participating countries' coal industries by making studies on the economics of coal production and utilization, and with the identification of new research areas. These studies will be specifically related to the economics of coal-based energy, to forecasting world coal production and use, and to differing standards for coal utilization plant and the associated plant costs. The economics of pollution control, coal transportation, and conversion of coal to other products will also be examined.

Fluidized Bed Combustion of Coal

Fluidized bed combustion of coal is a technique whereby finely crushed particles of limestone mixed with coal have air blown through them so that the mixture behaves like a turbulent fluid. During combustion the limestone chemically captures the sulphur in the coal, and because combustion temperatures are lower than in current techniques, nitrogen oxide emissions are also lower. There is also better contact between the burning fuel and boiler tubes, improving heat transfer and, thus, efficiency. A fluidized bed boiler is also capable of burning various grades of coal and other combustibles.

Fluidized bed combustion, if successfully developed, thus offers several advantages over conventional coal combustion techniques, namely, a reduction in the size of installation; an efficient method of reducing atmospheric pollution; and the ability to use a wider range of fuels.

There are two basic classes of fluidized bed combustion systems; one operates at atmospheric pressure and the other at high pressure (8-12 atm) which allows further reductions in size as well as the possibility of dual cycle energy generation with both gas and steam turbines. The IEA project now underway provides for the design, construction, and operation, beginning in 1979 at Grimethorpe in Yorkshire, UK, of a flexible experimental facility for investigating combustion, heat transfer, gas cleanup, corrosion and energy recovery in the pressurized class of system. The design also includes provision for the later addition of a gas turbine. Results from this experiment will be used in the design of commercial-scale plants.

OPTIMIZING THE USE OF COAL RESOURCES

W.L.G. Muir

The new awareness of the need to conserve non-renewable energy resources requires that the most effective use be made of them. At the same time advances in coal technology have increased the number of options from which to choose.

The main options are conventional uses in power generation and steel-making; new uses in fluidized bed combustion, gas turbines, and formed coke; and treating the coal as raw material for the manufacture of gas, oil, and chemicals, separately or together in a coalplex.

The criteria that determine the optimum use of coal include:

- Natural conditions--the quality and quantity of the coal and the geological conditions that influence the cost of mining.
- The nature of the market, which is determined by the degree of industrialization of the country concerned and the kind of alternative energy sources it possesses.
- Economic and political considerations which, since the oil crisis of 1973, have almost equal weight. The relative prices of alternative energy sources must be weighed against considerations of national self-sufficiency and security.
- Environmental considerations, which are constraints against opencast working and the direct use of high sulphur coals.

THE USE OF COAL IN POWER GENERATION

The low thermal efficiency of the coal-fired power station has led to a search for improved processes, and a number are now at various stages of development. Direct comparison of the thermal efficiency of a conventional plant with that of processes still in the pilot plant, or even the laboratory stage, must be made with care since pilot plant performance may not be attained in industrial scale operation. However, the following figures are an indication of the position:

- Present stations	33%
- Fluidized bed	43%
- Low energy gas, existing turbines	39%
future turbines	43%
- Magnetohydrodynamics	50% or more.

Of the new technologies the fluidized bed is the most promising. Its importance to the coal industry is that it can burn coal that is unusable in conventional plant either because of high ash or high sulphur content. Its use will therefore result in a significant increase in the world reserves of recoverable coal. Its most important use may well be in the pressurized system, to drive gas turbines, with the waste heat used either for further power generation in a combined system or for district heating. The fouling and erosion of the gas turbine blades is greatly reduced when the fluidized bed is used because its low temperature of operation produces a less abrasive and less corrosive ash than is produced by conventional coal firing.

The use of low energy gas in turbines is likely to increase, especially in conversion plants or coalplexes where surplus gas will be available as an economic fuel.

Magnetohydrodynamics is a third generation process based on the direct conversion of heat to electricity by passing a high temperature, high velocity, electrical conducting fluid through a magnetic field. Research is now being done in several countries.

THE USE OF COAL IN STEELWORKS

In steel making, prime coking coal (low volatile, low ash, low sulphur) has an assured market for an indefinite future, but one that will grow more slowly than in the past, and at a slower rate than the increase in steel production. This will arise from: a progressive reduction in the coke to hot metal ratio due to better blast furnace practice and the growing use of supplemental fuels; the use of formed coke; and increasing steel production by direct reduction.

In Japan the requirement of coking coal is expected to stabilize between 1980 and 1985 considerably above the present level. In the European Iron and Steel Community it is expected to stabilize near its present level. This is based on a 2% a year expansion of the Community steel production, which can be offset by the trends mentioned above. The market for coking coal in the main industrial nations is therefore moving towards stability. The movement is likely to be slower in other nations.

The use of formed coke is growing more slowly than might have been expected from a process that promised cost savings and the conservation of scarce coking coal reserves. Several near commercial scale plants are now in production or under construction and its use is likely to increase. Its usefulness has not yet been demonstrated in continuous operation in the largest types of modern blast furnace.

It should be noted that a substantial tonnage of medium and high volatile coking coal is used as boiler fuel in electrical generation.

THE USE OF COAL IN CHEMICAL MANUFACTURE

The use of coal as a feedstock for the chemical industry may take one of three forms: the production of synthesis gas (medium energy) from which mainly ammonia and methanol are derived; the production of solvent refined coal from which a range of carbon-based chemicals are derived; and the full conversion process to produce hydrocarbons, when a wide range of chemicals can be recovered as by-products.

The first of these processes is quite widely done now and is likely to increase since the possibility of using methanol as an additive to petrol, or even, by some modification of engine design, as a substitute for petrol, is attractive.

The use of coal, or coal-derived oil, as a direct feedstock for the chemical industry is some way off. The first contribution of coal to oil conservation will be in electric power generation, and, after conversion, by providing fuel for the internal combustion engine.

THE USE OF COAL IN CONVERSION TO HYDROCARBONS

Conversion to hydrocarbons is done now in South Africa but the conversion plants of the future are likely to be based on second generation technology now in the pilot plant, or demonstration plant, stage. The first such plants should be ready for production in the period 1990-95, except for substitute natural gas (SNG) plants using a modification of existing technology, which should be in production in 1980/85.

The many second generation processes now being researched give a wide range of thermal efficiencies. For conversion to SNG they range between 65 and 77%, and for conversion to liquid hydrocarbons, between 63 and 78%. Coal ranging in rank from brown coal to bituminous have given results within these ranges.

SNG made from coal is an efficient boiler fuel but not on that account cheaper than the direct use of coal. According to the energy value of the coal and the yield of gas the cost per heating unit of SNG at the conversion plant is at least three times the cost in the coal. The use of SNG in competition with coal depends on other considerations than a direct cost comparison.

The manufacture of SNG is one way of converting a high-sulphur coal to a pollution-free fuel. The low transport cost of gas will give some cost advantage against coal brought from afar. SNG will become important only in those countries that have natural gas and an extensive network of pipelines to distribute it. Where that situation does not exist medium energy gas from coal is likely to be preferred. The lower transport cost per heating unit of SNG does not in itself justify the cost of the extra methanation process unless long distances are involved. This is confirmed by South African practice, where the SASOL conversion plant produces as a by-product medium energy gas which is distributed to the Witwatersrand some 50-100 miles away. Where a country has natural gas and coal amenable to low cost mining, SNG from coal can be cost competitive with imported liquid natural gas and is therefore an attractive alternative for when the natural gas supply begins to decline.

Solvent refining may be a means of obtaining pollution-free fuel from high sulphur coal, or it may be a stage in conversion to oil.

It is not possible at this stage to gauge the quantity of coal that will be needed for conversion, or how soon the need will become acute. When the supply of natural oil and gas begins to wane, as some day it must, the demand for the synthetic products will be great. If, at the same time coal has to meet an increasing demand on its conventional uses, the mining industry will be stretched to the utmost. There is a strong case for the first conversion plants to be in operation as soon as possible to reduce the rate of run-down of the natural products, and to perfect the technology and train the manpower against the day when the need becomes urgent.

THE COALPLEX

The coalplex (Coalcom in South Africa, COG in the USA) may become the most general answer to optimizing the use of coal. All the incoming raw coal would be treated by one or several of the processes available. The range of products and their uses would include the following:

- Low ash char--formed coke, conventional coke, pulverized fuel, gasification.
- High ash char--fluidized bed combustors, gasification.
- Medium energy gas--turbines, production of ammonia and methanol, and of SNG by methanation, domestic supply.
- Syncrude--production of petrol and fuel oils, and a wide range of chemicals.
- Solvent refined coal--steam raising, and a range of carbon chemicals.

The range of products taken from a coalplex would be determined by the requirements of the market and the nature of the coal. Considerable flexibility in production will be required to meet fluctuations in demand for the various products, but the processes lend themselves to that. A plant of this kind offers the possibility of economies by heat transfer from one process to another.

THE CRITERIA OF SELECTION

In preparing the long-range plan of a coal basin all of these options have to be considered and tested against the criteria that determine the optimum use of the total resources of the basin. Market requirements will be easily determined by the usual market survey and need no further discussion. The main criteria are now described.

Natural Conditions

It is not appropriate to go into detail on the chemical, physical, and maceral qualities that will point to the most effective use of any one type of coal. The subject is not yet fully understood especially in regard to conversion. What can be said is that in the future the classification of coal reserves will have to be carried further than has been necessary up to now. They will be classified by their most effective end use. The work now being done by the Joint Coal Board of New South Wales and the Queensland Coal Board is a pointer. The conversion potential of a number of Australian coal seams is being measured by extraction using the hydrogen donor process to find the quantity and quality of oil produced. The options now open to the uses of coal require this detailed classification as an aid to determining which is the most effective.

The quantity of coal available has greater significance than in the past. If the coal is to be used in a large and costly plant, whether a power station, a steelworks, or a conversion plant, there must be enough of it to ensure a life for the plant commensurate with its cost. It is possible to bring in coal from other fields, but at a cost that is better avoided.

In a new power station to be based on brown coal in Victoria, Australia, the supplying opencast mine has a reserve of 1000 Mt to give a life of 30 years to a 4000 MW generating plant. The Petrick Commission on South African coal mining stipulates a reserve of 800 Mt, if underground mining has to be used, to give a life of 50 years to a power station of 2000 MW capacity. This is based on a 40% recovery and an annual coal requirement of 6 Mt of hard coal. Opencast mining could have a recovery of 90%, requiring a reserve of some 350 Mt.

Economic and Political Considerations

True cost comparisons between the alternative sources of energy are often concealed by the effect of taxation. Comparison between coal, oil, and natural gas is made difficult by the much greater range of the price for coal.

The drive to maximize the use of coal in the generation of electricity is not primarily based on the relative cost of the alternatives but on wider considerations of economic and political advantage, and the now apparent need to conserve resources of oil and natural gas. Even so, under some conditions, for example in a country that has to import its oil but has reasonably low cost coal, coal based power is cost competitive with oil and should become more so as new processes come into operation. It is also cost competitive with nuclear power with an advantage in the capital cost per unit of power produced.

The position is less clear in regard to the products of conversion. Table 1 shows the effect of the price of coal on the cost of SNG and Table 2 on the cost of synthetic crude oil, and the effect of adding various rates of discounted cash flow (DCF) yield to find an economic selling price. These figures are from the USA and the costs and prices are in mid 1975 currency. To be competitive the price of coal must be at the bottom end of the price range within which the world coal industry can provide it, and DCF yields must be modest by commercial standards. It remains true in general that economic considerations must be reinforced by political ones to justify conversion processes. It becomes a governmental responsibility to create a price structure covering all energy sources that gives the economic incentive to develop those that the nation's strategy needs.

Table 1. Cost estimate for Lurgi plant producing 250 × 10^6 st. ft^3/day gas.

Source: *Preliminary economic analysis of Lurgi plant producing 250 million SCFD gas from New Mexico coal.* US Bureau of Mines, Pittsburgh, Pennsylvania, March 1976. ERDA 76-57, US Energy R&D Administration, Washington, D.C., 1976.

Cost of Coal	Operating Cost	Selling Price $\$/10^6$ Btu DCF yield		
$/t	$\$/10^6$ Btu	12	15	20
5.5	1.82	3.43	3.99	5.02
7.7	2.03	3.63	4.20	5.22
9.9	2.23	3.84	4.40	5.44

Table 2. Cost estimate for Synthoil plant producing 50,000 bbl/day of liquid fuels.

Source: *50,000 barrels a day liquid fuels plant: an economic analysis*: US Bureau of Mines, Pittsburgh, Pennsylvania, 1975.

Cost of Coal $/t	Operating Cost $ per		Selling Price DCF $ per yield					
			12		15		20	
	bbl	10^6 Btu	bbl	10^6 Btu	bbl	10^6 Btu	bbl	10^6 Btu
5.5	8.95	1.42	15.69	2.48	18.03	2.85	22.37	3.53
7.7	10.19	1.61	16.92	2.67	19.27	3.04	23.60	3.73
9.9	11.43	1.80	18.16	2.87	20.50	3.24	24.84	3.92

The capital cost of a conversion plant in 1976 currency values is of the order of $2000 million, including the supplying mine and local infrastructure costs, for a plant with a capacity of 50,000 bbl/day of oil, 7×10^6 m^3 of SNG. The capital cost of SASOL II, now under construction in South Africa is estimated as $2180 million excluding the cost of the township and houses, based on prices in October 1975.

Environmental Considerations

There is a growing confrontation between the world's energy needs and the need to conserve land and quality of life. Its influence on the coal mining industry is perhaps most serious in the long term by the opposition to opencast mining. The problems of atmospheric pollution can be met by a combination of flue gas scrubbing, fluidized bed combustion, and conversion to clean gaseous and liquid fuels. Until these remedies are available in quantity the need to confine direct combustion of coal to qualities low in sulphur is a serious constraint where rigorous standards of air cleanliness have been set, but the solutions are known.

The same does not apply to environmental objection to opencast mining, which is growing in strength. It has already been mentioned that the products of conversion are competitive only if the coal is produced at a cost that in most countries can be met only by opencast mining. Conservation of coal reserves requires maximum recovery and this again requires maximizing opencast mining within the economic limits of depth. There is no way of mining by opencast methods without infringing the requirements of environmental protection during the period of mining. When mining is finished it is possible to restore the land to its original condition and usage unless a very thick seam has been extracted and natural drainage upset.

The only suggestion that might meet the conflict of interests is that environmentalists might take a long term view by accepting opencast mining on the assurance that the ultimate restoration of the land will be complete.

CONCLUSION

In Table 3 the main uses of coal have been put on a time scale up to the end of the century. It presupposes that governments will respond to the total energy problem by formulating policies and providing incentives that will encourage the coal industry to make its best contribution. The time scale is not a prediction of what will happen, but rather shows the earliest time at which the various technologies can be in industrial-scale production to judge by the present state of research and development and plant construction times.

The compression required leads to oversimplification. For example, the fluidized bed is the only process where the amount of ash is of little significance. In the other processes which can tolerate high ash, it is at the expense of some loss of yield and consequently higher cost.

An encouraging aspect brought out by the table is that the new technologies embrace all ranks of coal and a wide range of qualities.

Table 3. Long term development of coal markets.

USE		1980	85	90	95	2000
Metallurgical						
Coke	Bituminous: Prime coking, Weakly coking coals: Low A S					
Formed coke		Mixture of: prime and weakly coking coals, selected non-coking Low A S				
Electricity						
Conventional	All ranks: Low A, and low S until flue gas scrubbing operational, coking coal usually excluded					
Fluidized bed	All ranks: S tolerated, A tolerated beyond all other processes					
Pressurized fluidized bed			As for fluidized bed			
Chemical						
Medium energy gas	All ranks: S tolerated					
Conversion						
Solvent refined coal			All ranks: A and S tolerated			
SNG (modified)		Bituminous, subbituminous: S & moderate A tolerated, coking coal difficult				
SNG (second generation)				All ranks: S tolerated and A to a degree depending on process		
Oil				All ranks: remarks as above		
Coalplex					All ranks: flexible as to quality	

A, ash; S, sulphur

NOTES ON TABLE 3

Metallurgical coal: a decelerating growth rate towards stability in the main industrial nations 1980-1995, but more slowly in others. If formed coke is wholly successful an eventual decline may be expected.

Formed coke: subject to demonstrated success in modern large-scale blast furnaces, a progressive increase in use will result.

Electricity generation:

Conventional--short to medium term increase to conserve oil, stabilizing as new coal systems and other forms of power increase.

Fluidized bed--progressive increase in steam-raising generally, exploiting its versatility in accepting all qualities of coal.

Pressurized fluidized bed--progressive increases, exploiting the above, its thermal efficiency, and freedom from corrosion of turbine blades.

Chemical feedstock:

Medium energy gas--increase in use for the manufacture of ammonia and methanol. Large increase if methanol is developed as a substitute for petrol.

Conversion:

Solvent refined coal--main use in providing carbon based chemicals and feedstock for conversion, but used as clean fuel in special circumstances.

SNG, present technology modified--limited number of plants, mainly in the USA to overcome natural gas deficiency until second generation plants are ready.

SNG, second generation--progressive increase to replace declining natural gas supply, and eventual substantial usage.

Oil--progressive and eventually rapid increase to replace declining natural oil supply.

Coalplex--possibly the final answer to optimizing the use of coal from about the turn of the century.

All ranks include lignite and brown coal.

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CHALLENGES OF EXPANDING COAL PRODUCTION IN THE MAIN COAL MINING COUNTRIES

A.A. Arbatov and A.F. Shakai

Coal is considered one of the most probable alternatives in the reconstruction of the world energy balance. These structural modifications are expected in 30 to 50 years as natural hydrocarbon reserves are depleted. The coal demand and supply situation is not so unbalanced as that of oil and natural gas, since coal reserves are abundant and more evenly distributed throughout the world.

Coal also is bound to play an important role as chemical raw material used for numerous purposes.

There is a moderate growth in coal mining and consumption at present, due to a certain degree to the fivefold oil price increase and the continual expansion of energy demand.

The main coal mining countries have reached their present level of development in different ways. The capitalist States have suffered a serious depression in coal mining after World War II. During the postwar period coal production and research in that field were sharply curtailed due to competition from oil and gas. By contrast, planned-economy countries--the USSR and Poland--exhibited a stable rapid tempo of coal mining consumption and research.

In the current serious energy situation, with warnings of inevitable oil and gas shortages, one cannot doubt the absolute growth of coal production. Coal may be a rational alternative in a medium-term perspective because it is the only fossil fuel resource we have in abundance, even with existing technology. However, it is not clear whether there will be slow growth as at present, or rapid expansion over a short period in which mining output will double. To a large extent this depends upon the world oil and gas situation and progress in the development of nuclear, solar, and geothermal technology.

Coal mining and consumption are connected with certain technological, ecological, and social problems, which had already arisen in an earlier epoch when coal was the main energy resource. Mankind did not succeed in removing these constraints, because more convenient and cheaper energy sources became available: oil and gas. If the world accepts the coal alternative and large-scale mining begins, the leading coal powers would again meet some of these as well as new obstacles.

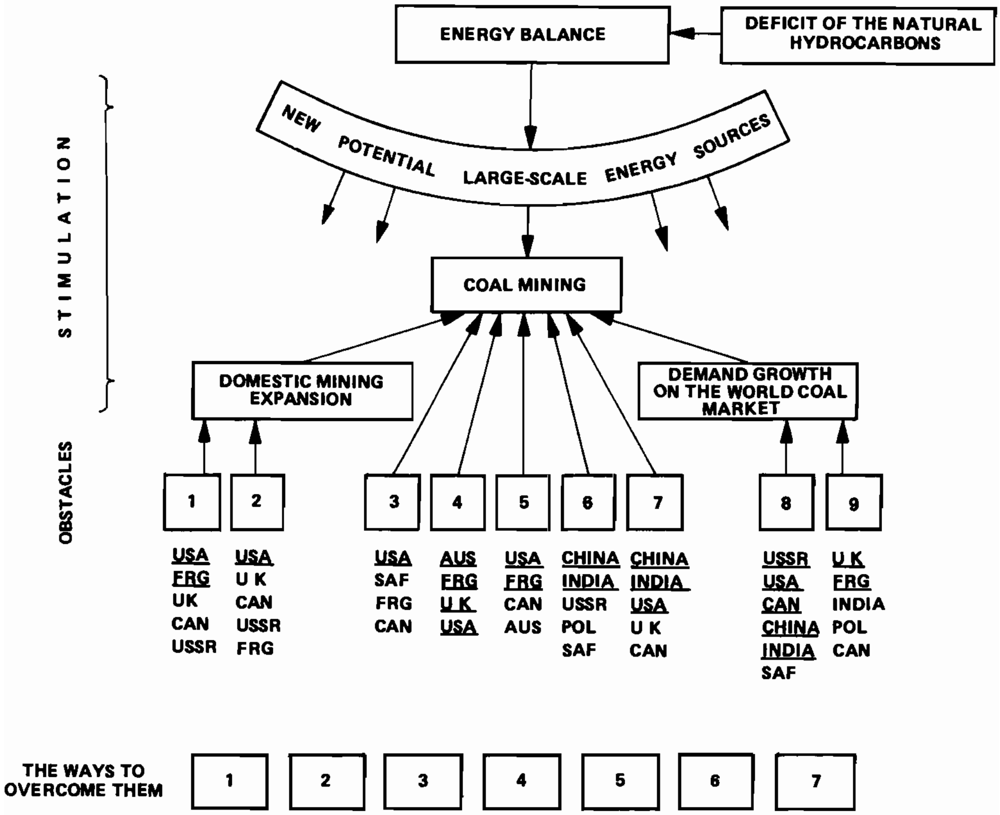
The possibility of solving these problems may seriously influence decisions to increase coal production in most States possessing large coal reserves. The identification difficulties will permit attention and efforts to be appropriately focused in each country and to use the opportunities of international cooperation.

Relaxation of technical constraints is of course closely connected with social aspects, but in this paper we deal only with technological questions. Figure 1 is an attempt to formulate these problems generally. Acceptance of the coal alternative is considered as one way to find a large-scale source of energy in a deteriorating energy situation. The main stimulus for mining expansion would be an increase in world and local coal consumption. The scales of coal consumption within countries may be limited by economic infrastructure orientation toward oil (intensive automobilization, and railway, sea transport, and aviation development). This is typical for the USA, where oil and gas dominate (80%) in energy consumption, and to a lesser degree for the UK, the FRG, Canada, Australia, and the USSR: gas and oil meet from 45 to 60% of the total energy requirements of these States. Reconstruction of the economy of these States in order to reorient the energy balance toward coal would take more than 20 years and billions of dollars. It can also lead to decreased labor productivity and weaken the competitive position of these States in world markets. China's position is better in this respect, because its economy is based on coal.

It is worth mentioning that the progressive energy balance of the developed countries has permitted them to raise labor efficiency, and that therefore no considerable change in energy balance need be expected from the increased share of coal.

A serious handicap to expanded coal mining is connected with air quality standards. This limitation has reached considerable scales in the USA, the UK, the FRG, and other countries, where air pollution regulations are primarily concerned with particulates, nitrogen oxides, and sulfur dioxides. For example, in most States in the USA, plants should have low-sulfur coal in order to meet strict emission standards. As a result the USA is facing an ever-growing shortage of low-sulfur coal. In December 1970, the US Congress issued the Clean Air Act, the most comprehensive air pollution bill in US history. The bill is intended to develop and use effective environmental protection systems and to restrict the burning of high-sulfur coal.

However, there is still a wide gap between the rising trend of sulfur dioxide emissions and the technological capability for bringing the problem under control. Even with rapid application of control techniques now being developed, it is unlikely that sulfur dioxide emissions will be greatly reduced. At the same time the process of coal desulfurization is rather expensive and difficult.



Obstacles (underline indicates considerable constraint; no underline, less)

1. The economy's orientation to gas and oil.
2. Pollution caused by coal burning.
3. Pollution caused by coal mining.
4. Lack of water resources.
5. Shortage of manpower.
6. Shortage of equipment.
7. Inadequate R&D financing.
8. Unfavorable transportation conditions.
9. High mining costs.

Ways of overcoming them

1. Synthetic gas and oil.
2. Underground gasification.
3. Desulfurization.
4. Land reclamation.
5. Automation and mechanization.
6. Increased R&D financing on the basis of joint programs.
7. New transportation methods and reconstruction of the ports.

Figure 1.

Air pollution standards caused a situation where several US electric generating plants could not burn high-sulfur coal and were compelled to use oil. In the FRG, due to the high density of industry and population, environmental problems are also of great importance. The government of that country passed an environmental protection bill, which turned out to block the way to expanded coal mining and consumption. The construction of new mines is also complicated by the lack of available land. The building of new coal facilities is possible here mainly by means of uniting mines in operation, a rather expensive and complex operation. In the UK, air pollution is a serious problem and one of the chief obstacles to widespread coal consumption.

In Canada, the USSR, South Africa, and Australia, pollution is becoming an issue as well. The situation there is better, due to their vast territories and some other reasons, than in the USA, the UK, or the FRG; but it is obviously a question of time.

Because of the chronic aggravation of this problem, the governments of the main coal mining countries are beginning to relax ecological limitations. Research to develop technology for removing sulfur dioxide from gases generated during coal combustion is promising. At present, the USA, the FRG, Canada, and the UK are planning to install commercial scrubbing systems. In the medium-term future we envision solid absorbent regenerative systems application and other sulfur-removing technology.

Another significant drawback of large-scale coal mining is stripping. Nothing and no one can live long in stripped areas where the vegetation has been destroyed, the water poisoned by mine acid, and the soil made infertile. Stripping disturbs about 0.6 acres per 1000 of mined coal. Most of the USA coal-producing States have tried to pass laws to control strip mining to some degree. The same is true in Australia and Canada. This problem has not yet become critical, but in case of coal mining expansion it will be a serious obstacle. Stripping is a real disaster to plantlife, wildlife, fish, and human beings. More than 40% of the total stripped land is of surface coal mining origin.

The problem is how to balance energy needs with environmental protection. The gap between stripping and reclamation must be diminished. One can expect that in 20 years, the mining industry of the developed States will be able to make total restoration of the land to its original condition or better.

Another problem limiting the production capability of the coal mining States is that of effective and cheap transport from mine to consumer. The costs of transport may be so high that the whole enterprise becomes noncompetitive. This is typical for countries with large territories. Long distances from the coast coupled with low efficiency of railroads and ports not only cause diminishing export but also curtail the State's own coal consumption. This is the case in China, Canada, the USA, the USSR, and South Africa. The US railroads have suffered a serious crisis, and hence the development of the coal industry in the western regions may be limited. The USSR faces the same problem in transporting coal from Kuzbass and Kansk-Achinsk to the European USSR.

China's railroads are in poor condition. In Australia, insufficient port capacity may limit increasing coal export. South Africa was compelled to begin the construction of a special seaport at Richard Bay for coal loading. India, having no ports where coal can be kept, cannot become a large coal exporter in the near future.

Another limitation is the lack of water for pipeline transport and underground hydromining. The FRG, the USA, the UK, and Australia are facing a growing shortage of water resources. In time, improvement of the transport system and the distilling process will encourage coal mining, thus compensating for the negative effects.

An important drawback to expanded coal mining in some countries is a higher production cost than that in States with more favorable geological conditions. For example, US coal is cheaper than West European, though it is transported across the ocean and US miners are better paid. The same applies to Australia, successfully competing on Asian coal markets.

In this connection, the rapid decline of the coal industry of France, caused by cheap coal import, is natural. The FRG is preparing to increase coal imports from South Africa, which may decrease domestic mining. Due to geological conditions, progressive mining methods such as stripping are not widely developed in the UK and China. That fact in some respects weakens the competitive position of these States in world fuel markets.

Nevertheless, continuing progress in mining technology will compensate the influence of unfavorable geological conditions. For example, the innovation of mechanical timbering, elaborated in the USSR, permits increased coal production despite difficult geological conditions.

A serious limitation for coal production growth is an equipment deficit. A great deal of time and capital are needed to produce bulldozers, giant earthmoving machines, huge power shovels, and big auger drills. Thus, being a very capital-intensive industry, coal mining can cause considerable economic change and imbalance. A lack of modern equipment is critical for China and India. Most mines in these countries are of medium or small size, which is often a barrier to more economic operation.

In India the most pressing need is that of total mine reconstruction and implementation of automation. The USSR and Poland are facing a growing shortage in some kinds of earthmoving machines, particularly rotor excavators used during stripping and large trucks. A relative shortage of mining equipment may occur in Canada. Complicated geological conditions in South Africa require specific and expensive equipment, which cannot be developed in a short time.

These facts compel the coal mining States to work out technological innovations. Some of the most promising applications concern the economic impact of full cycle automation control processes in the main coal mining States. A completely automatic control system must use advanced IBM technology; the FRG, Poland, and the UK are carrying out research in that field.

Among the factors limiting coal mining expansion is the growing lack of manpower. In spite of the mechanization and automation that has taken place in the USA, the UK, the FRG, Australia, and other States, the number of labor conflicts is increasing. Work in mines is well paid but less attractive than before. One can see a tendency toward decreasing labor productivity in the FRG, the UK, the USA, and Australia. In the eastern USSR, the lack of skilled manpower has been felt. China's and India's position is better because of their enormous manpower resources, but these States need skilled technical personnel.

The experts reckon that with the help of complex mechanization the negative effect of growing manpower deficit can be compensated for. Moreover, large-scale production of synthetic oil and gas will make the coal industry more attractive.

One more obstacle to coal mining expansion is the comparatively modest scientific and technological potential of the coal industry and the lack of capital for long-term investments. Private companies financing the coal industry prefer to have guarantees of long-term rentability and protection of their investments. During the postwar period, oil and gas were replacing coal, and the attention paid to nuclear energy prevented adequate R&D financing in the coal industry.

Such financing policies in the USA, the UK, Australia, and Canada prevented rapid innovations. Furthermore, the outlook for large-scale investment in the main coal mining States is gloomy. A good example is the state of the art of synthetic fuels produced from coal. Although the feasibility of coal conversion into synfuel was demonstrated 40 years ago in Germany, there is still no large commercial plant that can produce competitive oil and gas from coal. US and European corporations are in no hurry to invest in synfuel enterprises, demanding broad government support.

It is no secret that one needs not less than 100 billion dollars and a great deal of time to establish a new industry; and the task is very hard for any country other than the US and the USSR. But large-scale synfuel production is rather promising, and the FRG and the US are moving toward commercial plants.

In South Africa, with cheap and abundant manpower, conditions are favorable for large-scale industrial coal gasification. In the USSR a plant has been in operation for more than 20 years. It belongs to the Sasol Corporation and produces synfuel from coal. In other States, competitive synfuel production may begin in the mid-1980s. The ultimate commercialization of synthetic fuel depends very heavily upon process efficiency. Recently growing attention has been paid to underground gasification, research and development being financed in the USSR, the USA, the FRG, and the UK.

The FRG and Poland are developing coal-based chemical industries on a large scale, and there is no doubt that other States will do so as well.

Joint research programs of the International Energy Agency (IEA) have had a stimulating effect. The concentration of financial and scientific resources of the IEA member countries compensates the relatively low level of national efforts to develop new coal conversion technologies.

All the factors described undoubtedly help to relax the constraints posed by ecological, economical, and social concerns. Our report cannot embrace all the problems of large-scale coal mining: each of the main coal powers has its own specific problems, which are naturally better known to the scientists of these countries. We can merely highlight the questions that are most urgent. The problems must first be analyzed, and this conference is a good opportunity to discuss them. We hope that with the help of effective international cooperation, mankind will in the long run solve problems it now faces in the field of optimal coal use.

ECONOMIC PROSPECTS FOR SYNFUEL PRODUCTION FROM COAL

A.K. Arsky

Economic prospects for the coal based synfuel industry are closely connected with the increase in world oil prices, the depletion of low-cost oil resources, the need for new capital-intensive oil and natural gas resources, and strong market trends toward the use of a clean and versatile form of secondary energy. The USSR, the USA, and China, with abundant cheap coal resources, have the best possibilities for developing a synfuel industry. In Western Europe, and more still in Japan, coal resources may be recovered only at high cost. However, in the more distant future synfuel production may be developed in Western Europe, but not on the scale expected in the USA and possible in the USSR and China.

In the long run, during the transition to non-fossil-fuel energy, coal may become one of the main sources of synfuel liquid and gaseous fuels--clean fuels of desirable quality. Synfuels from low-cost coal will be much more economic than hydrogen or hydrogen-based synthetic liquid fuel. According to [1], specific hydrogen costs are 1.7 to 2.7 times higher than coal-based synfuel costs.

Synfuel production from coal is capital-intensive. Specific investments proved to be much higher than was estimated in the early 1970s. The sharp growth in costs cannot be explained only by inflation factors, as for example in [2], since it has by far exceeded inflation.

In the USA in the early 1970s, investment costs per unit of daily capacity were estimated at \$800 to 1200/ft^3 for syngas from coal and at \$5500 to 6000/bbl for syncrude (in 1971-1972 dollars), or, in terms of yearly capacity and metric units, \$80 to 120 per 1000 m^3 and \$110 to 120/t, respectively. Those appraisals were published as long ago as 1972-1973 [3]. But since 1975, specific investments (in 1975 dollars) were estimated at \$320 to 400 per 1000 m^3 of yearly capacity for high-energy gas and at \$400/t for syncrude. Thus estimates of spcific investments in current dollars increased by about 3.3 to 4.0 times from 1971 to 1975, while despite high rates of inflation the cost index of construction and of the basic equipment for coal-based synfuel plants* increased only by about 1.5 to 1.8 times over the same period.

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*Chemical equipment, pipes, tanks, pumps, compressors, electrotechnical equipment, and communication systems.

Environmental and safety standards for coal-based synfuel production have not generally been changed recently*. The considerable growth in the estimated specific costs of synfuel production may be explained mainly by more accurate calculations when the first commercial synfuel plants are projected. Apparently, earlier estimates were to a considerable extent based on subjective considerations as well: the desire of synfuel's promoters and planners and of interested companies to emphasize its economic attractiveness.

A commercial coal-based synfuel industry will be developed after commercialization of more economic oil production based on high-yield tar sands and oil shales accessible for strip mining. Apart from production of synthesis gas already under way for the petrochemical industry (ammonia and methanol) and reducing gas for blast furnaces, a synfuel industry based on coal cannot be developed without a considerable rise in world oil prices. Commercialization of syncrude production, for example, would entail an increase of roughly 1.5 to 2 times in world oil prices (in constant dollars). Plans in the USA to develop a coal-based synfuel industry in 1990-2000 may not be feasible if present world oil prices remain.

World oil and natural gas prices in the next 20 to 25 years will depend mainly on the policy of OPEC with respect to oil prices, and on growth rates in extraction of the available low-cost oil and gas resources, which are substantial but limited. In the more remote future, with depletion of low-cost resources, world oil prices will be determined by the costs of finding and extracting of those conventional petroleum resources now regarded as uneconomic, and by the cost of exploiting unconventional resources (primarily heavy oil, shale oil, and tar sands)**. For that reason a further rise in world oil and gas prices is inevitable in the long run, and this will make the coal-based synfuel industry profitable.

Statements about the near-complete exhaustion of petroleum resources neglect the availability of extensive resources that are economically unrecoverable or marginal at present world prices and often technically inaccessible at present [4]. Such resources are not included by most geologists in their resource estimates. Their development will presumably extend nature-made oil (crude and gas) production far beyond the twentieth century.

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*Specific investments in electric energy generation were largely affected by environmental (coal and nuclear plants) and safety (nuclear plants) standards.

**The high costs of petroleum substitutes, including coal-based synfuels, and the high marginal petroleum costs in conjunction with the shortage of low-cost resources, and also the reason for the present high world oil prices.

During the transition to the use of unlimited energy resources, a large-scale coal-based synfuel industry will develop side by side with oil production. Nature-made oil and synfuels from coal will jointly provide world petroleum supplies and will compete with one another. In the remote future, well-developed synfuel production based on coal may to some extent curb the further increase in world oil and gas prices, and through its cost and scale of development affect the volume of petroleum production.

In this connection, the world oil price in 2025, set in the Pestel-Mesarovic model at \$66 per barrel in 1975 dollars (\$460/t), seems to be greatly overestimated. A vast amount of coal-based syncrude can be produced at much lower cost, not only in countries with abundant low-cost coal but in Western Europe and elsewhere, even when rather expensive coal is used. It should also be taken into consideration that, as oil prices rise and development of recovery processes advances, more and more resources now disregarded (e.g., conventional oil that may be recovered by tertiary methods, heavy oil and gas resources of tight formations) become economic and may be brought into production. Enlargement of the oil and gas resource base will obviously delay price escalation.

Synfuel costs are very sensitive to the price of feed coal, as shown in Table 1. The cost of high-energy gas or syncrude produced from more expensive coal (calculating per 1000 m^3 or 1 t, respectively) will differ from the cost of synfuel from lower-priced coal by about twice the difference in coal price per ton of coal equivalent. But even synfuel production based on \$60/t coal may be profitable (at a 12% return) at a price less than half that of the Pestel-Mesarovic forecast (see Table 1).

If we assume the capital cost for a synfuel plant to be half as much again as the base cost data [5]*, and a cost of \$40/t of coal, the syncrude price (under complete equity financing at 12%) would be \$230/t (\$33/bbl)--half the Pestel-Mesarovic estimate of the world oil price for 2025.

In transition to a non-fossil-fuel economy, coal-based synfuel will supplement nuclear energy rather than compete with it. Synfuel will meet transport and domestic** fuel requirements, and nuclear energy will provide electric energy supply and district heating. The two will, however, compete in high-temperature heat applications.

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*Uncertainty concerning syncrude specific investments justifies this assumption when attempting to determine the possible upper level of syncrude prices at an assumed rate of return.

**For detached houses and low buildings.

Table 1. Estimated synfuel prices as a function of coal cost (in 1975 dollars)*.

Coal cost [$/tce]	Syncrude		High-energy gas	
	Estimated price [$/t]	Ratio of synfuel price to coal cost	Estimated price [$/t]	Ratio of synfuel price to coal cost
5-10 (lignite)	130-150	7-4	117-135	6.5-4
20	150	4	140	3.5
30	170	3	160	3
40	190	2.4	180	2.2
50	210	2	200	2
60	230	2	220	2

*As base cases, price estimates for syncrude and high-energy gas calculated [5] under complete equity financing at a 12% return were assumed.

Low- and medium-energy gas from coal for electricity generation will compete with nuclear energy at the beginning of the transition to a non-fossil-fuel economy; but here too they may supplement each other. Plants using low-energy gas (with combined gas turbine/steam turbine cycle), with their rather high fuel costs, will do better for peak and intermediate loads. At nuclear plants, as is known, the lowest electricity cost is achieved for base load. With advanced technology, synfuel and nuclear energy may mutually improve their economics. Heat from nuclear plants used at synfuel plants allows increased thermal efficiency of both synfuel and nuclear energy production and decreases heat disposal problems. That will be especially effective after commercialization of high-temperature reactors.

A coal-based synfuel industry need not compete even with hydrogen production. Comparatively low-cost synfuel from coal will of course hamper the development of hydrogen production as a main source of substitute hydrocarbons; but syncrude production based on coal will be a very large hydrogen consumer for hydrogenation and purification of synfuel. In situ coal gasification may become the biggest consumer of by-product oxygen. The use of hydrogen in coal-based synfuel production will simplify it and may reduce its costs. At the same time such use of hydrogen will considerably enlarge its market and improve nuclear plant loads.

While minimum specific water requirements for coal-based synfuel production, with optimization toward reducing water requirements, are quite substantial, they are--in terms of equivalent energy output--generally lower than for conventional coal-burning steam electric plants with wet cooling towers. A gasification plant with dry cooling might require as little as 25%, and a plant with wet cooling 50%, as much water as a steam-coal-burning plant using wet cooling towers for the same output. For comparison in terms of equivalent coal input, these figures should be doubled, in view of differences in thermal efficiencies. Coal-based synfuel production when using dry cooling towers would require about 2.5 tons of water per ton of hard coal.

Water constraints on the growth of a coal-based synfuel industry may be substantial in the case of large-scale synfuel production in areas with water shortage. A possible way to avoid these constraints is to transport coal by rail or coal slurry pipelines to locations with abundant water. Shipment of coal by rail would have negligible water requirements. Coal slurry pipelines are also favorable, requiring about a ton of water per ton of coal. But mass transport of high-energy gas, and especially of oil, is less costly than transport of coal.

The possibility of converting low-energy coal, which is expensive and often unsuitable for long-distance transport, into high-energy gas and crude is a great advantage of coal-based synfuel production, allowing the development of huge low-cost coal resources in remote areas of the USSR and the USA.

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ATMOSPHERIC CARBON DIOXIDE:
IMPLICATIONS FOR WORLD COAL USE

G. Marland and R.M. Rotty

It has been almost 40 years since Callendar [1] first wrote that fossil fuel burning was leading to an increase in the concentration of CO_2 in the atmosphere. Chamberlain and Arrhenius had suggested around the turn of the century [2] that such an increase in CO_2 could lead to significant climate changes and Callendar maintained that the global temperature increase was then (1938) already measurable. Callendar believed that a temperature increase was "likely to prove beneficial to mankind..." by stimulating plant growth, retarding the return of glaciers, and encouraging higher-latitude cultivation. However, Callendar's conclusions were questioned by others [1,3,4] and as recently as 20 years ago Revelle and Suess [2] concluded that while an increase in atmospheric CO_2 was to be expected, the data available to them were not adequate to define a baseline. Revelle and Suess also noted carefully the importance of potential feedback mechanisms to the climate system and pointed to the "far-reaching insight into the processes determining weather and climate" which could be obtained if this "large scale geophysical experiment" were properly documented.

In the late 1950s the International Geophysical Year provided the stimulus to begin accurate monitoring of atmospheric CO_2 [5] and the manner by which the infrared absorptive bands of CO_2 affected the radiative balance of the Earth were reexamined [6]. Now, with 18 years of continuous records from Mauna Loa Observatory [7] and extensive data sets from the South Pole [8], Point Barrow, Alaska [9], Swedish aircraft [10], and Australian aircraft [11], at least one of the fundamental questions has been unequivocally answered--the concentration of CO_2 in the atmosphere is increasing (Figure 1). At Mauna Loa Observatory the concentration has risen from 315.53 ppm in 1958 to 332.29 ppm in 1976. Rust et al. [12] have demonstrated that growth is occurring at an exponential rate very nearly the same as that for the expanding rate of fossil fuel consumption. Debate continues on the role of the land biota and the oceans and their effect as sources and sinks for atmospheric CO_2 [13,14]. Some insist that a major portion of the anthropogenic CO_2 input to the atmosphere has come from changes in the biota--largely through clearing of tropical forests [15].

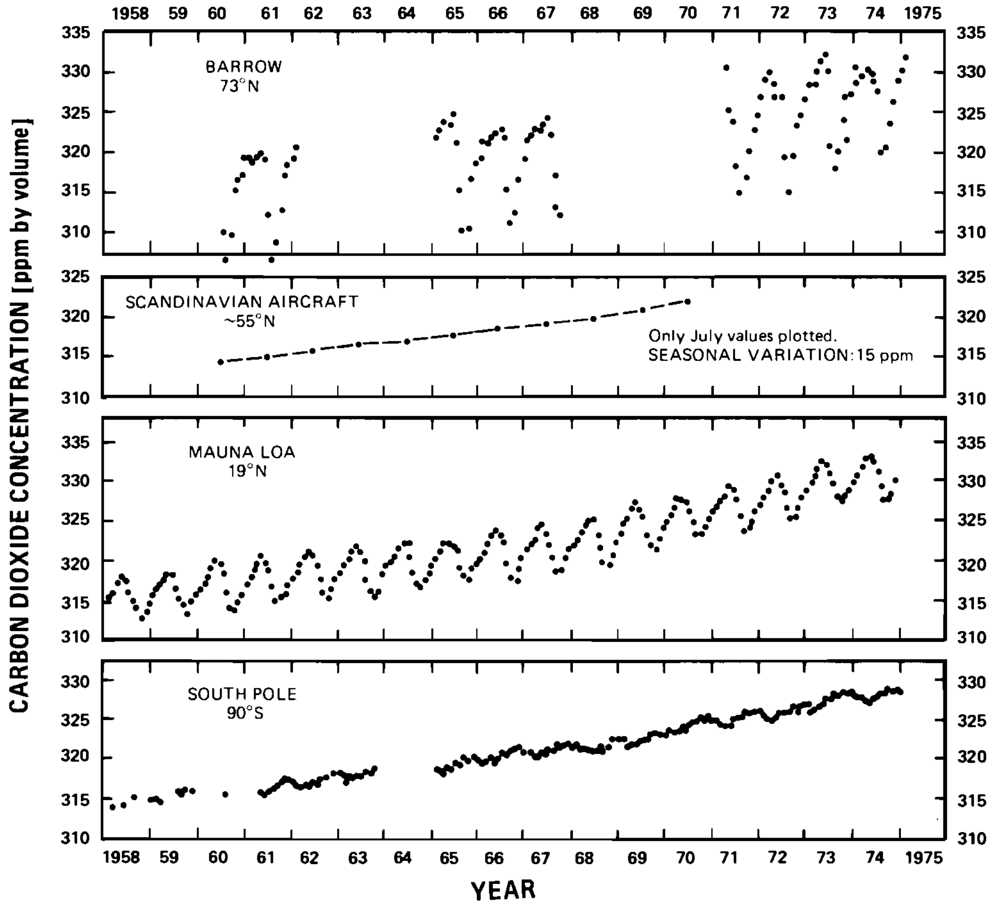

Figure 1. Atmospheric concentration of CO_2. Data are from Air Resources Laboratory, NOAA [9] (Barrow, Alaska), Bolin and Bischof [10] (Scandanavian Aircraft), Keeling et al. [7] (Mauna Loa), Keeling et al. [8] (South Pole), and Keeling, personal communication (Mauna Loa, and South Pole, 1972-1975).

At the same time that monitoring of CO_2 levels has been progressing, the physical understanding and mathematical sophistication for modeling the climate system have been progressing as well. Complex models like those of Manabe and Wetherald [16] and Augustsson and Ramanathan [17] (see also Schneider [18]) now suggest that if the atmospheric CO_2 concentration were to double, the mean temperature of the troposphere would increase by 1.9-2.9 °C and the temperature of the high latitude surface layers would increase by two or three times as much as the mean (Figure 2).

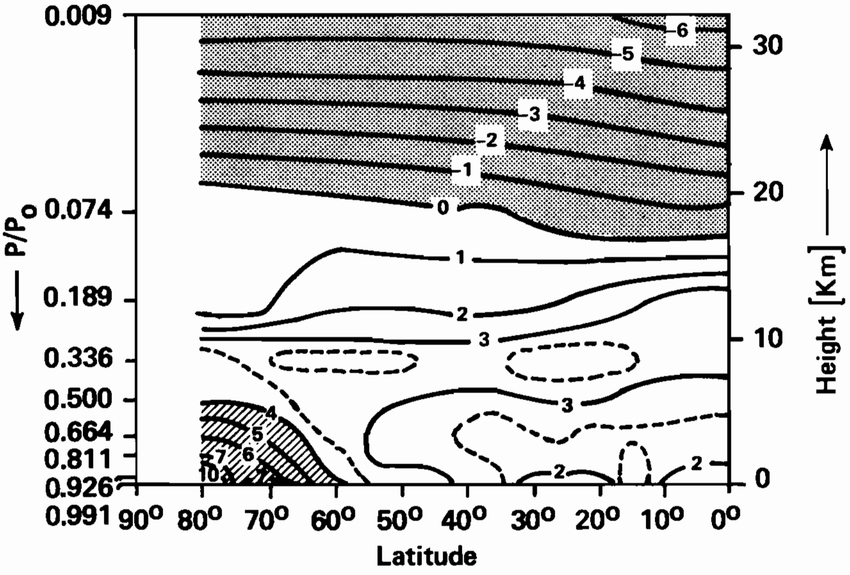

Figure 2. Changes in atmospheric zonal mean temperature for a doubling of CO_2 concentration in a general circulation model.

Source: Manabe and Wetherald [16]

These models still contain simplifications. For example, the Manabe and Wetherald [16] model contains fixed cloudiness, a swamp ocean, and no seasonal variation. Presumably the models do predict the direction and order of magnitude of changes which can be expected but refinement is still needed to deal adequately with the many feedback mechanisms. A very important aspect of these calculations is that the predicted climate changes will interact with the complex atmospheric circulation patterns and yield drastically different changes in various localized climates [19,20,21].

Over the last 2 years, visibility of and concern about the CO_2 issue have increased dramatically. This seems to have been stimulated, at least in part, by an article in *Science* [22]. Since then (1975) we have witnessed the Dahlem Conference on Global Chemical Cycles and Their Alterations by Man [23], a US Energy Research and Development Administration workshop on Environmental Effects of Carbon Dioxide from Fossil Fuel Combustion [24], a SCOPE (Scientific Committee on Problems of the Environment) Workshop on Biogeochemical Cycling of Carbon, an IAMAP (International Association of Meteorology and Atmospheric Physics) Symposium on the Carbon Dioxide Cycle, a major US National Academy of Sciences release on energy and the climate [25] and when President Jimmy Carter gave his energy message to the US Congress, in April 1977, the accompanying fact sheet issued by the White House [26] mentioned "almost $3 million to study the long-term effects of carbon dioxide from coal and other hydrocarbons on the atmosphere".

The evidence is not yet compelling that CO_2 is going to cause major climate changes, but the consensus leans heavily in that direction and the issue is being treated quite seriously. A very real part of the CO_2 problem is that climate theory may be insufficient to provide this compelling evidence for decades [27]. Because of the long lead times required to alter social systems, we will need to continue to examine alternative strategies as a hedge against consequences not yet fully understood.

The evidence that atmospheric CO_2 is increasing and apprehension about the future have prompted efforts to project future CO_2 concentrations. In general, these involve models of the global carbon cycle and efforts to understand the sizes of actual reservoirs and the fluxes between them. Virtually all models incorporate rates of ocean-atmosphere and biosphere-atmosphere exchange, and ocean mixing, and many incorporate the complexities of carbonate-water chemistry. The models differ in the complexity of the formulation, and the details of the exchange processes, such as consideration of short-lived and long-lived biota and interactions with living versus dead organic carbon. The relative importance of various exchange processes varies from model to model [13,28,29,30,31].

To estimate future levels of CO_2 in the atmosphere requires information on likely rates of CO_2 injection into the atmosphere (mostly from fossil fuel burning and forest clearing) and on the partitioning of this CO_2 among the various natural reservoirs. Historically, CO_2 from fossil fuel burning and cement manufacture have increased at 4.3% per year [32] (except for the periods of the two world wars and the global economic depression of the early 1930s). Cumulative CO_2 production from these sources since the beginning of 1958 and observed increases in the atmospheric CO_2 burden are compared in Figure 3 [33]. If, as a first approximation, we assume that CO_2 from forest clearing is balanced by enhanced photosynthesis from higher atmospheric CO_2 concentrations, then 54% of the industrial CO_2 produced since the beginning of 1958 have remained in the atmosphere. It seems reasonable to project that for the next several decades the airborne fraction will continue near 54% (although some oceanographers suggest that the capacity of surface ocean waters to accept CO_2 will decrease and hence the airborne fraction will increase with time).

If 46 percent of the CO_2 goes to reservoirs other than the atmosphere, the problem of estimating atmospheric concentrations reduces to predicting global fossil fuel use. (This statement will, of course, require modification if we demonstrate that man-induced changes in the biosphere are, in net, a major time dependent source or sink for CO_2.) CO_2 production is clearly

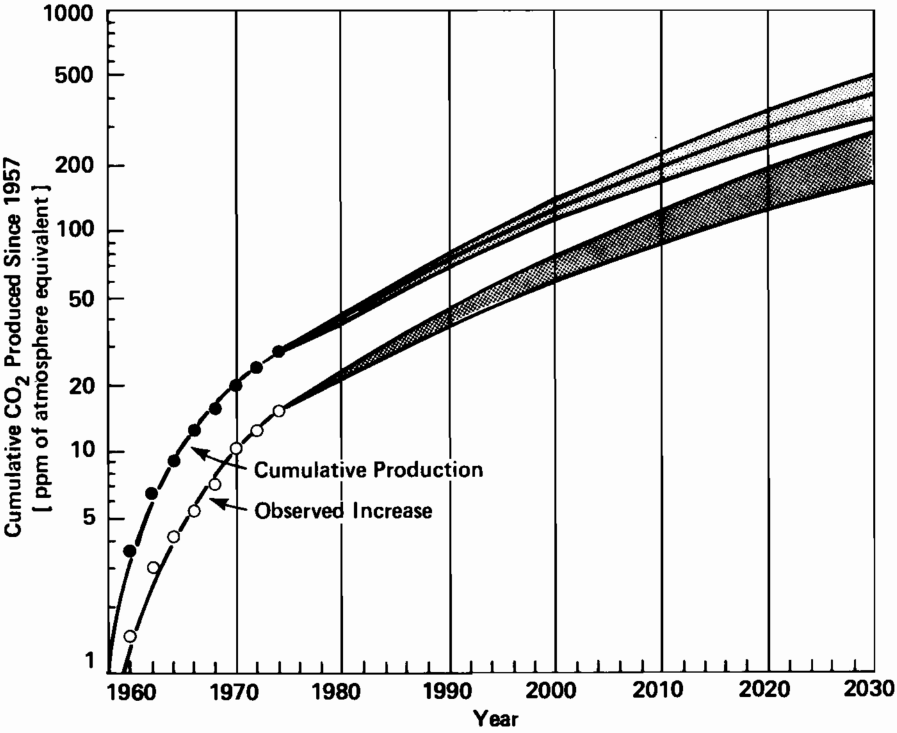

Figure 3. Cumulative CO_2 production and the observed increase in atmospheric CO_2 concentration since the beginning of 1958. Points to 1974 are based on historical data. For the projections to 2025, the center curve for cumulative production conforms to the scenario described in the text (1250 quads of global energy in 2025). The bands shown represent from 20% more to 40% less fossil fuel burned and the corresponding atmospheric CO_2 concentrations if 54% of the CO_2 produced remains in the atmosphere.

tied to energy consumption and, on a national scale, to economic development. Rotty [34] has calculated the rate at which CO_2 is now [1974] being produced by various world subdivisions and shows rather dramatically (Figure 4) that whatever the consequences are, the phenomenon is being imposed on the world principally by the USA, the USSR, and western Europe. On the other hand, Rotty has also projected a very simple model of world economic growth to the year 2025 and demonstrated the extent to which the CO_2 problem is tied to the growth aspirations of the entire world community. Briefly summarized, the model assumes that: US energy growth is from 73 quads* in 1975 to 125

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*1 quad = 10^{15} Btu; 1 quad per year = 0.033 TW.

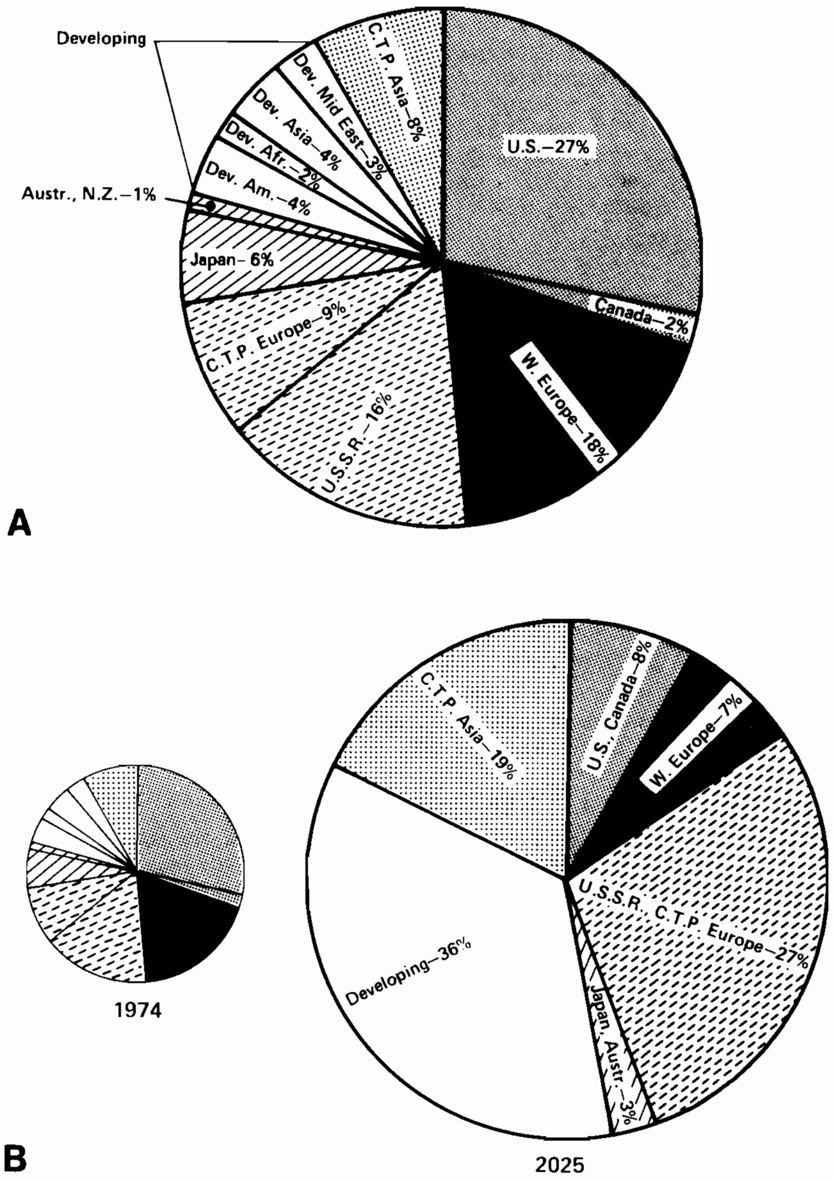

Figure 4. Global production of CO_2 from fossil fuel burning, by world segments; A, for 1974; B, for 2025, according to the growth scenario described in the text. The 1974 diagram is reproduced to illustrate the relative dimensions of the global emission rate.

quads in 2025 with 15% being nonfossil energy; western Europe, Australia, and Japan have 2% per year growth in energy use with 15% of the total being nonfossil energy; the centrally planned economies of Europe grow at 4% per year in energy consumption with 15% being nonfossil; the centrally planned economies of Asia increase energy consumption at 5.1% per year and this is almost exclusively fossil energy; and the developing countries of the world average 5.5% per year in energy growth and this is almost exclusively fossil. The consequence of this calculation is a world consuming some 1250 quads of energy in 2025 (42 TW) --compared with 240 quads in 1974 (8 TW)--with CO_2 production as illustrated in Figure 4.

Whether one is prepared to accept such a scenario (a point to which we will return briefly later) the point is amply made that if economic growth is to continue throughout the world, if the economic gap between developed and developing nations is to close at all, and if a sizable fraction of growth occurs through fossil fuel burning, then the CO_2 problem must be recognized as a genuine global problem. (For comparison, a working paper for the World Energy Conference in Istanbul in September 1977 [35], projected that world energy demand in 2020 would reach 760-1025 quads with 60-65% of that fossil energy.)

To examine what this 1250 quad scenario means in terms of atmospheric CO_2 concentration, we have calculated the cumulative production of CO_2 beginning in 1958 and assumed that 54% remains in the atmosphere (Figure 3). By 2025 the atmospheric concentration will have undergone a truly significant change and any climate changes should be clear.

We need to recognize, also, that the CO_2 problem is, to a large extent, a coal problem. Burning of oil and natural gas and man-induced changes in the mass of the terrestrial biosphere have certainly contributed CO_2 to the atmosphere and will likely continue to make sizable contributions for decades. Nonetheless, when we assess the total masses of carbon, it is obvious that coal alone is a large enough source to produce a truly substantial change in the atmospheric CO_2 concentration. While the total mass of carbon as live organic matter is about the same as the mass of carbon in the atmosphere (about 700×10^9 t) and the mass of carbon in that portion of dead terrestrial organic matter which exchanges with the atmosphere (humus and new peat) is half again as large (1080×10^9 t) [19], we cannot realistically envision a large fracion of this being oxidized as a result of man's activities. Recent calculations do suggest that this organic reservoir has already been depleted by as much as $70-120 \times 10^9$ t or more [14,36].

To illustrate how coal, as opposed to oil and gas, is tied to the CO_2 problem, we can examine the potential CO_2 level if the various fossil fuel reservoirs were burned and 54% of the released carbon were retained in the atmosphere (Table 1).

Table 1. Projected atmospheric CO_2 concentration from fossil fuel consumption if 54% of the released carbon remains in the atmosphere.*

Fuel Burned	Carbon Retained in the Atmosphere [10^9 t]	Atmospheric Concentration CO_2 [ppm]
(Present concentration)	(706)	(332)
Coal reserves	310	480
Ultimately available coal	1470	1030
World resources of coal	5640	2990
World resources of oil	95	380
World resources of natural gas	58	360

*Numbers for the various categories of coal were achieved by taking Averitt's estimate of world coal resources [37] and subdividing that number in the same proportion that Averitt catalogued total US coal resources. Oil and natural gas resource estimates are from Moody and Geiger [38]. This simple table does not include the possibility that we may ultimately see extensive development of large but relatively dilute fossil fuel sources such as oil shale and geopressurized methane.

Returning to our 1250 quad scenario for 2025, we recognize that a critical element is the availability of fuel. The scenario presupposes that all of the countries either have fossil fuel--i.e. coal--resources, or can obtain access to them in world markets. Despite the inadequacies and inconsistencies of the World Energy Conference data on energy resources, and despite the large discrepancy between these data and the Averitt data on which we based our CO_2 calculations (the primary difference is a much smaller number for the USSR), the World Energy Conference data [39,40] do give some idea of the distribution of known coal resources (Table 2). Acknowledging some major differences, the coal resource percentages bear (probably not surprisingly) a qualitative resemblence to the current CO_2-production contributions. The conclusion then is that most of the developing areas of the world, in order to develop long-term, fossil-fuel-based economies, will have to either discover new resources or import coal from those few nations that are well endowed.

An important question that remains unanswered is whether the dearth of coal resources in, for example, South America, really represents a lack of coal or simply a lack of exploration. While Grossling [41], for example, maintains we simply have not

Table 2. World coal resources.

Source: World Energy Conference [39,40]

World Region	Coal Resources $[10^9$ t]	Coal Resources [% of world total]
USA	3598	30.7
Canada	103	0.9
Western Europe	573	4.9
USSR	5710	48.7
CTP Europe	126	1.1
Japan	9	0.1
Australia, New Zealand	351	3.0
Developing America	41	0.3
Developing Africa	96	0.8
Developing Asia	105	0.9
Developing Middle East	<1	0.0
CTP Asia	1003	8.6
	11,715	100.0

looked, others seem to believe as strongly that the coal simply is not there. A recent UN study [42] does point out that resources in many countries may be very significant in relation to internal demands and long-term needs. They list more than 30 developing countries with either existing or promising coal potential. At present less than 10 percent of world coal production enters international trade and only about 3 percent--mostly coking coal--enters intercontinental trade. The other side of the coin is that if many developing countries are successful in identifying large, new coal resources, then the total potential for altering the atmospheric CO_2 concentration will be increased correspondingly. (This discussion ignores, of course, such potentially important issues as the availability of capital to buy coal and the willingness of potential exporters to bear the other environmental consequences of coal development.)

Harrison Brown [43] has proposed a series of syndromes for world disaster, one dealing with CO_2. He raised the very important query whether the developing nations, for example, would be willing, or able, to curtail fossil fuel burning or to implement expensive CO_2 control measures. It is doubtful that all nations would assign equal priority to concerns about climate changes. Economic growth, social stability, etc. might be of greater concern to some nations than changes in climate. Also, it seems likely that as the climate changes related to the atmospheric-CO_2 increase become well defined, some nations may perceive the changes as being to their benefit while others perceive them as being to their detriment. We have already seen that any climate change is likely to be more pronounced at higher latitudes and, as an extreme example, Kopec [44] has calculated that a complete melting of polar ice would inundate 16.8% of North America but only 7.2% of Africa.

In this same vein, Dyson and Marland [45] have posed a very critical question. If, in the future, we demonstrate that the atmospheric CO_2 level is leading to an acute ecological disaster, we will have to switch to alternative energy-supply systems. However, would it be possible to halt or reverse the rise in CO_2, within a few years, by means less drastic than the shut-down of industrial civilization? After examining a science-fiction sounding array of "technical fixes", ranging from CO_2 scrubbers on power plants to vast tree plantations, the inescapable conclusion was that any conceivable solution would be immense in scale and require virtually unprecedented global cooperation. For example, in a tree planting scenario undertaken at some unspecified time in the next 25 years, the USA could provide only one tenth of the required planting. Although some localities might realize benefits from climate changes, Budyko [46] has pointed out that "an essential change in global climate would not be desired because national economies of different countries of the world are adapted to present climate".

While it seems likely that, regardless of the total impact on humanity, global agreement will be difficult to achieve if the costs and benefits of fossil fuel burning are unequally distributed on this political Earth, it is possible that global agreement may not be required. If, as suggested by Table 2, the USA, the USSR, and China control almost 90% of the world coal resources, these three countries may be able to manipulate world coal markets according to their perceptions of the danger to their particular interests. If these three high-latitude countries conclude that impending climate changes would be to their disadvantage, they could presumably restrict the long-term availability of coal. Examples for such an effort to control international trade for the benefit of national interests are already available in the OPEC oil cartel and US efforts to discourage nuclear proliferation by restraining trade of nuclear materials and technology.

On a shorter time scale there is probably enough fossil fuel available to nearly all nations, and the world commitment to economic growth and a fossil-fuel-based economy may be so strong, that decisions will be extremely complex and involve more participants. Our concern is that some commitment may be required in the relatively near future and that the time scale for action may be relatively short--of the order of a few decades. Such a commitment will have major implications for the socioeconomic systems in the developed countries and for the growth aspirations of the developing countries.

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FUTURE COAL SUPPLY FOR THE WORLD ENERGY BALANCE

Third IIASA Conference on Energy Resources,
November 28-December 2, 1977
Michel Grenon, Editor

There is growing concern and interest in the re-emergence into the energy picture of "King Coal." Coal, as it is produced today and, still more, as it will be produced tomorrow and in the next century, has many new features. Reserves and resources are revised upward, by jumps greater than the total estimated world oil resources. Production techniques are shifting from fully automated underground mines to gigantic surface mines with annual capacities of some tens of millions of tons. Coal slurry pipelines will be used for transportation, and sophisticated processes can transform coal into almost any other fuel: gas, syncrude, methanol, gasoline, and so on.

How do the various nations, whether producers or consumers or both, react to these changing conditions? And what could be the effects on the future world energy balance, and on a potential world coal market trying to compete with the world oil market?

All these questions—and many others—were raised and dealt with during the Third IIASA Conference on Energy Resources, devoted to Future Coal Supply for the World Energy Balance. More than seventy experts from East and West—technicians, economists, futurologists, modelers—contributed. The papers presented in this book treat technical aspects and prospects and economic (national, international, and global) problems and perspectives.

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