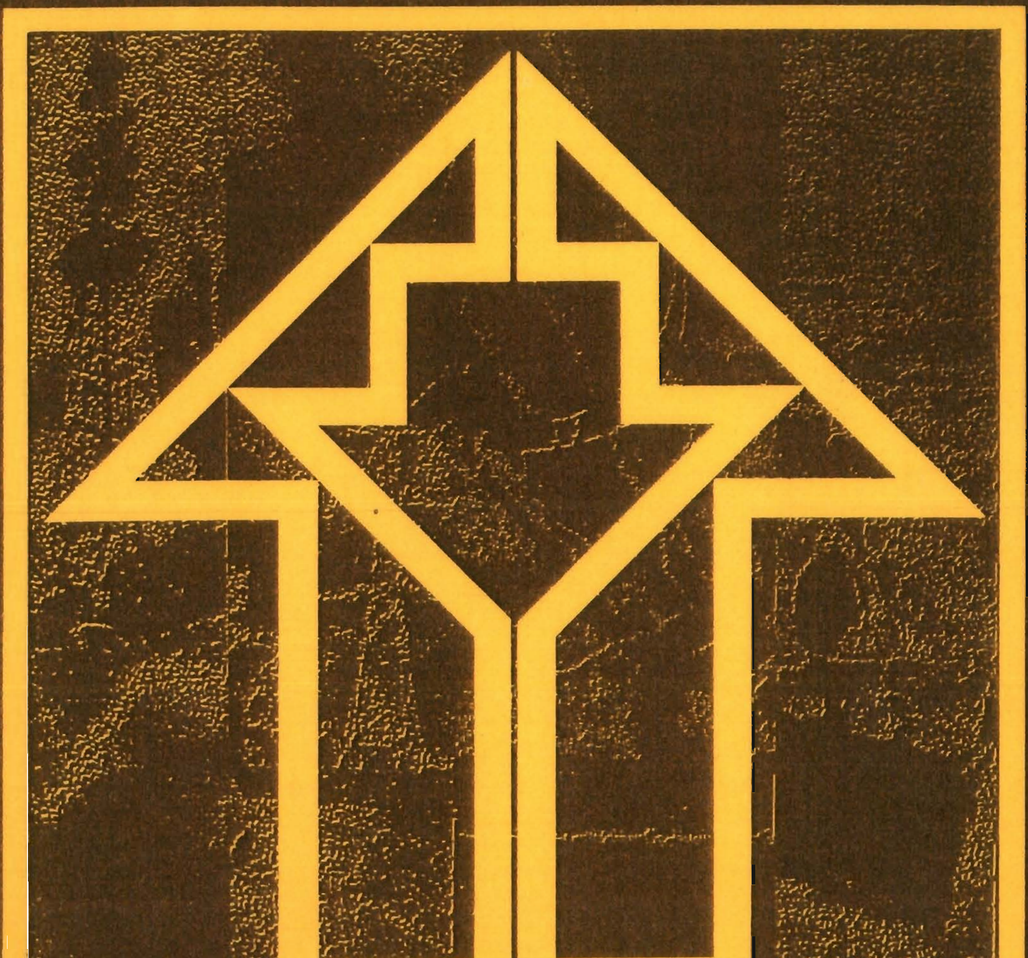
IIASA PROCEEDINGS SERIES

Methods and Models for Assessing Energy Resources

First IIASA Conference on Energy Resources, May 20-21, 1975

Michel Grenon, Editor



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IIASA PROCEEDINGS SERIES

Volume 5

Methods and Models for Assessing Energy Resources

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METHODS AND MODELS FOR ASSESSING ENERGY RESOURCES

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MICHEL GRENON
Editor

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FOREWORD

Next to the clash of ideologies, the most critical middle- to long-term problem affecting humanity is the supply of energy. If this problem can be solved, populations can be fed, mineral resources of lower grades mined, and industry maintained. If it cannot, the outlook for our children is very serious.

Conventional energy sources need to be balanced against, perhaps augmented by new, unconventional sources. Some observers think that within 33 years, petroleum production must seriously decline. Coal, though plentiful in some countries, is attended by social and environmental problems if it is to be won in larger quantities. There is said to be as little as 10 years' supply of proved uranium for the fission reactor. Fusion, solar, geothermal (especially injection-hot rock), and tidal energy sources all need to be considered.

IIASA is uniquely placed to consider and balance the possibilities, taking into account the numerous variables. These conferences, on sources and demand,* make a first attempt to do this.

Sir Kingsley Dunham
Foreign Secretary of the Royal Society
Member of the IIASA Council

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*See "Proceedings of the Workshop on Energy Demand, May 22-23, 1975" (1976), W.D. Nordhaus, ed., CP-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

PREFACE

It is generally agreed that mankind must prepare for a major shift in its energy structure. With a growing energy demand (even if people no longer agree on the actual growth rate of the energy demand, they nevertheless generally agree that it will continue to increase on a worldwide basis) conventional energy resources, and especially petroleum, will last only a limited time. This has been dramatically emphasized by M. King Hubbert, who demonstrated the shortness of the oil era within a total time span of plus or minus 5000 years before and after Christ. Even with coal, of which the resources are possibly 10 times greater than those for hydrocarbons, many scenarios point to a limited use period.

Fortunately, there are other energy alternatives. One of them is quasi-infinite, namely solar; others open the way to very great possibilities: nuclear fission with the breeders, thermonuclear fusion if successfully demonstrated, and possibly geothermal energy. Incidentally, various forces may even lead us to introduce some of these energy alternatives long before the conventional ones are exhausted: the growing concern about the impacts of energy production and consumption on the environment and on other resources such as land or water; political constraints or the national search for energy independence; simple economic considerations. Is there not, for instance, a school of thought that claims that nuclear electricity is already much cheaper than conventional electricity produced from coal or oil at today's prices?

If all possible energy alternatives were to be developed, we would progressively shift from a threatening energy shortage to an endless energy surplus. But, in fact, each energy option has its problems and, unfortunately, its negative effects. It is thus a major task to compare the various energy alternatives. The International Institute for Applied Systems Analysis (IIASA) has undertaken such a task. But it is also an extremely difficult task because the tools for making such comparisons simply do not yet exist. Scientists have to develop these new tools while at the same time trying to obtain preliminary answers.

Among the many factors that must be taken into account, the amount of resources is of major concern. It is not sufficient to say that under given conditions (say, with the nuclear breeder) these resources are quasi-infinite, or unlimited on a time scale of many centuries. Such an oversimplification–or such overconfidence–has already brought its share of problems in the past. Resources will have to be harvested with a large impact on the environment. It is necessary to know where they really are and of what "quality" in order to assign them to various classes or categories, as the various classification schemes tentatively do.

And this task must be performed for the resources of the future to allow the recognition of choices and to illuminate these. But, never really having been done before, it must also be performed for the resources of today or say, of the next 10 to 50 years or so because the further we dip into the energy problem, the better we are able to sketch the possible energy picture of the future, and thus the more seriously do we realize the importance of the transition period. Owing to the size of the energy sector and its concomitant inertia, wrong–or premature–choices can be synonymous with a national economic catastrophe because of the required level of capital investment and the time scale involved.

A crucial question related to the future shift toward nonconventional energy resources is how long do we have to complete such a transition? How long can we continue to use our existing resources? If we discard them too soon it will cost us dearly because the accelerated conversion will be extremely expensive. If, on the other hand, we plan to use them for too long, we will have to rely increasingly on the less economical of them, with a resulting financial penalty. What then is, or what could be, the right time?

These are some of the reasons and questions that prompted IIASA to devote a special and continuous effort to resource assessment as part of its task of comparing energy alternatives and studying the transition. Within the framework of such an effort it became apparent that periodic conferences on resources would be a powerful instrument to help perform such a task, giving scientists from all over the world an opportunity to express and exchange views on energy resource assessment, as well as providing the IIASA staff with up-to-date information on the most recent data and methods. These methods are at least as important as the data and fit in very well with IIASA's general concern for developing systems analysis methodologies.

This Conference Proceedings is a publication of the first IIASA Conference on Energy Resources, which was held in Laxenburg, Austria, May 20-21, 1975, and which brought together about 100 participants from roughly 15 different countries.

Owing to the very broad nature of the subject of energy resources, it was decided that this first Conference would be devoted to a number of general problems (including the fundamental problem of resource terminology and classification) and would include three other main sessions on conventional energy resources, namely: coal, conventional hydrocarbons, and uranium. It is clear that these three types of energy resources are very different:

- Coal has enormous resources, nearly all of which have been located, if not always completely identified (say, in their three dimensions, or in quality or workability). For many years–many decades in most cases–there has been practically no coal deposit research or exploration, apart from a local scale for determining the next coal field to be mined.

- Oil and gas resources, the known amounts of which are far less considerable than those of coal, correspond to only a few decades of present consumption; for this very reason they are continuously being sought by the most powerful industry in the world. Methods of assessing these vital resources are becoming very sophisticated and are under continual development.

- Uranium resources (not including thorium resources, which are not of any present commercial or scientific interest) are again of a completely different nature. With the existing type of reactor, they hardly compete with oil insofar as possible duration is concerned. As is supposed, and probably correctly, with future thermal or fast breeders these resources would surpass coal by one and probably two or more orders of magnitude. But big industry has not considered them a target up to now (compared to oil, for instance) and most of them were discovered by private enterprise, if not by amateur geologists.

Because of these differences, the same emphasis could not be given to the various resources during the first conference. For coal, we tried to select the contributions that illustrated the diverse viewpoints and to stress the fundamental problem of converting these resources into reserves and sometimes, unfortunately, the reverse problem of converting known reserves into noneconomic resources. For uranium resources, the first and main problem is to locate them There is also a general consensus that we have not yet really scratched the surface of the potential uranium resources. To locate these resources, an adequate economic and industrial environment, which does not now exist, must be established. If it is really to be established, scientific methods of search and exploration will have to be used, drawing partly on other energy and mineral resource models or methods, in order to respond to the high demand of a commodity market able to grow faster than any other—if forecasts materialize, that is.

The hard core of this conference was the oil and gas session. In addition to a few general approaches, and reflections or comments on the modeling of petroleum resources, it was one of the first times that various types of models were really presented, discussed, and compared, both during the conference itself as well as during a follow-up specialized session organized on the spot. Behaviorist models, geological analogy, and objective and subjective probability approaches were openly and keenly discussed. Their evolution was, of course, recently boosted by the world oil situation. But this lack of maturity or, let us say, their margin for improvement, can be illustrated by the fact that their independent utilization by different oil companies results in bids for unexplored prospects that differ by an order of magnitude, if not more.

It is hoped that this book will make a valuable contribution to the state-of-the-art of the methodology of energy systems, which is also one of the goals of IIASA.

ABOUT THE BOOK

For organizational reasons, the various contributions to the Conference were divided into five sessions. However, we have preferred here to adhere to the original division into four main sections: General Activities and Classification of Resources, Methods for Assessing Petroleum Resources, Coal Resources, and Uranium Resources.

During the conference, all discussions were tape recorded and the typed version was revised by the contributors. During the sessions question and answer sheets were also used, which the participants completed most cooperatively. For this book, we have selected the better of the two versions, and we take responsibility for making some rearrangements and omissions. For clarity we have also added a very few papers that were registered for the conference but could not be delivered. Finally, in order to help the reader better understand our own line of thought in organizing this conference, we have added a few pages of linking text when considered appropriate. I gladly assume full responsibility for any error or mistake, my efforts having already been largely rewarded by the unforgettable kindness and support of all the participants.

ACKNOWLEDGMENTS

It is with great pleasure that I thank Sir Kingsley Dunham who accepted the Honorary Chairmanship of this conference in spite of his many other obligations, and who agreed to write the Preface. Sir Kingsley enjoys a justified reputation as a highly accomplished scientist among all resource experts. He is the representative from the UK to the IIASA Council of National Member Organizations.

I also owe a debt of thanks to Wolf Häfele, head of the IIASA Energy Project, who supported the idea of holding this conference from the onset, took a constant and active interest in its organization, and enlightened many of the discussions by questioning and commenting on the fundamental points of energy resources in the right perspective of long-term energy alternatives.

Gregory Baecher, with his two contributory papers, and through his astute advice on the organization of the conference as well as the assumption of full responsibility for the follow-up session on the modeling of petroleum resources and subsequent revision of its typing, has contributed extensively to the realization of our meeting and of this book and merits even more than these very warm and heartfelt thanks.

On the scientific side, all the conference participants contributed most valuably and our sincerest thanks are owed them. We should like to thank, in particular, those who kindly chaired the various sessions: M. King Hubbert, U.S. Geological Survey; M. Styrikovich, USSR Academy of Sciences; J. Masseron, Institut Français du Pétrole; and J. Cameron, International Atomic Energy Agency. The heavy workload of the IIASA staff during the sessions was lightened by the enthusiasm with which everyone tackled his individual tasks.

On the organizational side, I owe an inestimable debt of thanks for their kindness and indefatigable contributions to all the IIASA staff involved.

M. Grenon

CONTENTS

GENERAL ACTIVITIES AND CLASSIFICATION OF RESOURCES

GENERAL ACTIVITIES

Having emphasized in the Preface the general importance of assessing energy resources, it will be seen from the first paper how this work fits into the overall tasks on resources in the IIASA Energy Project. The other contributions in this section deal with energy resource data, their collection and use, and with a systems approach to the economic estimating of fuels.

One of the tools employed daily in energy is, of course, the handling of data. Going into detail it is easy, and unfortunate, to discover how scarce and, most often, how inconvenient these data are--a fact which was made dramatically evident by the energy crisis. If we can say that the situation is already difficult with national energy statistics, it is worse on the world scale and especially so for resources.

For many years--and especially with the three Surveys of 1962, 1968, and 1974--the World Energy Conference has been making a strenuous and valuable effort to improve the data situation; the results are still, however, far from perfect. In the last Survey, prepared from the World Energy Conference in Detroit in September 1974, special attention was devoted to the processing of the data, and this work, the reasons for doing it, and the plans to extend it, all were presented at the very beginning of the IIASA Conference during the session on General Activities and Classification of Energy Resources.

At a more restricted level, the concrete problems of a nationalized country--in this case, Hungary--are presented in the short paper presenting the energy situation there, and national statistics are used to illustrate historic trends.

Finally, the general application of mathematical models for the development of fuel estimating was reviewed, based on the impressive experience accumulated in the USSR with the mathematical models used to study the energy economy of the country.

CLASSIFICATION OF RESOURCES

In the WEC Surveys, and specifically in the last Survey in 1974, special attention was devoted to the classification of energy reserves and resources, although finally, because of the many varying features of the national classifications (when they exist), in most cases a simple classification dichotomy was chosen: proved reserves and then all other resources put together.

As long as resources are considered, let us say, in a static way like idle capital for a distant future, such a classification may be acceptable. This is no longer the case when studying strategies for which long term resources must be classified in various categories of cost and/or geological evidence (and/or extractability, plus many other possible factors) as far as possible. Moreover, if we consider strategies for future energy development it will also become necessary to introduce the time dimension into the classification systems, with forecasts of the possible evolution of the various categories of resources, from the least known and most expensive to harvest, to the proved and economic type; such a shift can occur through better geological knowledge (which means exploration programs) or improved technologies.

This problem of classification of energy resources is thus very important. But it is also controversial, as will appear from the lively discussions that followed the two papers devoted to it: the first paper considers resource assessments and the necessity for developing better methodologies--a fruitful reflection on all the domains that overlap a simple classifying and estimating problem; and the second paper, summarizing a study performed for the Electric Power Research Institute, analyzes the pros and cons of the USGS-USBM classification of energy resources, the so-called McKelvey diagram. This last paper is especially important as new efforts will possibly be made in various places (including IIASA) to improve the different existing classifications and maybe to explore the possibilities of standardizing them in order to reach some common definitions, which can dramatically aid any further global study of world energy resources.

These two papers are followed by a review of the classification of petroleum resources and reserves in the USSR, and a comparison of the classifications used in the USSR with those in other countries. This paper comments on the common points of the various classifications and stresses that it would be interesting to explore the possibility of adopting similar classifications throughout the world.

Immediately following the IIASA Conference, an informal meeting was held to discuss this problem of classification further. One of the main problems discussed at length was how to correlate existing classifications for exhaustible energy resources and future classifications for nonexhaustible energy resources (like solar energy or hydraulic potential) *for practical purposes*. During this meeting the possibilities for creating some permanent international group to promote reflection and to achieve some progress on this complex problem was also explored.

OPENING REMARKS

M. King Hubbert*, Chairman

One of the most important developments in contemporary scientific and technical thought is the growing awareness of the significance of energy in human affairs. The universality of energy in terrestrial activities can be appreciated when we consider that the earth is a nearly closed material system through whose surface environment occurs a continuous influx, degradation, and efflux of energy. As a consequence, the mobile materials of the earth's surface undergo either continuous or intermittent circulation. These statements encompass just about everything that happens on the earth, including our being here today at this Conference.

This flux of energy is a continuing process that, with only minor variations, has persisted throughout the span of geologic time. The principal sources of energy influx are but three: the solar radiation intercepted by the earth, geothermal energy from the earth's interior, and tidal energy from the potential and kinetic energy of the earth-moon-sun system.

Measured in units of 10^{12} thermal watts (Wth), the rates of influx from these sources are solar, 174,000; geothermal, 32; tidal, 3. It is thus seen that the solar influx is about 5000 times the sum of the other two.

Of the solar influx, about 30%, or $52 \cdot 10^{12}$ Wth, is reflected and scattered into outer space as visible short-wavelength radiation. This fraction is ineffective with respect to terrestrial processes. The remaining 70%, or $122{,}000 \cdot 10^{12}$ Wth, warms the earth, drives the circulation of air and water, and a small fraction, stored chemically by the process of photosynthesis, becomes the basic energy source for the physiological requirements of the plant and animal kingdoms of the earth's biological system. With one small exception, this energy undergoes a series of

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*M. King Hubbert is a research geophysicist with the USGS. He has taught geology and geophysics at Columbia University for 10 years, and was a professor of geology and geophysics (part time) at Stanford University for seven years. After 20 years in research with Shell Oil Company he joined USGS in 1964.

degradations until it reaches an end state of heat at the lowest ambient temperature of the earth's surface. This is then reradiated to colder outer space as long-wavelength thermal radiation.

The minor exception pertains to the minute fraction of plant and animal materials that become deposited in peat bogs and other oxygen-deficient localities where they cannot completely decay. When these became buried under great thicknesses of sedimentary sands and muds during the geologic past, they were preserved and converted into the earth's present supply of fossil fuels.

These processes are occurring now, and they also have been occurring during at least 600 million years of geological history. The oldest gas field of which I am aware has been found in Australia in late Pre-Cambrian rocks--perhaps 600 to 700 million years ago. In the USA and other parts of the world, oil and gas accumulations have been found in rocks of all geological ages from the Cambrian, nearly 600 million years ago, to the last million years in the Mississippi delta of coastal Louisiana.

The oldest major coal deposits are the bituminous and anthracite coals of the Carboniferous Period, about 280 to 350 million years ago. Then there are younger subbituminous coals of Mesozoic age (65 to 200 million years ago), Tertiary lignites, and finally peat which is accumulating at present.

The energy stored in the initial supply (before human exploitation) of recoverable fossil fuels is estimated to amount to $2.3 \cdot 10^{23}$ thermal joules (Jth). Other static stores of energy within mineable or drillable depths beneath the earth's surface are represented by earth heat, and by the nuclear energy obtainable from the heavy elements uranium and thorium by fissioning, or from the lightest element, hydrogen, by fusion.

An informative comparison can be made between the magnitude of the stored energy of the fossil fuels and the rate at which energy impinges upon the earth from sunshine. The energy obtainable from the fossil fuels, as we have noted, amounts to about $2.3 \cdot 10^{23}$ Jth. The effective solar energy influx is at a rate of about $1.22 \cdot 10^{17}$ Wth, or joules per second. This amounts to $1.05 \cdot 10^{22}$ joules per day, and the time required for the energy accrual from the solar influx to equal the stored energy of fossil fuels is only 22 days.

Considering that the solar influx is continuous and has been at about the same rate for hundreds of millions of years, it becomes obvious that the largest source of energy available to the earth, past, present, or future, is that from the sun.

Let us now consider the human historical evolution which I think is pertinent to this Conference. We have noted that the time required for the accumulation of the fossil fuels was about 600 million years. It has been only within the last 2 or 3 million years that man has emerged as the world's dominant animal species. During this period man began to do things with the environmental energy flux that no other animal in geological history had ever done before. Initially, this consisted of the manipulation of the ecological-biological system in such a manner as to increase the food supply. Then, about a million years ago, he did a momentous thing: he learned to build a fire, thus tapping the energy of wood--still a biological source of energy, but one not previously utilized for human purposes. By the time of the ancient Egyptians, he tapped a nonbiological energy channel, namely windpower, and by Roman times, waterpower. The net effect of all such activities was to increase the human population, both in density and in geographical extent, with corresponding adjustments in the populations of all other plant and animal species of the ecological system. However, the energy per capita increased but slightly because these changes occurred so slowly that the growth of the human population was fully able to keep pace with the increase of the energy supply. In fact, it was not until continuous exploitation of the fossil fuels was begun--coal about nine centuries ago and petroleum in 1859--that a supply of energy became available whose rate of increase of exploitation was capable of being greater than the rate of growth of the population.

There is a great contrast between the recent past and the present. Despite the fact that coal has been mined continuously since the eleventh century, the amount of coal mined since 1940 exceeds somewhat the amount mined during the preceding nine centuries. Similarly, the amount of oil produced since 1965 is slightly more than all the oil produced before 1965.

Finally, the fossil fuels are absolutely exhaustible. When coal or oil is burned the material constituents remain on the earth, but the energy content, after a series of degradations, eventually leaves the earth by outward radiation. According to the best present estimates of the world's ultimate crude oil supply--which I think are reasonably accurate--the world will probably reach the peak in its rate of oil production before the end of the present century. Disregarding the first and last 10-percentiles of the ultimate production each of which will require a longer period of time, the time required to consume the middle 80% of the world's ultimate oil supply will probably be close to the 60-year period from about 1970 to 2030. Thus, a child born within the last decade, if he lives a normal life expectancy, will see the world consume most of its oil during his lifetime. In the case of coal, the time span for the middle 80% is somewhat longer, but, according to one of the papers to be given at this Conference, it is possible that recent estimates of the world's coal resources may have been too large. In that case the peak in the rate of coal production may be reached within about a century from now. The time required to produce the middle 80% of coal may be as short as 200 years.

Hence, if we regard the period of exploitation of the world's supply of fossil fuels in the context of a period of human history extending from about 5000 years in the past to 5000 years in the future, the curve of the rate of production of energy from the fossil fuels would appear as a Washington Monument-like spike of about two or three centuries width for the middle 80% of the ultimate production. It would thus be evident that the epoch of the fossil fuels is but a transient and ephemeral event in the totality of human history, an event nevertheless that has exerted the most profound influence upon the human species that it has experienced during its entire biological existence.

In the light of these circumstances, it is hoped that the world's resources of the fossil fuels to be reviewed in this Conference may be perceived in their proper relation to the world's total energy system.

RESOURCE STUDIES IN THE ENERGY PROJECT OF THE INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

M. Grenon

INTRODUCTION

One of the main tasks of the International Institute for Applied Systems Analysis (IIASA) Energy Project is to compare the various long term energy options or alternatives (nuclear fission, nuclear fusion, solar, geothermal, and "carbon"--that is coal, conventional and non-conventional hydrocarbons, such as oil shales, tar sands, and heavy oil), and to analyze their embedding in the various "spheres" of human interest: the atmosphere, the hydrosphere, the ecosphere, the sociosphere, etc. After some limiting values have been elaborated (assuming an equilibrium population with a given energy consumption), two main tools are used for such studies and comparisons, generally applied to "model societies" (250 to 350 million people, various growth rates and/or types of energy consumption):

- scenarios for the transition from a pure fossil energy economy to a nonfossil or mixed energy economy, through linear programming models such as the Haefele-Manne model;[1]
- decision trees, showing the paths and branching points for implementation of new energy resources on a large scale. Generally these decision trees stress the importance of secondary energy forms (electricity, hydrogen, or methanol, etc.) and the necessity of planning their application very soon in the development of a new energy resource (as has been emphasized by the relationship between nuclear energy and electricity).[2]

Risk assessment (as studied intensively by a joint research project group of the International Atomic Energy Agency and IIASA) is an important chapter in these comparisons.

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[1] See W. Haefele and A. Manne (1974), "Strategies for a Transition from Fossil to Nuclear Fuels," RR-74-7, International Institute for Applied Systems Analysis, Laxenburg, Austria.

[2] See W. Haefele and A. Sassin (April 1975), "Applications of Nuclear Power Other Than for Electricity Generation", European Nuclear Conference, Paris.

Resource assessment is another important chapter. It is clear that energy resources are badly known and the decision makers realize the truth of this statement every day with growing acuteness. Compared to the reserves, the resources are like an insurance for which we have not really--or regularly--paid the premium, that is to say that we have not made a serious effort to improve our knowledge of them.

But in fact, what do we need to know about the resources? For our scenarios and/or for the decision makers, there appear to be two different points of view for this question of assessing energy resources:

1) An "absolute" point of view: one can try to know as much as possible about the various energy resources of importance today (mainly fossil) and then decide when do we need a new energy option? How long do we have to develop and implement a new energy resource?

2) A "relative" point of view: knowing that in any case we need a new energy option (or two, or three new energy options), and knowing also that we need a certain amount of time to implement it, do we have enough resources to make the transition as smooth as possible.

In the first case, we would like to know the maximum, or ultimate, amount of energy resources, and we would possibly like to live as long as possible with them. In the second case--more decision oriented--we need some kind of acceptable minimum value, assuming a more or less tight planning of energy development. The various attitudes toward the coal resources, depending on time, are somewhat illustrative of these two possible points of view.

Owing to the fundamental importance of this assessment of energy resources for any transition scenario and/or any decision trees for the implementation of energy alternatives, it has been decided in the IIASA Energy Project to perform our own assessment of energy resources. The main lines of effort, and preliminary results, are presented here.

RESEARCH STRATEGY FOR ENERGY RESOURCE ASSESSMENT AT IIASA

Generally speaking, the research strategy at IIASA is based on four modes of research activity:

a) in-house research,
b) collaborative research,
c) information agency,
d) conferences.

It is clear that this first IIASA Conference on Energy Resources is self-explanatory as far as point d) is concerned. Let me make two comments:

1) We have emphasized in the Conference invitations the methodological aspects of energy resources because development of adequate methodologies is one of the main objectives of our Institute through systems analysis, as shown by our research program.[3]

2) The fact that we have concentrated this Conference mainly on nonrenewable resources (and not all of these, moreover) does not mean that we underestimate the importance of renewable resources, for which a similar Conference could possibly be held later on, maybe next year. In fact, in the IIASA Energy Project, for example, we have had a major effort on solar energy since last year.

Concerning the information agency role of IIASA, the IIASA Energy Project is cooperating with the IIASA Survey Project[4] and will contribute to a systems analysis State-of-the-Art Series on energy resource assessment and to the Handbook on Systems Analysis for the energy systems sections.

As far as collaborative research is concerned, that is, research performed at IIASA and in various other organizations with a common objective under the initiative of IIASA, let us mention a few examples:

- a Coal Task Force is being organized to study the various aspects of possible utilization of coal on a very large scale. The National Member Organizations who have participated in our first session (on March 17-21, 1975) were the USA, the United Kingdom, and Czechoslovakia;

- a study has been initiated on the energy expenses of mining operations for energy resources. Collaboration has begun with France, and this is being discussed with the USA, Canada, and the United Kingdom;

- a Working Group on the Classification of Energy Resources has been initiated.

Finally, in-house research in the IIASA Energy Project is summarized in Figure 1, emphasizing three steps from the resources in the ground to primary energy consumption: energy resource assessment, energy resource production and world energy trade.

Regarding world energy trade, which is mainly concerned with the physical availability of energy commodities, explora-

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[3] See IIASA Research Program, 1975 (1974), Summary.

[4] See Research Program, pp. 22-23.

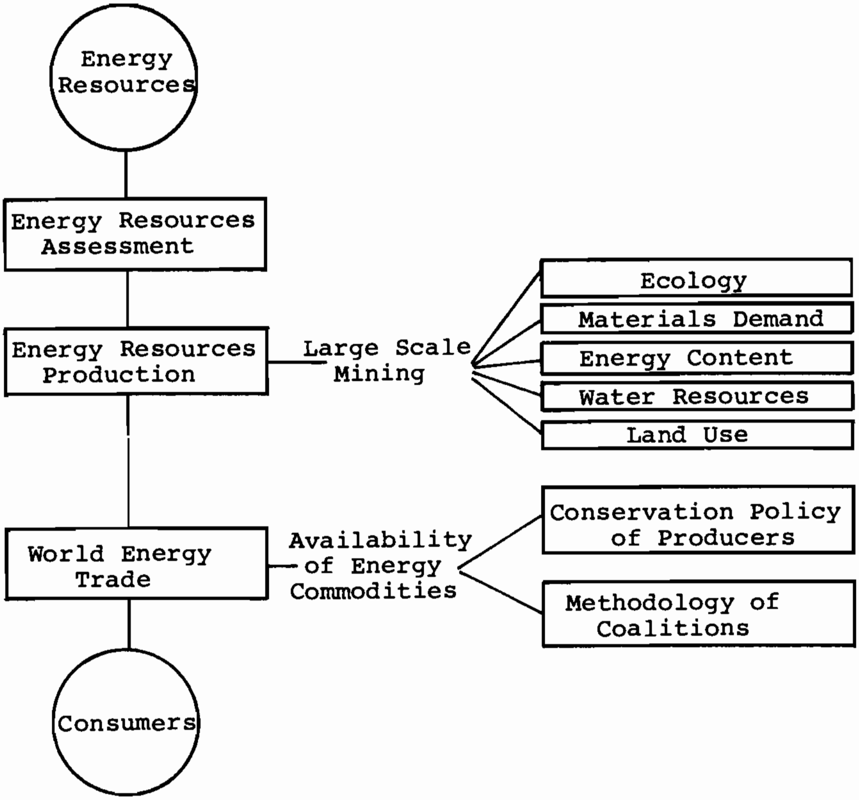

Figure 1. From resources in the ground to energy consumption.

tion studies are being performed on the methodology for assessing the formation and possible weighting factor of producer and/or consumer coalitions, and scenarios are run to estimate the effects of possible conservation policies of producers (calculations of necessary discoveries over a time span assuming various policies of domestic consumption and of international export commitments).

For energy resource production, the main emphasis is given to large scale mining problems (coal, oil shales, uranium ores of low content, etc.) including ecology, materials demand, energy expenses, water resources, land use, risk assessment, etc., that is to say, to the identification of systems effects of harvesting energy resources on a broad scale.

ENERGY RESOURCE ASSESSMENT

The studies on energy resource assessment are divided into three main chapters (see Figures 2 and 3): definition and classification, data, and methodology and models.

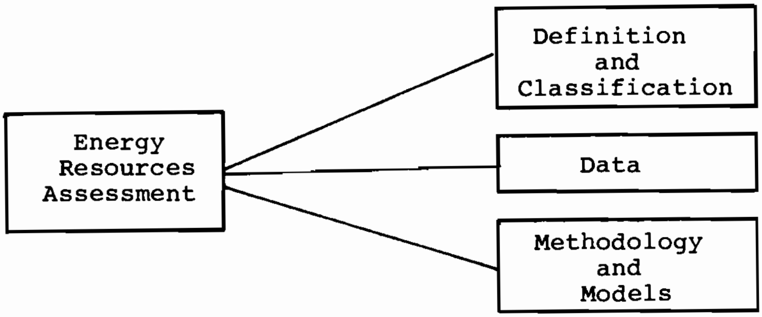

Figure 2.

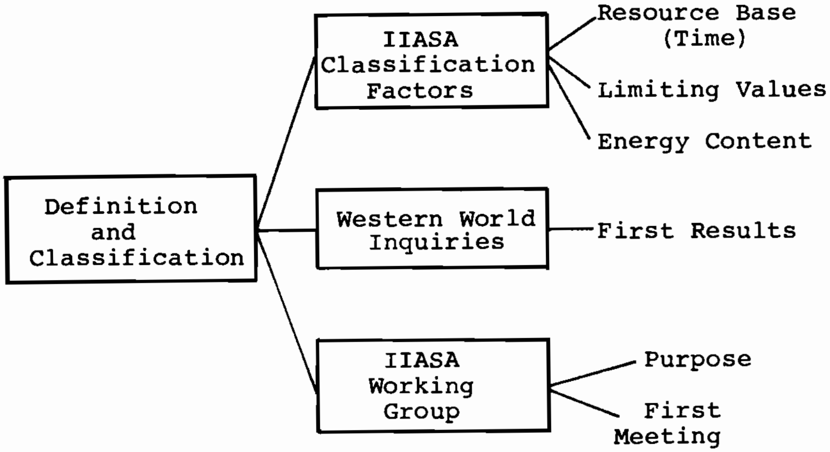

Figure 3.

Classification of Energy Resources

The classification of energy resources is a broad and interesting problem to which we think insufficient attention has been paid. Among the pioneers, it is worth mentioning McKelvey,[5] Schurr and Netschert,[6]

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[5] See various papers by McKelvey, such as USGS Professional Paper 820 (1973), and note USGS-USBM on new classification.

[6] See S.H. Schurr and B.C. Netschert (1960), "Energy in the American Economy".

Govett and Govett,[7] etc.

At IIASA, in fact, we are not so much aiming at a new classification as at a better understanding of the factors involved in some of the classifications of broader acceptance, such as the recent USGS-USBM classification of mineral resources evolved in 1974 (see Figure 4)[8] and/or the classification proposed by the Canadian Department of Energy, Mines and Resources[9] (see Figure 5).

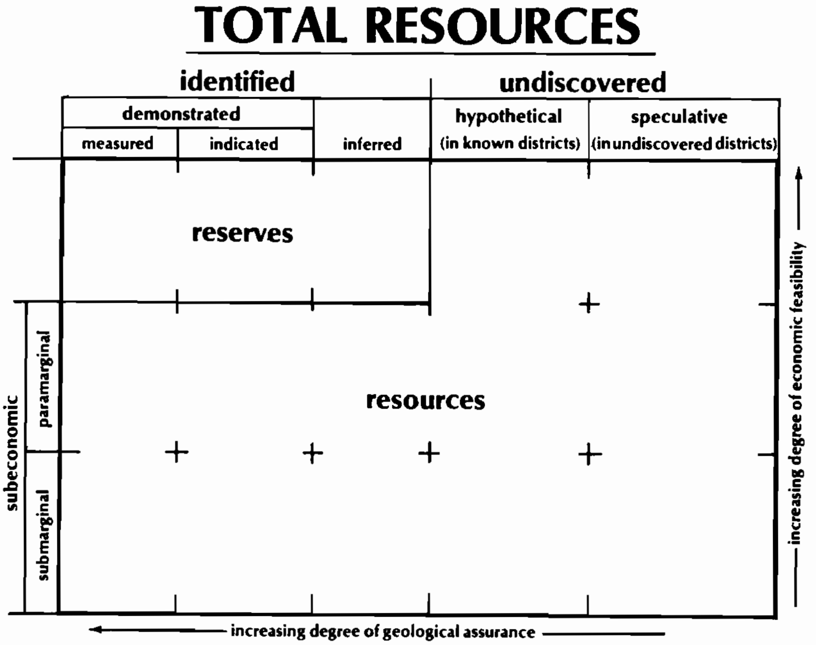

Figure 4. USGS-USBM reserves/resources classification (1974).

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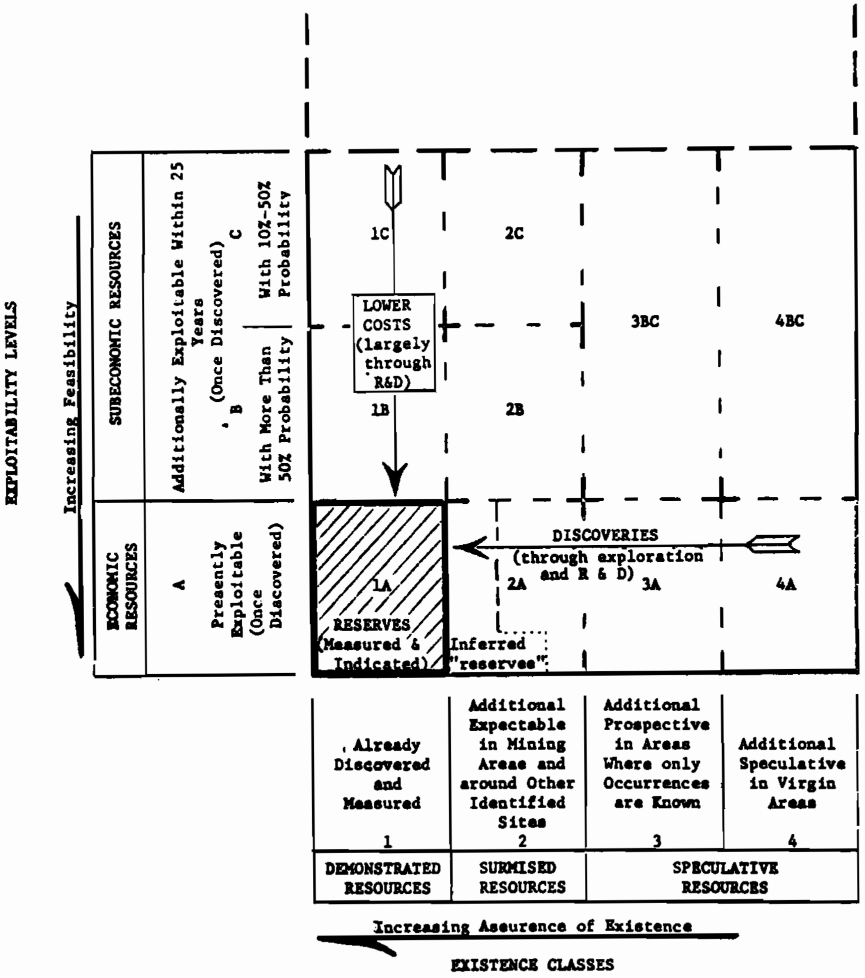
[7] See G.J.S. Govett and M.H. Govett (September 1974), "The Concept and Measurement of Mineral Reserves and Resources", Resources Policy.

[8] See, for instance, J.J. Schanz, Jr., "Problems and Opportunities in Adapting US Geological Survey Terminology to Energy Resources", in this volume.

[9] Department of Energy, Mines and Resources of Canada (1975), "Terminology and Definitions of Reserves and Resources".



RESERVES (measured & indicated) = 1A (that is, demonstrated economic resources)
RESOURCES = RESERVES + all other numbered areas
RESOURCE BASE = RESOURCES + indefinite area beyond top of diagram

Note: It has been found impossible in practice to make distinctions between 3B and 3C, and between 4B and 4C.

Figure 5.

The dilemma is that one either makes simple and clear classifications (at least at first sight) but leaves many factors inexplicit, or else one makes a much more complicated scheme but much more difficult to use generally. The choice of coordinates in the two criteria diagrams is a crucial one. Generally, in North America, the degree of certainty of geological knowledge versus the economic cost of production has been selected; this latter economic factor was until now much less emphasized in the classifications of the USSR and Eastern countries. The geological knowledge probably lends itself better to definitions than the economic costs, although the limit between known areas and unknown areas is not so easy.

For the economic ordinate, we think that the situation is far from clear. A simple example is given by the "forward cost" of USAEC, now ERDA, for uranium, which does not include leasing and exploration expenses, etc. It is, of course, much easier to compare different deposits of the same energy resources than to compare two different energy resources (a problem that faces the decision maker and that is of great importance in our program), and it is difficult to know what must be--or must not be--included in cost evaluation: transportation factors, ecology cost and/or land reclamation, technology involvement of subsequent elaboration of the resource to make it usable, etc.? It seems particularly difficult, especially in the era of rapidly changing economic conditions which we have now, to attribute reliable values to the paramarginal and submarginal limits of the USGS-USBM diagram. Here there is some conflict between the difficulty of knowing even the short term values of economic resources, and the long term planning requirements. Even the 25 years forward time of the Canadian classification is a short period for energy planning, where plans have to be made more and more on a 50 year basis at least.

Also related to the limits defining the various classes of energy resources of such diagrams--which are indeed badly defined transition zones rather than limiting lines--it is interesting to consider the mechanisms of passage of one class to the other through these "osmotic transition zones". Such passages occur when resources become reserves because of technological progress and/or rising prices, and when reserves unfortunately become noneconomic resources by the nature of the exploitation itself, as is well known for coal (for example, we can see the dramatic contraction of coal reserves in the United Kingdom) and sometimes emphasized for uranium resources. We think that the notion of the resource base, as introduced by the Canadians, is an extremely interesting one, even if we express some reserves about the 25 years time span mentioned above.

In a somewhat similar frame of mind, we have given some consideration to the problem of energy expenses relative to a given energy resource. Although these considerations concern in fact the whole energy chain or system, let us consider here the energy expenses involved in mining operations.[10] At its extreme, the problem can be stated as follows: with existing (and not necessarily energy efficient) technologies, can we consider as a resource the resources for which energy has to be spent in equal or greater amounts than can actually be recovered by using the commodity produced? The problem is probably not as severe as such a statement seems to indicate, but this concept of energy expenses is probably useful for the comparison of different energy resources (such as uranium shales versus oil shales of low content), if used in conjunction with other factors such as water resources requirements and land use and/or reclamation.

It is clear that the more we have recourse to low content ores or low content fuel resources the more severe the mining problem will become, as shown schematically in Figure 6. Opposition between, for instance, uranium (especially with the breeder reactors) and oil from shales is very evident; uranium from seawater has been included for comparison.[11] Figure 7 shows the theoretical curve of energy expenses (including depollution and possible land reclamation) versus energy content assuming that energy expenses can be split (as proposed by Brobst of the USGS) into a part independent of the grade and another part proportional to the tonnage of ore that is mined. Of course, it is clear that such a single theoretical curve does not exist, but it has apparently been approached for some copper deposits, and we are trying to investigate it for uranium and possibly for oil shales. Similar kinds of deposits must be considered; and for a range of grades, we try to calculate the energy expenses (direct, indirect and "investment energy") by also taking into account a few other factors, such as the depth of the deposit. For the broad classes of uranium deposits such as considered by Battelle for the National Science Foundation[12] (see Figures 8 and 9), similar calculations can be performed for purposes of comparison; some of them have effectively been performed, for instance for the uranium shales of Tennessee. Incidentally, this Batelle-NSF study is an interesting tentative study in estimating the amount of resources as a function of their cost, however imprecise it still may be.

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[10] As mentioned above, collaborative research is being developed on this subject with the French Commissariat à l'Energie Atomique and the French Bureau de Recherches Géologiques et Minières, and further research is being discussed with other organizations.

[11] See A. Brin, "Uranium From Seawater: A Review of Recent Papers", in this volume.

[12] See "Assessment of Uranium and Thorium Resources in the United States and the Effect of Policy Alternatives" (December 1974), Battelle Pacific Northwest Lab (supported by National Science Foundation).

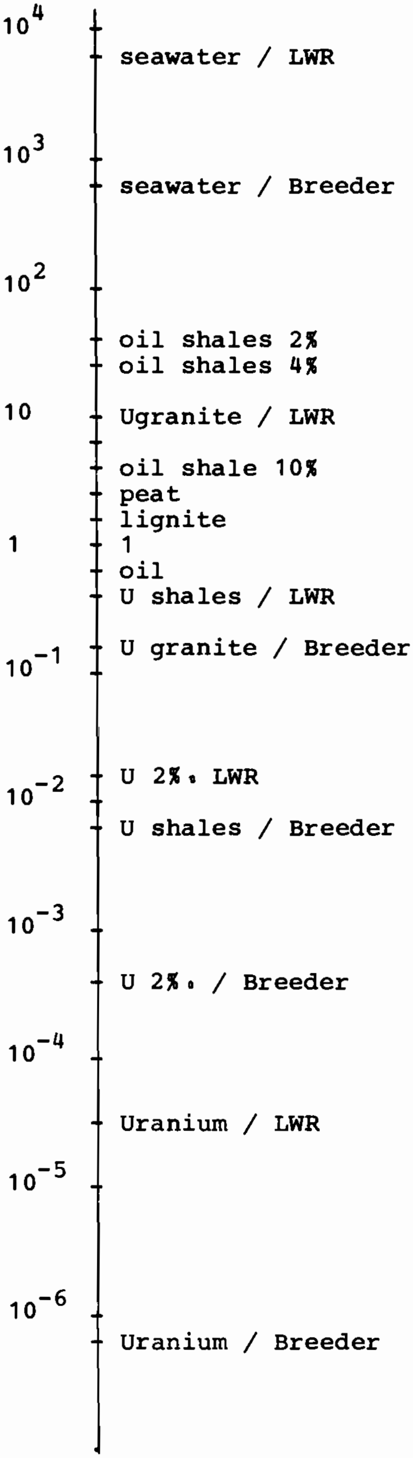
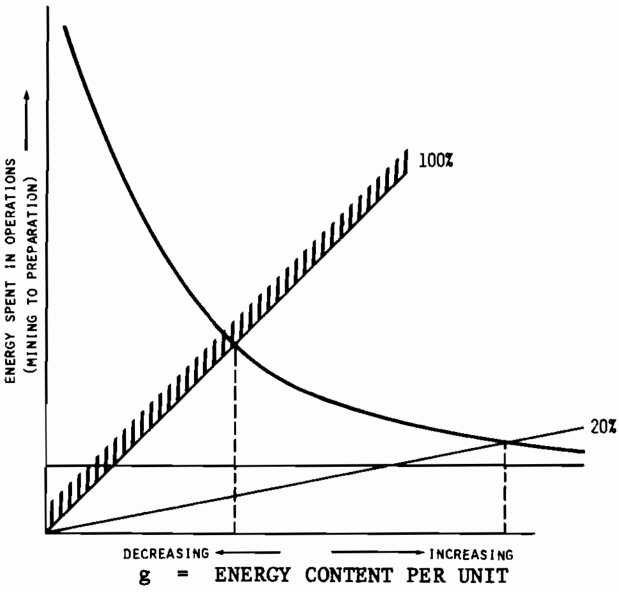

10^4
seawater / LWR
10^3
seawater / Breeder
10^2
oil shales 2%
oil shales 4%
10
Ugranite / LWR
oil shale 10%
peat
lignite
1
1
oil
U shales / LWR
U granite / Breeder
10^{-1}
U 2‰ LWR
10^{-2}
U shales / Breeder
10^{-3}
U 2‰ / Breeder
10^{-4}
Uranium / LWR
10^{-5}
10^{-6}
Uranium / Breeder

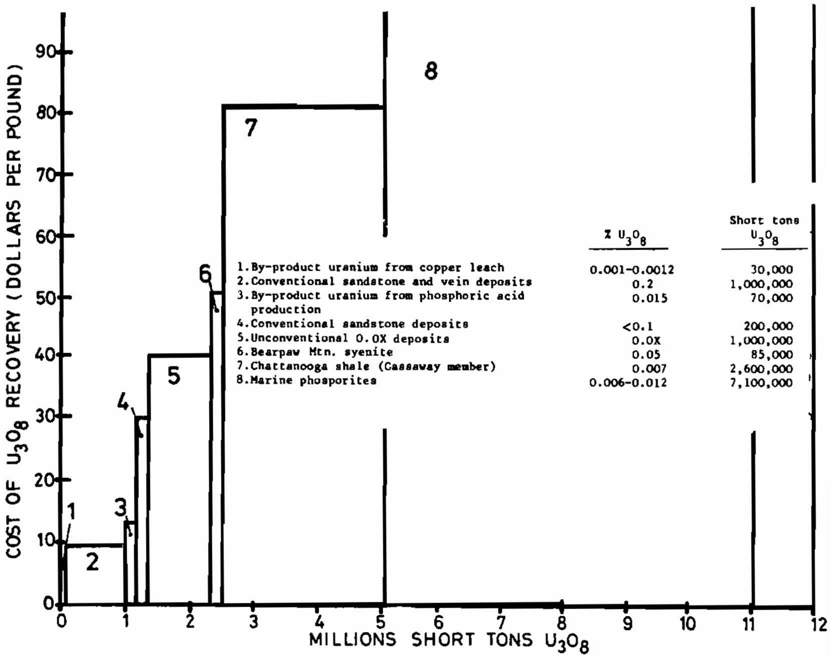
Figure 6.



$$E_s = E_c + E_m(T)$$

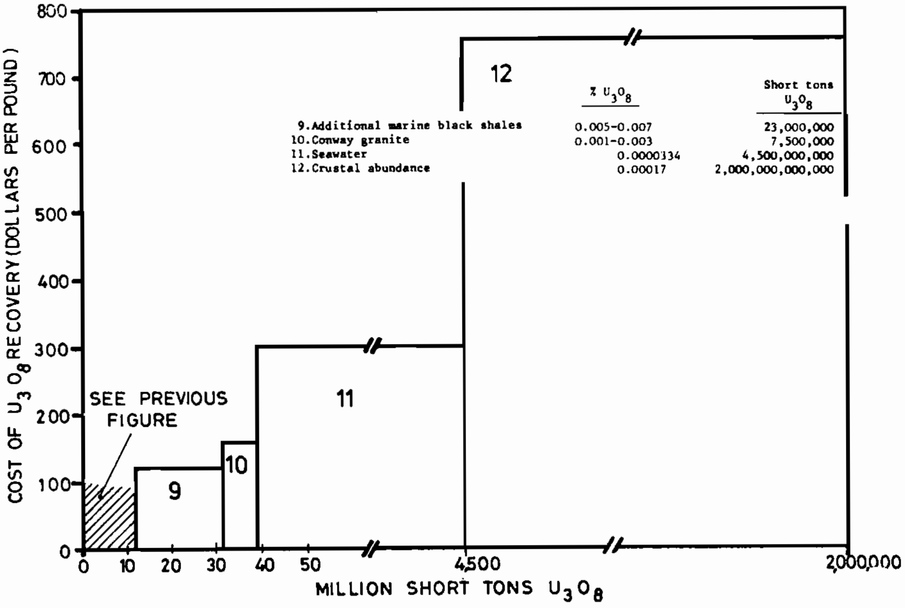
$$= E_c + E_m/g$$

Figure 7.



	% U_3O_8	Short tons U_3O_8
1. By-product uranium from copper leach	0.001-0.0012	30,000
2. Conventional sandstone and vein deposits	0.2	1,000,000
3. By-product uranium from phosphoric acid production	0.015	70,000
4. Conventional sandstone deposits	<0.1	200,000
5. Unconventional 0.0X deposits	0.0X	1,000,000
6. Bearpaw Mtn. syenite	0.05	85,000
7. Chattanooga shale (Cassaway member)	0.007	2,600,000
8. Marine phosporites	0.006-0.012	7,100,000

Figure 8. Estimated US uranium resource availability.



	% U_3O_8	Short tons U_3O_8
9. Additional marine black shales	0.005-0.007	23,000,000
10. Conway granite	0.001-0.003	7,500,000
11. Seawater	0.0000334	4,500,000,000
12. Crustal abundance	0.00017	2,000,000,000,000

Figure 9. Estimated US uranium resource availability in relation to US crustal abundance.

Lines of the ratio of constant energy expense to energy content--as shown by the line at 20%--can be used for the comparison of various energy resources, and for the identification of cost factors for the economic ordinate of resources classification. Similarly, this can help toward a better understanding of the "transition zones" and for orienting efforts in research and development.

Two types of comments of interest have been made on such classifications, one by M. King Hubbert and one by Milton Searl. As pointed out by Hubbert,[13] if an index is given to the various classes, growing with the economic factor and/or the geological uncertainty, it is clear that in the series giving the total amount of the resources:

$$Q = Q_{11} + Q_{12} + Q_{21} \mid + \mid \cdots \mid + Q_{mn}$$

---

[13] See M. King Hubbert (June 1974), "U.S. Energy Resources, A Review as of 1974", US Senate Committee on Interior and Insular Affairs.

(m, n depending on the number of subdivisions), the uncertainties will increase with the indices, and the value of the figures put in the higher class can be highly questionable. It may well happen that the uncertainty on, say Q_{mn}, may be higher than the reasonably known value of Q_{11}.

In his EPRI study on uranium resources,[14] Searl has assigned probabilities to the various values in different classes. The Canadians have also assigned fixed probability limits--although recognizing their difficulty--to their B and C classes of resources. This is surely an interesting development to pursue.

We think that there must be a correlation between the various classes of resources, as defined by the above diagrams, and the different mathematical models which have been developed for assessing energy resources (some of them will be presented during this Conference). Such work, as well as synthesizing the models, as will be explained later, must in reality be discussed with the people who have developed the models; this is really what we plan to do during and as a follow-up to this Conference. However, some preliminary and tentative results are shown in Figure 10. Figure 11 shows the "centers of gravity" of main development requirements as seen by a geologist.

Incidentally, it can be stated that, for the decision maker, the two coordinates of the USGS-USBM or Canadian classification schemes also point to two different kinds of action: the first, to improve technologies of recovery--probably at some cost--and move paramarginally and submarginally identified resources into the reserves area;[15] such action can significantly improve "energy independence". The second type of action, as proposed by geologists (and this is very clear for uranium, where probably many new areas are awaiting to be discovered all over the world)[16] is to improve dramatically geological knowledge through better models supporting exploration programs; owing to the fact that many unknown areas are probably located in foreign countries, this means relying more on international energy trade, and possibly on lower costs (if not always on lower prices).

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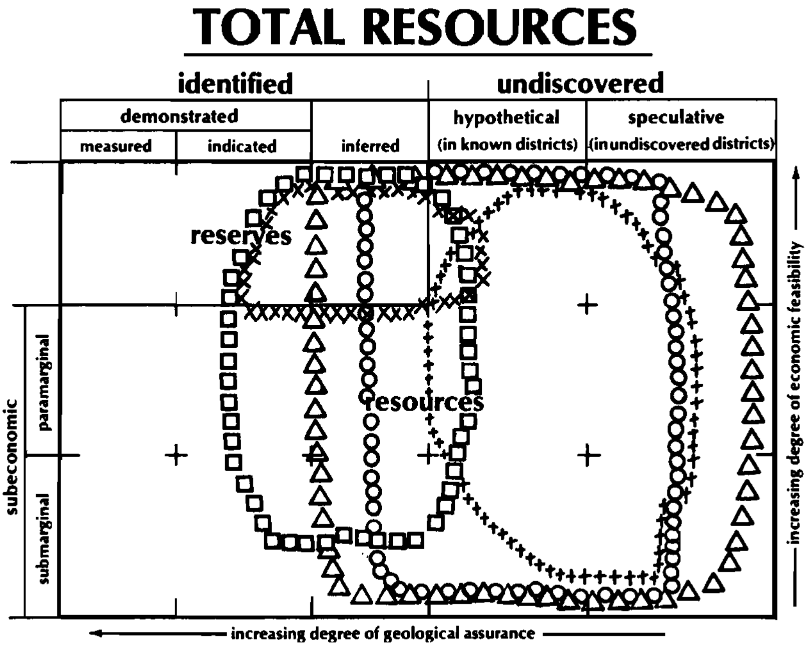
[14] See "Uranium Resources to Meet Long Term Uranium Requirements" (November 1974), Electric Power Research Institute, EPRI SR-58.

[15] Or to increase prices, deciding on a possible minimum price as discussed at the International Atomic Energy Agency.

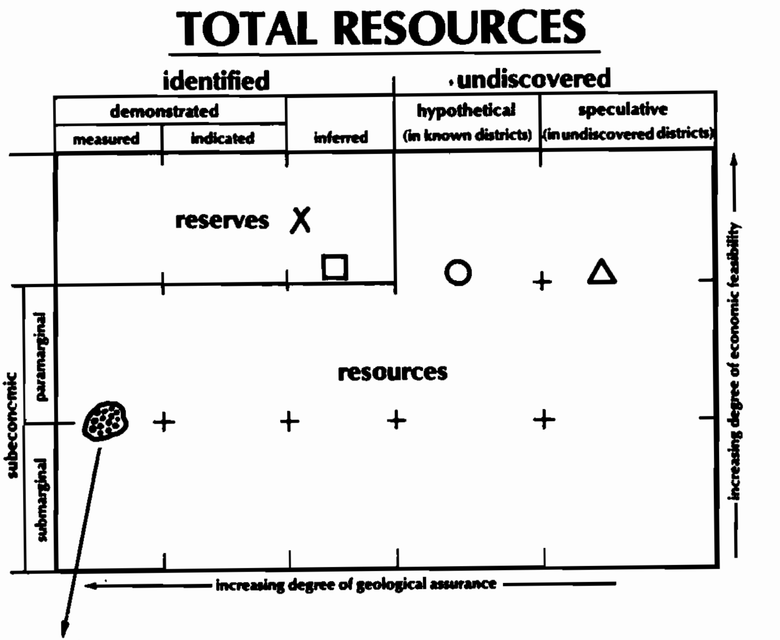
[16] See Yu.A. Rosanov, "Hypothetical Probabilistic Prototype of An Undiscovered Resources Model", in this volume.



xxx	Trend Extrapolation :	Hubbert, Moore
□□□	Sampling + Exploration Models :	Kaufmann, Uhler + Bradley, Rosanov, Griffiths, Slichter, Ryan
OOO	Regression + Factor Analysis :	Harris, Ray, DeGeoffray, Bates
++++	Volume or Area of Seds:	Many People
△△△	Subjective :	Harris et al., Kaufmann

Figure 10. USGS-USBM reserves/resources classification (1974).

Finally, we have recently launched at IIASA a survey on the uses of such classifications in various countries (with the exceptions of North America, which is surveyed by Resources for the Future--see Shanz cited above--and others, and of socialist countries) and we are now collecting and analyzing the answers. The objective of the World Energy Conference Survey of 1974 is quite different since we do not propose common classification nor do we collect data (although some organizations have sent us some figures). In fact, we are mainly interested in learning the comments of classification users, and, in a later phase,



not of present importance

most appropriate spots (center of gravity)

Figure 11. USGS-USBM reserves/resources classification (1974).

exploring the chances of adoption of a common classification system. Up to now, 30 countries have answered, and some of them have submitted very interesting comments that we are now beginning to discuss with them. A preliminary report, related to this first phase, will be written soon.

Data

IIASA does not collect data on energy resources (see Figure 12) and relies on other organizations, essentially the World Energy Conference for World Resources, or well known publications like World Oil, Oil and Gas Journal, Annales des Mines for sectorial resources.

Generally speaking, we confine ourselves to a critical analysis of these data. In some cases, as for instance for the Coal Task Force, it is planned to review in great detail, and possibly according to some guidelines briefly mentioned in the above section on classification, the available data for coal resources, especially in some countries where coal can play an even greater role than it is playing today.

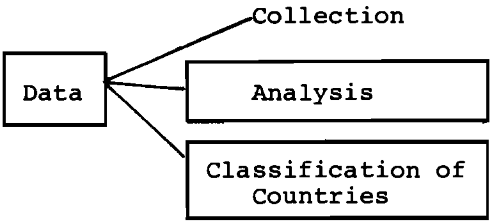


Figure 12.

A different activity, related to energy policies and energy strategies, has been to class tentatively various countries according to their energy reserves per capita (and later on, according to their energy resources) versus their energy consumption per capita. Figure 13 shows the principles of such a classification for various fuels. Figure 14 shows rough division in energy regions, with two diagonals delimiting energy self-sufficiency and the directions of energy trade. For one country, case histories can be drawn and some of the various directions and reasons for changes are illustrated in Figure 15. For a group of countries and one fuel, relative positions can be compared, both for present real values as for a virtual value corresponding to a given (increased) and "normalized" level of energy consumption per capita (Figure 16). This activity is systematically continued to progressively include all countries and the various energy resources.

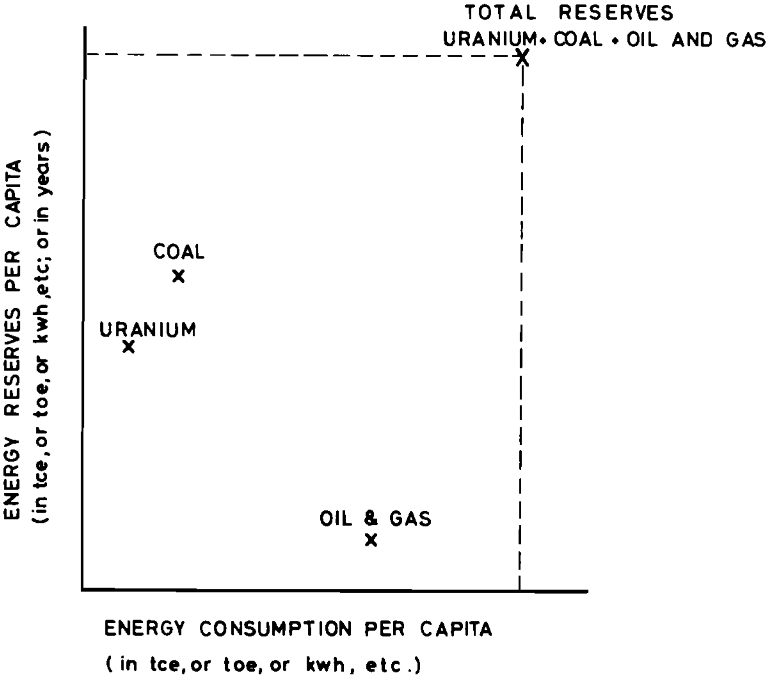


Figure 13.

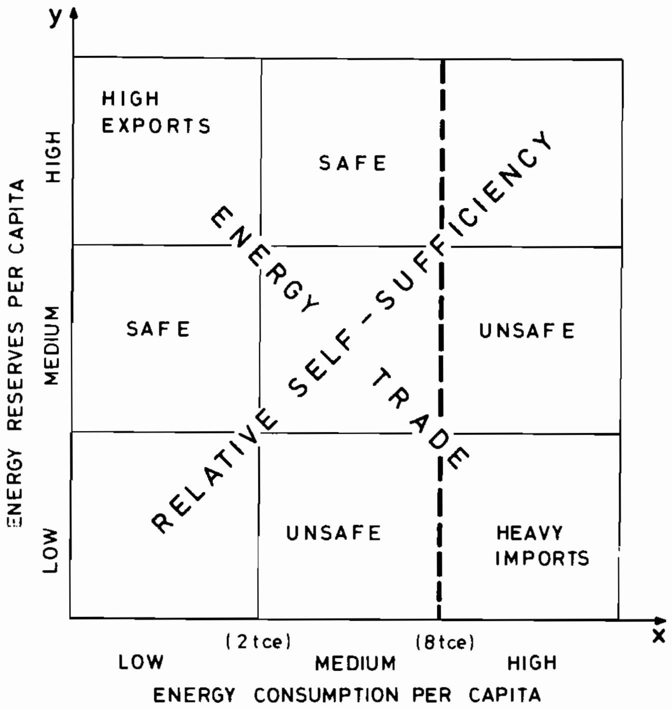


Figure 14.

Direction	Meaning	Possible Mechanisms
↑	Increase of Reserves	Discovery New Technology
↓	Decrease of Reserves	Consumption Abandon
←	Decrease of Consumption	Technology (that is, Efficiency) Conservation Change of Living Styles Political Decline
→	Increase of consumption	Development "Passivity"

Figure 15.

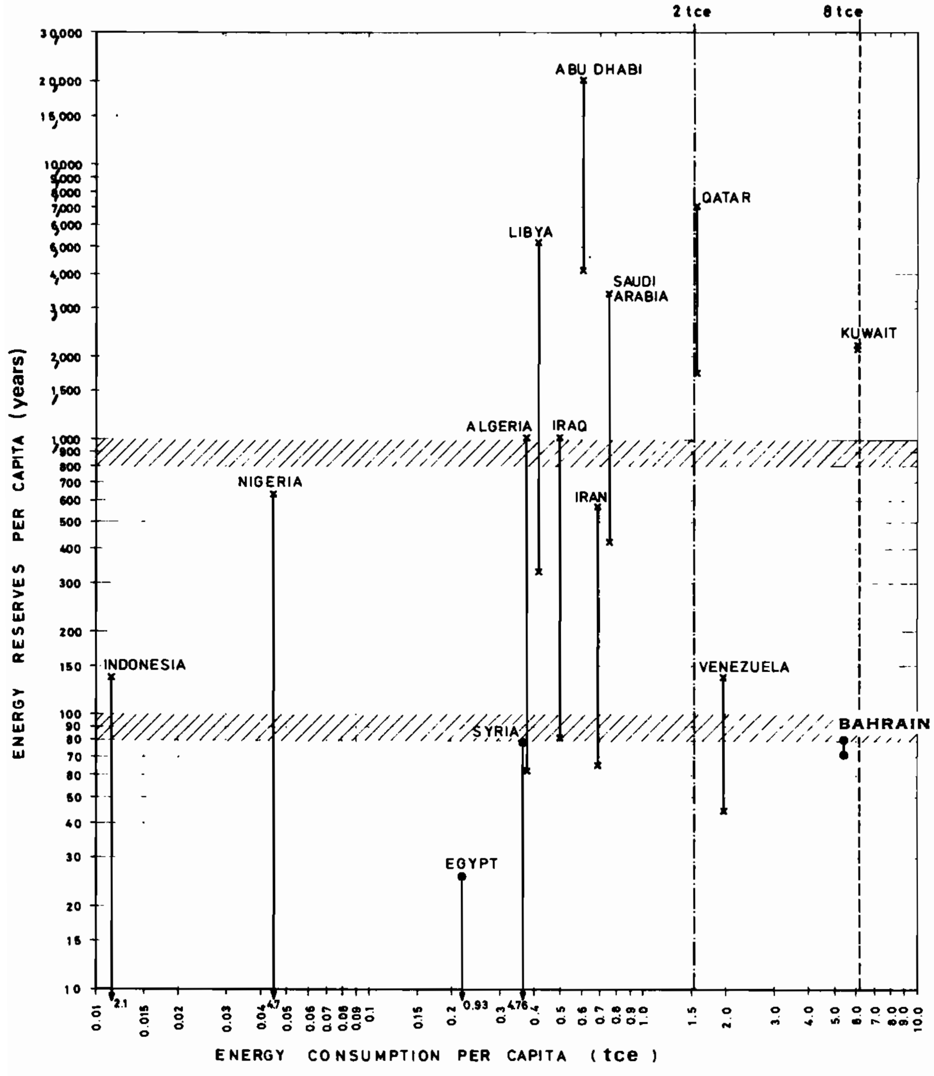

2 tce
6 tce
ABU DHABI
QATAR
LIBYA
SAUDI ARABIA
KUWAIT
ALGERIA
IRAQ
NIGERIA
IRAN
INDONESIA
VENEZUELA
BAHRAIN
SYRIA
EGYPT
2.1
4.7
0.93
4.76
30,000
20,000
15,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,500
1,000
900
800
700
600
500
400
300
200
150
100
90
80
70
60
50
40
30
20
15
10
ENERGY RESERVES PER CAPITA (years)
0.01
0.015
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.15
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.5
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
ENERGY CONSUMPTION PER CAPITA (tce)

Figure 16.

Methodology and Models

Some models for assessing energy resources are being developed at IIASA (see Figure 17), and some will be presented during this Conference by Yu.A Rozanov (mentioned above) and G. Baecher and J. Gros.[17] We are also pursuing a systematic analysis and cataloging of models used in the field of energy resources.[18] It is expected that the analysis, as mentioned above, will be continued with the help of the authors of the models. We plan to include them in the next annual issue of the Review of Models. Table 1 shows an example of the analysis of one model (Kenneth Hoffman's Brookhaven model for national energy planning), as published in the 1974 issue of the "IIASA Review of Energy Models".[19]

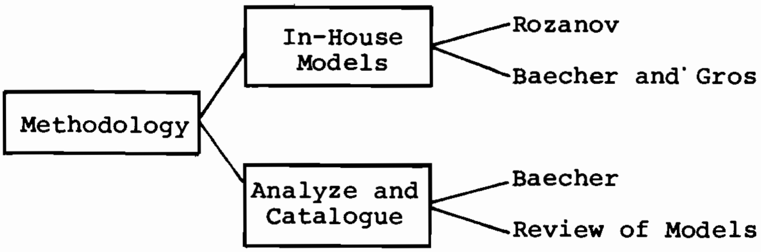


Figure 17.

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[17] See Gregory B. Baecher and Jacques G. Gros, "Extrapolating Trending Geological Bodies", in this volume.

[18] See Gregory B. Baecher, "Subjective Sampling Approaches to Resource Estimation", in this volume.

[19] See Jean-Pierre Charpentier (1974), "A Review of Energy Models: No. 1 - May 1974", RR-74-10, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Table 1. The analysis of one model.

The Model		Kenneth Hoffman, 1972 (61), Brookhaven National Laboratory, Upton, L.I., N.Y. Planning Framework for Energy System Planning.
Subject and Goal		Optimal technical structure of the US energy system. The model reflects a wide range of energy technologies and interfuel substitutability. It traces paths from primary consumption to final demand for each type of fuel.
System Described		This model is concerned with the substitution of different fuels at the level of disaggregated demand and supply. In addition, it estimates the volume of each type of pollutant produced by the energy system.
Area	**Time**	Static model for a particular point in time (has been applied to the years 1985 and 2000).
	Space	USA as a whole.
Modelling Techniques		Optimization model using linear programming. The model provides a feasible path between n=13 exogenous supply categories and m=15 exogenous demand categories. The objective function is the minimized solution of the present cost of the possible paths. Three constraints must be satisfied: the level of each kind of demand, the possibility of each kind of supply system, and the levels of the different pollutions. An expanded model is under development with 27 supply categories and 22 demand categories.
Input Data	**Physical**	n=13 supply categories are considered as follows: - 8 kinds of central stations that produce electricity as an intermediate energy form: hydropower, geothermal, coal-steam electric, LWR electric, LMFBR electric, gas turbine electric, pumped storage electric and solar energy. - 4 general purpose fuels that are directly delivered to consumers: oil products, natural gas, synthetic fuel (hydrogen) and coal gas and coal. - 1 decentralized electric supply system known as: total energy (up to 5 MW output) (diesel generators or gas turbine or fuel cells.) For each supply category, the model needs the knowledge of: - the supply constraint given in units of 10^{15} Btu. - the amount of energy that can be delivered by a particular supply category, limited either by the energy conversion capacity or by the quantity of available energy resources. m=15 demand categories are considered as follows: The demand is divided into 2 sub-categories: - exogenous demand, i.e. different categories of energy demand: space heat, air conditioning, electricity at 3 different load factors, water desalination, pumped storage, production of synthetic fuels, water heating, miscellaneous thermal heating, air transport, ground transport (public and private), iron production, cement production, and petrochemy and synthetic materials. - endogenous demand: for the electricity mentioned above the model takes into account the load duration curve of the system. For certain demand categories, the different plants can be mixed in order to optimize the global load factor curve. The load structures on a seasonal and weekly basis are taken into account.
	Ecological	The model incorporates air pollutants and other wastes generated by energy conversion activities that are proportional to the amount of energy delivered: CO_2, CO, SO_2, NO, particulates, hydrocarbon, radioactive wastes and thermal wastes. Other pollutants and land use will be incorporated in the expanded model.
	Economic	The coefficients of cost in the objective function reflect the necessary cost of the facilities used in the energy supply system as well as fuel and other operating costs. The necessary cost of capital for the electric supply category is a function of the plant load factor which is also a function of each specific demand category.
Output Data	**Physical**	The model gives for a specified level of each demand the optimal utilization of the different available supply systems.
	Economic	The model gives the total cost of the energy system but the resulting optimal path is greatly dependent on the different input costs.
	Ecological	The model gives the volume of the different polluting emissions.
Observations		- This model is static; it can be used only for one year. For that year it is necessary to know the demand and the supply categories. The level of the different kinds of demands can be obtained by using an input-output model. - The price electicity of demand is not taken into account in the current model but is being added to the expanded model. - Dynamization of the model is being studied.

Summary reviewed by the author of the model.

WEC ACTIVITIES IN THE FIELD OF SURVEYING WORLD ENERGY RESOURCES

L. Bauer and R. S. Carlsmith

1. MOTIVATION AND PROCEDURES

Since its formation in 1924, the World Energy Conference (WEC) has played an active role in efforts to improve and publish comprehensive data on world energy resources and their utilization. In 1929, the Central Office of the Conference published an initial study on the "Power Resources of the World, Potential and Developed." There followed a series of statistical yearbooks (1933 to 1958) that included information on resources and the available annual statistics on the production, stocks, imports, exports, and consumption of the several forms of energy in various countries.

In 1952, the United Nations began their "J" Series of Statistical Papers on the annual production, trade, and consumption of the various solid, liquid, and gaseous forms of energy and of electricity in individual countries and geographical areas of the world. The second number of this "J" Series was published in 1957 and the third in 1959.

In 1958, by agreement with the United Nations, the World Energy Conference became the primary source of information on world energy resources, and the United Nations continues to provide data on world energy production, trade, and consumption. At present, the WEC is the sole body undertaking a global survey of resources. United Nations data have been issued annually, with the sixteenth paper in 1973, giving annual statistics for the years 1968 to 1971.

In light of this agreement, the International Executive Council of the Conference decided in 1959 to discontinue its statistical yearbooks and to issue at intervals of six years a new series of publications entitled "World Energy Conference Survey of Energy Resources." A Consultative Panel was then appointed by the International Executive Council to advise on planning the details of the new series, the first of which was published in 1962 and the second in 1968 and the third in 1974. The US Atomic Energy Commission (USAEC) was asked to take a leading role in the conduct of the Survey 1974. Resource experts from other agencies assisted in the difficult task of preparing the resource questionnaires.

Preliminary versions of the questionnaires were presented in draft form for review by the Consultative Panel at meetin held in September 1972. Final revised questionnaires reflecting the Consultative Panel's directions were completed late in 1972. Arrangements were made for work on preparation of the latest Survey to be done at the Oak Ridge National Laboratory, Oak Ridge, Tennessee. The Laboratory was designated to receive the completed questionnaires, to collect and compile the resource data, and to write the document. The tasks of compiling, converting, and checking the resource data were all carried out at Oak Ridge. A computer system was used to store, rearrange, and prepare tabular material for publication. Narrative discussions on each of the energy resources were prepared by professional staff at the Laboratory.

Of the 69 National Committees of the WEC to whom--in the preparation of the 1974 Survey--energy resource questionnaires were transmitted, about 54 returned partial or complete replies. Four of these National Committees also returned a total of 27 replies for their dependencies. In addition, complete questionnaires were received from 11 nonmember countries, and three other nations reported that they had no energy resources of any significance. All data in the Survey are given in International System (IS) units.

2. DEFINITIONS

2.1 Energy Resources

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. Reserves, however, 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.

Considerable confusion, however, still remains in defining energy reserves and resources, particularly on a world basis, and one of the purposes of the current survey has been to attempt to resolve some of this confusion. To achieve this goal the Consultative Panel for the energy resources survey were very careful in preparing instructions for questionnaires in order 1) to meet the needs of as many groups of readers as possible, 2) to keep the instructions as simple as possible in order to promote maximum response based on readily available information in each nation, and 3) to obtain data from all countries on as uniform a basis as is presently feasible. A general summary of terms used in the present survey is tabulated in Table 1.

One of the reasons for a wide disparity in definitions of reserves and resources of energy raw materials among the various regions and nations is that present local usage is based on historical precedents which have evolved under differing social, legal, economic, and technical experiences and commercial practices. Thus, differences are most pronounced for long used resources such as coal. Definition for oil and gas, and more recently for nuclear fuels, are much more uniform not only because they have been used for a shorter time, but also because they relate to commodities of extensive

Table 1. Summary of reserve and resource terminology used in the present survey.

	Reserves		Other Resources[1]
Type Resource	Total	Recoverable	
Solid Fuels[2]	Known Reserve-in-place	Known Recoverable Reserves	Additional Resources
Oil and Natural Gas	Original Reserve-in-place[3]	Proved Recoverable Reserves	Additional Resources
Natural Gas Liquids	-	Proved Recoverable Reserves	Additional Resources
Oil Shale and Bituminous Sands	-	Potential Total Known Recoverable Resources	
Uranium and Thorium	-	Known Recoverable Reserves[4]	Additional Resources

Note: Terminology for Hydraulic Resources includes installed and installable capacity (power in MW) and probable annual generation (energy in GWh/year). Similar terminology applies, in general, to other renewable resources.

[1] Includes indicated (probable) and inferred (possible) reserves as normally defined.

[2] Total resources are also given for solid fuels.

[3] Includes past cumulative production.

[4] Alternative terminology (OECD) is reasonably assured resources (recoverable at costs up to approximately $26 per kilogram of U or Th). Reasonably assured resources recoverable at costs above $26 per kilogram are regarded as part of additional resources.

world trade necessitating common standards. The terminology of the American oil industry, for example, became standard national nomenclature and has now been introduced in many other countries throughout the world.

It should be noted, however, that the measurement and evaluation of energy reserves and resources may serve different purposes in different settings, and the use of a common world terminology may still mask important differences in local basic data. Differences in definitions have arisen partly through the extent to which geologists, engineers, economists, and businessmen have imposed their outlook on definitions. Thus, until recently, resource definitions have been more geologically and technically oriented in the countries with centrally planned economy and more economically directed in other nations. The result of all of these factors is that there are rational bases for the disparity in definitions, and that fully acceptable and effective world wide definitions, for some resources will be difficult to achieve.

In the latest survey resources were divided into two general categories. Category 1) includes identified or known reserves-in-place which are well delineated or closely appraised, while Category 2) embraces all other additional resources including those not yet discovered but believed to exist on the basis of geological evidence. Category 1) included the total identifiable amount of material estimated to be in-place in known deposits, as revealed by outcrops or by mining or drilling and by detailed sampling to establish its type and grade. The fraction of material unlikely to be recovered under existing technological conditions is part of the estimated total. By difference, the portion recoverable under current economic conditions and using current technologies is the Known Recoverable Reserves. Category 2), Additional Resources, includes all other classifications with a lower degree of geologic certainty as to their existence than those indicated as known. This includes resources estimated to exist on the basis of general knowledge of geological conditions favorable for their occurrence. It also includes deposits for which there are few, if any, samples or actual measurements.

Thus, estimates of quantities are generally based on the results of geological or exploratory information or on evidence of duplication or parallelism of geological conditions in which known deposits occur. Such definition gives wide latitude for estimates in this category which is necessary for large parts of the world where little or no data exist that would permit reporting under rigidly specified criteria. Careful consideration of each of these points in using the data in the report 1974, and in other resource documents should prevent misuse of such data and the drawing of unwarranted conclusions based on the limited scope and accuracy of such data as are now known.

2.2 Standardization of Terms of Energy Economy

In a major effort to reduce possible misinterpretation of data, experts of the four German speaking nations (Austria, the FRG, the GDR and Switzerland) compiled a catalogue of approximately 800 special terms in the following fields of energy economy:

1) general terms,
2) electricity economy,
3) hydro economy,
4) mining and processing of solid fuels,
5) mining and processing of liquid fuels,
6) mining and processing of gaseous fuels,
7) nuclear economy,
8) environmental production.

For all of these 800 terms, definitions were established having given due consideration to already existing practices and definitions arrived at and established by various national and international bodies like UCPTE, UNIPEDE, GAS UNION, etc. By agreement with the Executive Council representatives of English, French, Spanish and Russian speaking members will evaluate these definitions in order to arrive at closely correlated corresponding definitions. The WEC will then propose these terms and definitions for general use.

3. CRITICAL ASSESSMENT

Analyzing the described procedures the following details of data compilation and survey preparation have to be mentioned. Reference is made in particular to the Survey 1974 as it represents the present state of the art.

Because it was possible only to change the raw data as received from the contributing countries in minor ways, the data were not treated in so much of a formal statistical way as they could have been had such restrictions not been imposed. Prior to the receipt of the formal official data provided in the standard questionnaires by each contributing nation, literature searches were made for data on each energy resource and for each nation. This resulted in preliminary tabulations of the latest published estimates of the various energy resources from nations where data could be found. Where duplicate data did not agree, attempts were made to resolve such discrepancies and to choose the more accurate quantities. The data in these tabulations provided the basis for reporting resources for those nations that did not return questionnaires. When available, data from the WEC "Survey of Energy Resources 1968" was used, except where later information could be proven to be more accurate.

As the questionnaires were received from each reporting nation, the reported data were checked against the preliminary tabulations. Where there were significant variations, a letter was written to the reporters in the particular nation to determine whether they had made an error. In some instances reporting errors were corrected, but in most cases the initially submitted information was found to be correct. Probably the largest error in the existing resources literature corrected in this way was the downward revision of Canadian coal resources from 1,000,000 million tonnes to the real value of 100,000 million tonnes. In any event, the answers to queries were used without question because it was agreed that national knowledge resources were the most accurate source of data.

In a few instances questionnaires were filled out in a language other than English. These were first translated into English. When all data in a set of questionnaires were verified, the comments and references were edited when necessary to make comments from various nations as uniform as possible. Then the numerical and keyed data were appropriately marked and the questionnaires sent to the computer center for alpha numeric key punching. Much information was reported in non-metric units; such data were automatically converted to the equivalent units by the computer. The computer also made all additions to obtain national totals when resources were reported for national subdivisions. Only single totals were necessary for most resources; however, for solid fuels totals were first made for coal ranks, and then the national total for all ranks.

The computer was of great value in rearranging data for output as given in the 100 pages of appendices in the finished document where statistical data are given first, followed by comments, and then by references. Use of the computer was also valuable in making last minute changes and in avoiding the need for tedious proofreading which would have been necessary had all this information been typeset. The final computer output was sent to the printer where it was reduced about 60% in size for direct offset printing.

The two most detailed tasks in preparing the computer inputs were the extensive editing of the geological descriptions in Appendix 1 and editing of the renewable resources descriptions in Appendix 9 of the Survey 1974. Since the replies to questionnaire 9 were provided almost exclusively in descriptive form it was impossible to give data on renewable resources in tabular form.

It was unfortunate that an early decision was made to do the summary tables in each chapter by hand so they would be more attractive. Computerization of these tables would have been quite simple and would have saved at least one to two man months of work. In addition it would have eliminated the few relatively minor errors that have been noted which resulted from last minute changes that had to be made manually. It is highly recommended that if the computer approach is maintained for the next edition then summary table output should also be computerized.

In preparing the summary tables, which listed only national totals data (and data by coal ranks), data for reporting nations were transferred from the appendices and combined with data for nonreporting nations from the preliminary tabulation sheets for each resource. Total energy contents of fuels were then computed using unit heat value data from the "WEC Survey of Energy Resources, 1968," or from other sources. Since many returned questionnaires were only partially filled out, attempts were made in the summary tables only to supply the missing data from other references; such auxilliary data were appropriately referenced to indicate a nonquestionnaire source. Finally, subcontinental (regional), continental and world totals (see Table 2) were computed manually.

Table 2. World energy resources and production as of 1974.

World Energy Resources[a]	Reserves	Additional Resources	Production[b]	
			1971	1972
Solid Fuels, 10^9 mt (Coal equivalent)	551	10,755	2.39	2.43
Liquid Fuels[c], 10^9 mt (Coal equivalent)	119		3.17	3.34
Natural Gas, 10^9 mt (coal equivalent)	69.9		1.53	1.62
Hydropower, TWh	10,300[d],[e]	80,000	1,300[f]	1,390[g]
Uranium, 10^3 t	5,000[h] (U_3O_8)		18.5	19.2

a) WEC. b) UN. c) North American shale oil and oil from bituminous sands are thought to outnumber oil reserves by a factor of two. d) 10,300 TWh of 300 GW. e) With a 95% dry period: 4,340 TWh at 540 GW. f) 1,300 TWh at 300 GW. g) Total hydro and nuclear energy production of 1972 amounted to 0.18×10^9 metric tons coal equivalent. h) Equals 4.25×10^6 metric tons metallic uranium.

The location of resources on the maps at the end of the Survey were derived partly from marked maps submitted with the questionnaires. In most cases, however, contributors did not send maps, so resource locations had to be obtained from other sources. For about half the countries that reported data by national subdivisions the subnational boundaries were shown on maps provided; for the other half, the boundaries were put down on the basis of good to poor descriptions and are not too accurate in some cases. Further, subdivisions were different for different resources in many cases. For example, fossil fuels were given on the basis of sedimentary basins, but hydraulic resources were reported for existing river basins.

Most of the text was written without the need for returned questionnaires. However, about 40% to 50% of each chapter giving the descriptive material on quantities and location of resources could be finalized only after receipt and evaluation of all questionnaires. Long delays in receipt of the last of the questionnaires made the writing of this part of the text a very rushed affair.

4. FUTURE ACTIVITIES AND INTENTIONS

Future intentions of the WEC in the fields of data collection, data interpretation and classification of resources can briefly be described as follows:

The intervals at which fresh data should be produced should not be greater than three years and should certainly not be more frequent than yearly. A period of eighteen months between the publication of fresh data would seem to be worth trying as an experiment. It would also conform to the triennial spacing of World Energy Conference.

Revisions of the 1974 Survey should provide for a possible observation of reactions from international and national bodies and individual experts on the quality and form of the 1974 Survey data. The text of the present chapters should remain unchanged except for minor modifications until the publication of the next full edition in six years' time.

The computerization of the tables should be extended to include those tables at present part of the text. This processing would be particularly valuable if it were decided to revise the data at frequent intervals.

Tables should be closely overhauled for inconsistencies arising either from the form of the questionnaire, the form of the answers or from obvious inaccuracies.

Efforts should be made to achieve great comparability of data. This may involve a revision of the questionnaire with the cooperation of the members of the Consultive Panel and possibly other international organizations.

Classification of resources and reserves is dependent not only on the inherent richness of the source material but on the technical means and the economic costs of unlocking the energy potential. These, in turn, depend upon the state of the technical arts and on the relative costs of the processes required to extract and use the energy. Consequently, the measurement and evaluation of energy reserves and resources will differ from one society to another and within any particular society as its needs change and its technologies improve.

Definitions or classifications acceptable for general use are difficult to formulate in view of these important basic differences from one region of the world to another. One answer is to minimize the differences relating to current economics and stress geological criteria, indicating the probable occurrence of deposits containing energy-rich materials. However, practical considerations require the use of definitions widely recognized for individual energy resources to permit the reporting of data already available.

The need to prepare a questionnaire not unduly complicated and in accord with conventional practice led to adoption of the following procedure: Total resources were divided between known resources, which are well-delineated or closely-appraised, and additional resources, including those inferred on the basis of relevant geological evidence. The first category of known resources was further subdivided into proved reserves, that is, the portion of the total recoverable under current conditions and employing existing technology.

The second category of additional resources was meant to include all other classifications with a lower degree of certainty than the resources reported as known. The Consultative Panel recognized that many countries would have difficulty estimating data in this category and that problems of comparability might limit the usefulness of the information. It was nevertheless agreed that the category was essential since the survey would be incomplete without broad resource estimates.

The ultimate goal of a classification of energy resources naturally has to be a classification according to quality and cost, as established, for example, for uranium. As quality and cost are complex functions of mining conditions, content of contaminants, local labor, etc. it appears that a systems analytical approach should be the proper method of tackling these difficult problems. The WEC would very much welcome the views of IIASA on this subject and appreciate IIASA's cooperation in this field of research.

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DECREASING ROLE OF RESOURCES IN HUNGARY

K. Patyi

This paper does not entirely cover the methodological problems of the assessment of energy resources. I focus here on the importance of energy resources in the energy system and national economy of a small country such as Hungary.

Prior to 1945 Hungary was a typical agrarian country, although industrial development had started at a moderate rate a century before. First of all light industry was developed, including precision engineering in the machine industry. The energy sources of the industry, transport (almost solely steam traction) and domestic sectors were the products of the coal basins and the domestic exploitation of coal almost kept up with increasing energy demands. For a long period of time energy imports were able to remain stable, their share in supply varying between 10% and 20% (see Table 1). During this period no energy problems arose.

Table 1. Trends of energy sources and consumption.

Year	Production of primary energy 10^6 tce	Import of Energy 10^6 tce	Import of Energy %	Consumption 10^6 tce
1930	6.7	1.0	13	7.7
1940	7.9	2.3	23	10.2
1950	10.2	1.5	13	11.7
1960	15.8	5.4	27	20.3
1970	21.7	13.1	38	32.7
1980	21.1	27.6	57	48.7
1990	24.0	51.0	68	75.0
2000	23.0	77.0	77	100.0

Since the early 1950's a forced development policy has prevailed for Hungarian industry, and energy intensive heavy industry has taken the first place in development. At the same time living standards have also increased considerably. Both points indicate an increase in energy demand, and the growth rate of energy demand now surpasses 4% per year.

The growth rate of domestic energy production has been falling behind the growth rate of energy demand, and energy imports have been covering the shortage. In 1970 energy imports reached 38% of energy demand.

But regarding the energy production and demand forecast for the Hungarian energy system in 2000, we see a new situation getting under way. The growth rate of energy demand, presumably, will remain at 4%, with a simultaneous fall to zero of the growth rate of energy production. According to the forecast, in 2000 energy demand will reach 100 times 10^6 tce, and imports will have to cover 80%. The expected population growth rate will remain stable (near zero), a fact that will ease the problems from the point of view of demand.

One can characterize the energy position of the country using a system of axes for "energy demand per capita--energy production per capita" (see the points in Table 2). The consumption per capita increases dynamically, but in 2000 it will reach the upper limit of the "medium" category or, to be more exact, 9.1 tce.

Table 2. Energy position of Hungary.

Year	Energy production per capita, tce	Energy consumption per capita, tce
1930	0.8	0.9
1941	1.0	1.1
1949	1.0	1.2
1960	1.6	2.0
1970	2.1	3.2
1980	1.9	4.4
2000	2.1	9.1

After drawing up Table 2, data concerning the energy resources also were taken into account (see Table 3). The figures show that the country has energy resources in a very small amount. Taking the actual production levels, the lifetimes of the different kinds of energy resources are as follows: coal (75% of the coal is lignite), 70 years; hard coal, 90 years; hydrocarbons, 30 years.

Analyzing the energy resources, too, one can see that energy imports will become the dominant factor in energy supply. Here an alternative course of action arises: we can make a greater effort to further search for energy resources in order to diminish import dependence. As a matter of fact, the success of further prospecting for energy resources may be estimated on a probability basis. In any case this alternative has the disadvantage that Hungary is a well prospected region, though the search for energy resources will continue in accordance with five-year and one-year plans. This will include, in the first place, high cost deep prospecting, a difficult technical task.

Table 3. Energy resources of Hungary (1969).

	Geological resources 10^6 tce	Minable resources 10^6 tce	Minable resources %	Lifetime in years
Brown coal, lignite	1,919	456	24	69
Hard coal	613	284	46	90
Crude oil	186	32	17	27
Natural gas	190	125	66	33

The rather high and increasing share of energy imports promotes foreign trade. Foreign exchange as a constraint factor has not so far played any role in investigations of the energy system of Hungary. The economy was able to find the required monies to cover energy imports.

In the new, forthcoming situation we need not analyze the energy system in itself, but we must take into consideration its relations with the national economy. In terms of systems analysis, a new problem arises: the embedding of energy in the sphere of the economy.

Two similar tasks arising from relating the energy system and the national economy are worthwhile considering specifically. The first is to compare the energy content of import commodities to the energy content of export commodities. This complex problem can be analyzed with the help of input-output techniques. By this method an import and export structure, or rather a production structure, that serves the energy system can be elaborated.

The second task is to find a counterpart to energy imports, that is, determine exportable commodities, the economic returns from which cover the increases--both in terms of quantity and value--in energy imports. Considering the current national economy two commodity groups can be seen: first, agricultural crops and food-stuffs, and, second, labour, excluding energy-intensive industrial products.

In the near and mid-term future the Hungarian economy has to answer the following question in practical economic life: how can it change the production structure of Hungarian industry and agriculture so as to adapt them to the international division of labour?

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A SYSTEMS APPROACH TO THE ECONOMIC ESTIMATING OF FUELS

M. Albegov

INTRODUCTION

Owing to events of the past few years, worldwide energy relationships nowadays are especially faced with some acutely important problems, and among them are those of the prospective development of fuel-energy economy:

1) What is the maximum possible level for fuel extraction costs in individual regions?
2) What is the shadow price level of fuel consumption in individual countries and regions?
3) What in economically justified costs are the differences between extraction and consumption for different quality fuels?
4) What are the maximum possible costs for financing and for the utilization of a new energy resource?

Naturally, all these questions can be solved with a thorough analysis of the problems of extraction, transport, and consumption of all possible types of fuel and energy with due accounting for various categories of consumers. Such an analysis should be of a dynamic character and should, to determine prospective energy developments, take the factor of uncertainty into consideration. For a long-range perspective this analysis can be carried out using optimization models. However, for the time being, when one has to solve time consuming problems practically, linear programming models seem to be the most promising. In the Soviet Union, there is considerable experience in using mathematical models in analysis of the fuel-energy economy of the country. This experience may be used in solving the above listed questions.

APPLICATION OF MATHEMATICAL MODELS TO DEVELOP A FUEL ESTIMATING SYSTEM

For an economic estimate of fuel, one needs two types of information: direct costs and maximum possible costs for fuel. The former characterizes the costs of fuel extraction in individual basins or fields. The initial data on the costs of fuel extraction in individual mines, pits, oil and gas fields can be grouped depending on the quality of the fields. In the end, it is important to construct a dependence of fuel cost upon the amounts of the resources used in a given basin or field.

Reliable information on maximum attainable costs of fuel can be obtained from a systems analysis of the condition of prospective development of all the means of the fuel economy. The mathematical programming methods developed in the last few decades have provided a powerful means for realizing a complex approach to an analysis of the national economy and its important branch, energy relationships.

One of the most significant applications of mathematics to energy was the use of linear programming in the calculation of shadow prices of fuel extraction and consumption. If the model of the fuel economy is represented in a simplified form as:

$$\sum_{i,j} C_{ij} x_{iy} \rightarrow \min$$

with constraints

$$\sum_{j} x_{ij} \leq a_i (i = 1,2,\ldots,m) \quad ,$$

$$\sum_{i} \lambda_{ij} x_{ij} = b_j (j = 1,2,\ldots,n) \quad ,$$

$$x_{ij} \geq o \quad ,$$

the dual estimate of the problem is

$$\sum_{j} b_j v_j - \sum_{i} a_i u_i \rightarrow \max$$

with constraints

$$\lambda_{ij} v_j - u_i \leq C_{ij}$$

$$u_i \geq o \quad .$$

Here the following designations are adopted:

x_{ij} - the amount of fuel sought from the field i used by the consumer j;

C_{ij} - the cost of extraction, transport, and consumption of unit fuel of the i-type by the consumer j;

a_i - fuel resources in the field i (in conventional fuel);

λ_{ij}- the consumption of i-type fuel per unit of production j;

b_j - the output of the i-type production;

v_j - the estimate of a consumer; and

u_i - the estimate of a fuel source.

The problem in reality is more complicated, but the significance of this estimate is stable.

A solution of the optimization problem will provide a characteristic equilibrium state of the system as a whole and the two vectors of fuel variables u_i and v_j corresponding to this state. Along with an optimum solution, one derives two systems of estimates which have an explicit economic sense: the values v_j characterize an estimate of fuel for consumers (in other words, marginal cost); that is, they correspond to a change of the objective function with slight variations in fuel (energy) consumption by the consumer j. The values u_i represent a reserve of the "economic stability" of extraction of a fuel (energy production); that is, they show the difference between the real cost of a fuel and the maximum possible cost of a similar-quality fuel extracted in a given place and at a given time. For example, the reduced cost at some pits of the Ekibastuz field, is about 3 rubles/ton of fuel (7,000 kcal/kg) (see "Coal Fields," 1971), while the maximum economically justified cost of extraction is 9 rubles to 11 rubles/ton of fuel (7,000 kcal/kg) (see Main Methodological Instruction, 1973). That is, the reserve economically justified cost of extraction in this region is 9 rubles to 11 rubles; the reserve of economic stability is from 6 to 9 rubles.

If the resources and demand for a fuel are known, the following factors are decisive in the formation of a system of marginal cost of fuel:

1) level of direct costs of extraction of so-called marginal fuel of the country,

2) direction of rational fuel transport or energy transmission and costs of transport in this direction, and

3) a comparative economics of utilization of individual energy carriers by various categories of consumers.

By the marginal fuel of the country we mean the fuel from those basins and deposits which, in total, are able to compensate for variations in the volume of energy consumption or in the economic resources of energy for a whole country; and every type of marginal fuel in a country can compensate for variations in at least a group of regions (see Main Methodological Instructions, 1973).

The marginal functions can be fulfilled only by those resources in which, at a given period, the technically possible output exceeds the consumption in an optimized energy balance, and the resources available and the quality of the fuel are sufficient to meet the requirements of a rather broad spectrum of consumers, at least for electric power plants. Thus the marginal fuel of the country does not include fuel from local sources: peat, wood, coal deposits of local value, etc.

To estimate fuel consumption to allocate production quotas for regional plants, the intraregional differences in consumer fuel estimates depend entirely on rationally directed transport costs. The most probable direction of fuel transport or energy transmission in the Soviet Union will be from the eastern region of the country to the European part. The costs of fuel transport in this direction will determine the interregional differences in the marginal cost of fuel in the USSR (see Table 1).

For example, we transport natural gas from the Komi region to the Volga basin. The difference is equal to the cost of transport. We transport hard coal from the Krasnajask region to the Volga basin. The difference is the transport cost. We have a different quality of coal and gas (oil) from the point of view of combustion. In some regions the differences between estimates of hard coal and natural gas amount to three or more rubles and the differences depend on the combustion costs in so-called marginal combustion installations.

An analysis of the system of dual estimates of the optimum plan has revealed that the differences in the estimates of qualitatively different types of fuel are determined by the effect of utilizing a higher-quality fuel by, from the efficiency viewpoint, a marginal consumer. This value is determined by the formula

$$\Delta 3 = (z_c^{\mathrm{II}} - z_c^{\mathrm{I}}) + \left(\frac{\eta_c^{\mathrm{II}}}{\eta_c^{\mathrm{I}}} - 1\right) z_T^{\mathrm{II}}$$

where

z_c^{I}, z_c^{II} - the cost of combustion of fuel types I and II (rubles/tons of 7,000 kcal/kg fuel);

η_c^{I}, η_c^{II} - the combustion efficiency of the fuels concerned; and

z_T^{II} - the marginal cost of fuel type II.

It is evident from calculations that in the USSR the marginal consumers of high-quality fuels (natural gas, oil) in the European part of the country are condensation electric power stations, while in Siberia they are boiler-electric power plants.

Table 1. Marginal costs of fuel[1] in some regions of the USSR in 1975-1980,[2] rubles/ton of 7,000 kcal/kg fuel.

Region	Natural Gas	Oil	Hard Coal		Brown Coal from Kansk-Achinsk
			Out-of-mine	Sized	
1. Northwest	23-26	22-25	22-24	23-25	-
2. Komi SR	17-20	16-19	14-16	15-18	-
3. Northern Caucasus	21-23	20-22	20-22	21-23	-
4. Volga Basin	21-23	20-22	19-21	20-22	-
5. Southern Urals	19-21	17-20	15-17	16-19	-
6. Novosibirsk	15-18	14-17	10-13	12-14	8-10
7. Krasnoyarsk territory	-	15-17	10-12	12-13	2.5-3.5
8. Primorsk territory	-	19-21	16-18	17-19	-
9. Western Ukraine	23-26	22-25	21-23	22-24	-
10. Byelorussia, Lithuania	24-27	23-26	22-24	23-25	-
11. Georgia	21-24	20-23	21-23	22-24	-
12. Uzbekistan	15-17	14-16	14-16	15-18	-

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[1] All calculations were completed before the recent energy crises, and now these estimates are higher.

[2] All the figures are based on Main Methodological Instruction for Utilization of the Marginal Cost of Fuel and Electric Energy (1973).

In the former, coal combustion costs about 3 rubles more and in the latter 4 rubles to 5 rubles more as compared with gas or oil combustion.

The system of fuel estimating for consumers (marginal cost of fuel) is rigidly associated with the system of estimating fuel extraction. The maximum attainable cost in a mining region is related to the real costs of extraction of a fuel as follows:

$$z_o = z_c + \sum_i R_i$$

where

z_o - the economically justified cost of extraction of a given field;

z_c - the real cost of extraction of a given fuel; and

R_i - the i-type rent, which generally includes a mining rent, a rent of location, and a rent determined by the quality of a fuel. If the marginal fuel of the country is replaced by a given fuel, one has

$$R_i = C_i^c - \frac{\lambda_{ij}^c}{\lambda_{ij\ max}} C_i^{max}$$

where C_i^c and C_i^{max} are the costs of extraction, transport, and consumption of the fuel concerned and of the marginal fuel of the country, respectively.

Thus, an estimate of the fuel extracted is the sum of three rents--a mining rent, a transport rent, and a rent determined by the quality of a fuel (see Table 2). The magnitude of the rent serves a criterion of the efficiency of extraction of a fuel. According to calculations (see Albegov, 1968), under the conditions assumed, the following fuel estimates were obtained.

A knowledge of the fuel rent estimating system helps in making correct decisions not only in the fuel industry but in solving other power problems of values as, for example, in choosing a type of drive in gas line compressor stations, in determining rational losses in power transmission lines, etc.

The fuel estimating system is applicable to power economy calculations provided the system is not very sensitive to variations in the initial data. The influences of natural and social economic uncertainties and accidental factors make solving optimization problems necessary (and hence, defining fuel estimating systems) under the conditions of uncertainty. At present a possibility of deriving power-economy solutions under such conditions is being investigated (see Makarov and Melentiev, 1973).

Table 2. Approximate rents of some fuel bases in the USSR (rubles/ton of 7,000 kcal/kg fuel).

Fuel Type	Fuel Estimate
Gas from Western Ukraine	16 - 17
Gas from Northern Caucasus	14 - 15
Gas from Orenburg	12 - 13
Gas from Middle Asia	9 - 11
Gas from Tumen	3 - 9
Coal from Ekibastuz	4 - 5
Open pit coal from Ekibastuz	3 - 4

Available rent estimates provide a possibility of pursuing a correct technical policy in the mining industry.

It is noteworthy, however, that the dual estimate system is less sensitive to varying initial conditions than the optimum plan is. Though it is difficult to find a quantitative criterion of such a relative stability, some relevant considerations are presented below.

An absolute value of the marginal cost is determined by the level of direct cost of a "regulating layer". Since in our case "regulation" is provided by the marginal fuel of the country, that is, by the largest basins and fields, the level of the marginal cost of fuel is relatively stable.

The interregional difference in cost of fuel is determined by the cost of transport and is independent of the amounts of fuel supplied in a given direction (no matter whether millions, tens of millions, or hundreds of millions are supplied).

Finally, the difference in estimates of high- and low-quality fuels is determined (at least in many regions of the USSR) by the fuel consumed by electric power stations, the latter accounting for 40% of the increase in field consumption. So, in this case the regulating layer is sufficiently wide to provide a stable relationship between the estimates of the major types of fuel.

All these considerations provide for a quantitative estimate of the consequence of certain economic decisions which do not introduce radical changes into the structure of the energy balance, of individual achievements in energy relationships, geology, etc. For example, knowing the mechanism of formation of a fuel estimating system, one can state that a discovery of new gas fields in the European part of the USSR with a yearly gas output of tons of billions of cubic meters will not affect this system substantially. The latter may be severely changed only with an advent of cheap fuel sources equivalent to hundreds of millions of tons of conventional fuel. In a similar way, the consequences of the development and introduction of new techniques of fuel extraction, energy production, etc. can be estimated.

ON THE SIMULATION OF THE WORLD FUEL-POWER ECONOMY

Naturally, the efficiency of utilizing energy resources in terms of the fuel-power balance of an individual country cannot be estimated completely. External contacts should be taken into account, too. These contacts can be expressed in two ways: a) by fixed volumes of exports and imports and b) by fuel estimates (cost of fuel). The latter way is more accurate and assumes that the prospects for development of the world power balance are known.

The necessity for studying the trends in utilization of world power resources invites an application of a mathematical approach to optimize the structure of the world fuel-power balance. A national experience may prove very useful in this case. For example, it is not difficult to draw an analogy to the concept of the "marginal fuel of the country" with respect to the world conditions. This function can be fulfilled by such a rich fuel source as the oil from the Middle East. The oil flow from the Middle East to Europe and Japan can be expected to account for higher fuel estimates in these directions.

Innumerable analogies can be listed on and on, but one should bear in mind, among other things, the following points:

1) The possibility of deliberately concealed and distorted initial information.

2) The necessity of overcoming the inconsistency between the requirements for accurate calculations and the constraints upon the problems solved.

3) The necessity of a common measure for different currencies.

4) The necessity of investigating not only an equilibrium state of the power balance but its other states as well.

When solving the optimization problem of the energy balance of an individual country, it is rather easy to get reliable and comparable information (say, on fuel in stock, or on the costs of its utilization), but to make this information comparable on a worldwide scale, some problems will arise.

In order to have more accurate calculations, one should definitely differentiate between regions, types of consumers, transportation facilities. For example, in the case of the USSR, there is no point in grouping together regions for which the costs of fuel transport between them is over 1 ruble to 1.50 rubles/ton of 7,000 kcal/kg fuel; otherwise the calculations will be very rough. Therefore, the territory of the country had to be divided into about 40 regions.

Clearly, in a model of the world power balance the territory of the USSR must not be represented in such detail, or the world fuel system would fall into several hundred (about 300 to 400) region-consumers. The problem of such a dimension is difficult to solve practically. Therefore, one is to solve first a complicated problem of a rational degree of differentiation and aggregation of territories, groups of energy producers, fuel consumers, etc.

In addition, one more question needs a satisfactory solution: what units to measure costs should be used in performing optimization calculations? In principle, the objective function can be represented in relative units, but it seems most interesting to measure in money units.

Note, however, that the relationships between national currencies may deviate from the relationships between costs in power economy of individual countries. To make money costs commensurable, one may resort to equivalents which would represent the relationships between costs in the power economies of individual countries more accurately. These may be established based on the construction costs of a typical thermal electric station having an up-to-date capacity (say, about 2 to 4 million kw).

The Soviet economic system is characterized by a balance between production and consumption and by a tendency toward minimum costs to achieve this balance. These conditions are met by the optimum plan of the optimization problem of the power balance of the country, that is, by the found point of equilibrium between production and consumption at minimum costs. The resulting system of fuel estimating in the USSR is recommended for use in stimulating decisions at lower economic levels, which would correspond to the optimum national economy.

At the same time, the estimating system for optimization of the world power economic structure can be considered only as one of the possibilities. The thing is that every state (group of states) may arrive at a decision which greatly differs from that recommended by the optimum plan. Hence, of great concern are not only the characteristics of an equilibrium state of the corresponding estimating system, but also the states known to be non-optimal, which consider, for example, a substantial increase in certain types of resources, limitations on exports and imports, etc.

The national experiences acquired in applying mathematical models for estimating fuel extraction and consumption promise successful investigations for optimization of the prospective world power balance. The solution of this problem will help elucidate the trends in the world power economy development and outline (on a national level) a long-term policy in the fuel economy of individual countries with due reference to developing international relations.

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THE UN CENTER FOR NATURAL RESOURCES, ENERGY AND TRANSPORT

I. Stancescu

The worldwide interest in natural resources and energy has led to increased activities within the UN system, particularly by the UN Economic and Social Council; the UN Committee on Natural Resources, from which emerged last year the Center for Natural Resources, Energy and Transport; and the UN Economic Regional Commissions and the Specialized Agencies. From this work and the resulting cooperation and coordination activities, the needs for a widely accepted classification and definition of energy resources and reserves, and for common terminology and methodology in their evaluation and assessment were found to be essential for establishing an energy information basis, so strongly requested by the UN member countries.

At its 1975 session, held in Tokyo, the UN Committee on Natural Resources reinforced decisions to strengthen the voluntary exchange of information on natural resources and energy on a global basis, and it suggested that the Secretary General propose to the Economic and Social Council implementation of recommendations concerning the intensification of UN information services for natural resources and, of course, energy. The Committee also suggested that the Secretary General convene a group of experts, selected on an equitable geographical basis, to prepare a report recommending a common set of definitions and terminology that might be used internationally for reporting to the UN on mineral resources. The Committee on Natural Resources also suggested that the Economic and Social Council recommend that the UN University consider including research on solar and geothermal energy in its priority program, and that they also pay serious attention the next few years to the development of such energy sources as coal, oil shale, and solar and geothermal energy.

RESOURCE ASSESSMENT AND SUPPLY CURVE DEVELOPMENT: TOWARD BETTER METHODOLOGIES

Milton F. Searl*

INTRODUCTION

The methodology of resource assessment is a much neglected topic of research in the United States. I am referring, of course, to the methodology for assessing resources at the aggregate or macro level. A great deal of work has been directed at assessing resources in individual reservoirs and deposits, and there has been some work on assessing resources in less limited geologic environments, such as sedimentary basins.

There have been few systematic efforts at establishing resource assessment methodologies. Among the pioneering efforts in the United States have been those of M. King Hubbert and the United States Geological Survey who have developed very different approaches and estimates. However, according to Richard Sheldon, chief geologist of the US Geological Survey, the art of resource estimating is "in a very unsatisfactory state of affairs right now."[1] It is somewhat surprising that the topic of resource assessment methodology has received so little attention from economists considering that a major purpose of resource assessment is to provide input to the derivation of long-run supply curves.

In this paper I shall deal mainly with ideas and approaches to resource assessment that appear to us in the Energy Supply Program at the Electric Power Research Institute to offer promise for improved supply assessments. For the most part, the suggestions are largely a matter of employing available techniques in a systematic manner rather than of applying dramatic new methods. The elements of this approach can be seen in our report on "Uranium Resources to Meet Long Term Uranium Requirements"[2] although that report was prepared on an accelerated schedule with limited resources and by no means

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[*] Jeremy Platt of the program staff assisted in the preparation of this paper.

[1] Science (February 28, 1975).

[2] Electric Power Research Institute, Special Report Number 5, November 1974.

fully exemplifies our approach. In general, the estimating methodologies will involve a great deal of professional work by interdisciplinary teams. I do not believe that it is possible to adequately deal with the complexities of the subject by strictly mathematical or statistical approaches although such approaches may be highly useful in dealing with certain aspects of the assessments.

I will not deal at any length with what may be called terminological problems. Pioneering work in resource concepts and terminology was carried out by Blondel and Lasky[3] and extended by Schurr and Netschert of Resources for the Future.[4] V.E. McKelvey,[5] Director of the US Geological Survey has also made important contributions. John Schanz of Resources for the Future will report at this Conference on work which he is doing for us on the subject of terminology. I shall, however, occasionally make comments related to terminology since time did not permit coordination of our papers.

It is not so much that the terminology itself is important but rather that confusion about terminology also reflects confusion as to concepts, and differences in terminology often reflect differences in concepts and constraints. Perhaps the worst aspect of the terminological problems is that they result in great confusion in the public mind and in the mind of many of those who make public policy. A particular problem is that owing to lack of general acceptance of common terminology, resource estimates with substantive economic and technological constraints are frequently accepted as resource base estimates. This results in serious concerns about resource exhaustion which may lead to ill-considered public policies and may direct research in directions which may not be the most productive. In resource estimating, as in many other areas of technical endeavor, we need a new standard of professionalism in which researchers are much more conscientious about carefully defining the limits of their research and are more vocal in their insistence that those limits be publicly recognized.

This discussion is organized around three aspects of resource estimating, namely: the input data on which the resource estimates are based, the analytic or estimating procedures by which the output is derived, and the nature of the output. No attempt is made at complete coverage of any of

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[3] F. Blondel and S.G. Lasky, "Mineral Reserves and Mineral Resources," Econ. Geol., LI, 7 (November 1956), 686-697.

[4] Sam H. Schurr and Bruce C. Netschert, Energy in the American Economy - 1850-1975 (John Hopkins University Press, Baltimore, 1960), pp. 296, 297.

[5] V.E. McKelvey, "Mineral Resource Estimates and Public Policy," American Scientist, 60 (1972), 32-40.

these subjects. That is far beyond the scope of this paper. My purpose is rather to advance certain ideas and methods for discussion. Quite possibly some of these may be more fully developed in other countries; they are not unique in the United States, although they certainly are not in widespread practice. The discussion is based almost entirely on experience and conditions in the United States.

INPUT DATA

Many of the limitations imposed by input data are widely recognized. However, there appears to be an almost complete lack of attention to the manner in which the historical data on which resource estimates are based have been conditioned by economic and institutional factors. Yet, this conditioning almost certainly introduces substantive biases into the assessments. We have tentatively labelled studies of how economic factors condition the data as geo-economic studies to distinguish them from geo-statistical studies in which the economic conditioning is ignored.

At the micro level, that is the deposit, reservoir, and well level, statistics are clearly conditioned by economic factors. Many crude oil and natural gas wells which have discovered hydrocarbons are classified as dry holes because it was not economic at the time to develop them.

There have been many reports of noncommercial (at $6 to $8 per pound) uranium in the United States. Here again the statistics have been conditioned by economics. How much uranium is in such deposits is a subject of great uncertainty. On the basis of our uranium study[6] it appears that there may be large numbers of lower grade uranium deposits, potentially containing large amounts of uranium, which were discovered but not considered of interest and which may therefore significantly bias estimates of United States uranium resources in a downward direction. Because we are not entirely satisfied with the data base which this analysis used, we did not include these amounts in our uranium estimates. We will pursue this matter in the future along with other possible data conditioning factors.

There is also reason to believe that uranium discovery data have been conditioned by depth limits on what constituted an economic deposit. It is important to note that no criticism of the oil, gas, or uranium statistics are intended, although valuable information may have been lost by the lack of public information on noncommercial discoveries. What is intended is criticism of the apparently uncritical use of this data by resource estimators in a manner which implies the nonexistence of substantive quantities of lower grade or more costly resources.

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[6] Special Report Number 5, p. 67.

It is frequently assumed that this economic conditioning of the statistical data used for resource estimating is not particularly important since the missed resources are somehow of lower quality. Although this argument has some merit, it ignores a tendency for the volume of resources to increase with decreasing grade and for either technology or rising price to make such resources economic. In the case of crude oil and natural gas it is not at all clear that the data rule out large amounts of resources in low permeability reservoirs or in lower grade resources. Indeed there are examples of this in the United States. There are large gas resources in low permeability formations in the west which are not generally included in gas resource estimates for economic and technological reasons. Similarly, there are large resources of shallow, low-gravity oil which are not counted as oil resources. In the cases where these deposits are so large as to have attracted public attention, the problem is not serious since they can be explicitly included in resource estimates. More serious is the question of how much oil, gas, and uranium have been found but not included in discoveries because of their noncommercial character at the time and how the inclusion of these materials in our resource data base would affect projections of yet undiscovered resources. As a basic proposition, I would assert that all micro resource data, even when stated in physical units without economic parameters, have been tainted by economics and that projections using such data are implicitly projecting certain economic, institutional, and technological conditions and constraints.

The manner in which adjustments to account for the economic and other conditioning of physical data on resource development is to be made is a subject for future study. In some cases, the adjustments may be fairly obvious, in other cases, quite uncertain. Where there have been obvious depth or grade limitations and there are no reasons to believe that there are discontinuities in the natural distribution of the resource, then the nature of the correction may be indicated. In other cases, much more study may be required to determine appropriate correction methods. In general, because of the economic conditioning of the data on which conventional resources estimates are based, use of the data for resource base estimating appears to have an inherent downward bias. By postulating various distributions of resources in nature and then simulating exploration and development under various economic and technological constraints, we may be able to gain some insight into the bias introduced by the conditioning of the micro resource data.

At the macro level, discovery, reserve, and production statistics are also conditioned by economic and technological factors as well as reflecting resource characteristics and the operation of random factors. These factors must be disentangled before we can be sure that we have valid data for use in resource assessment. Throughout the history of petroleum development in the United States there has been a strong tendency to interpret adverse discovery, reserve, or production statistics as reflecting a deteriorating resource position when, in fact, the deteriorating supply conditions were primarily owing to nonresource factors. From shortly after the discovery of oil in the United States, there have been frequent pronouncements by responsible government authorities and respected geologists about prospective oil shortages in the United States. In general, these past pronouncements were highly misleading. This is not to criticize those who made the pronouncements nor to imply that those who are currently convinced of impending exhaustion of oil and natural gas resources in the United States are wrong. They may be correct, although I do not believe the evidence is conclusive. Rather, attention is called to the historical record to emphasize that very careful analysis of the causes of adverse trends in reserve, discovery, and production statistics is necessary in order to insure that unfavorable trends are really owing to the underlying resource situation and not to economic and institutional conditions.

It is sometimes felt that rising prices provide confirmation of views of approaching resource scarcity. However, this has not been the case in the past. Real (that is, constant dollar) prices of crude oil in the United States were as high in 1871 and 1920 as they are today and these prices did not, in fact, represent the effect of significant depletion in our underlying resource position. The long term trend of real crude oil prices appears to have been roughly level. The response of supply to rising prices may be a better indication of the resource position than prices themselves. However, even the response of supply to price requires careful analysis. Price increases may be owing to rising unit costs of labor, equipment, taxes, or capital or institutional factors rather than the cost of developing lower quality resources. Moreover, short term supply responses must be distinguished from long term responses.

Economic forces condition physical measures of performance in unexpected ways. In a period of sharp price increases, producers tend to expand activity not only by increasing exploration activities but also by drilling in areas where marginal resources are known to exist in order to increase output as rapidly as possible. This expansion of activity in marginal areas tends to result in unfavorable trends in some performance indicators such as reserves added per well. Such declines are frequently interpreted as a confirmation of pessimistic views about the quality of remaining resources when, in fact, they are a proper short term response to increased prices and have no particular long term resources implications.

It is thus imperative in using even macro data on historical performance to assess resource endowments to carefully examine the manner in which the data have been conditioned by economic and other nonresource factors. In some cases, the interpretation is quite complex and is perhaps best carried out by examination of experience relative to expectations based on appropriate short and long term models of industry behavior. It is even possible for price increases to produce declines in activity. For example, increases in the price of both crude oil and natural gas can produce a decline in discoveries of one or the other if the price increases significantly change the relative profitability of the two resources. In the absence of proper economic analysis, declining discoveries in the face of rising prices would almost certainly be attributed to difficulties in finding new resources rather than to cross elasticity effects.

There are, I fear, no reliable substitutes for a detailed understanding of the factors conditioning resource statistics if they are to be successfully used in assessing resource endowment.

OUTPUT

Consideration of the purpose of resource assessments is appropriate since this affects the nature and form of the output as well as the choice of input data and the selection of the estimating procedures. The purpose of most resource estimates is to provide information about future supply in the sense of price and quantity through time. Time need not, of course, be specified solely as a function of real time. Other measures of the future such as a function of cumulative discovery of the resource, or even joint measures with time, may be more appropriate.

An alternate use of resource assessments is to provide information as to when complete depletion will be approached. For this purpose some projected or hypothetical pattern of consumption is also required. While such applications of resource assessments have some value, they often pose serious pitfalls because of implicit assumptions in the evaluations. Resource assessments oriented toward supply curve development can also yield, as a by-product, the same information about complete depletion as the less detailed resource assessments used to evaluate resource exhaustion and probably with much greater confidence.

Practically all resource estimates place, implicitly or explicitly, some constraints on the resource; that is, they are not true resource base estimates. The most frequent constraints are economic or technological although there may be institutional and other constraints. Some of these constraints are implicit as a result of the input data utilized to construct the resource assessment. In this case they present a serious problem for long term supply curve development. Implicit constraints, of which the investigator may not be fully cognizant, can even be in conflict with explicit constraints that the investigator establishes. Under the heading of INPUTS some of the ways in which the input data may unknowingly constrain the output were considered although the discussion was by no means complete.

Canadian investigators have introduced time constraint on resource exploitation as well. Schanz and perhaps others will tell us more about this. While time constraints appear useful for some of the purposes to which resource assessments are put, for other purposes, such as assessing the pace at which new technologies are required, time constraints may be of limited utility.

Only those resource assessments which provide us with resource base information, that is assessments which are free of economic, technological, and other constraints are particularly useful for dealing with problems of resource exhaustion. There appear to be few true resource base estimates. In the United States, some of the Geological Survey estimates come closest to meeting the resource base criteria.

In view of the great uncertainty about most resource endowments, it seems obvious that resource assessments should be presented, not as point estimates, but as probability distributions. In most cases these probability distributions will not be derived in a rigorous mathematical manner since the resource estimates themselves are not usually derived in this manner. However, even the subjective probabilities of the researchers who have prepared the resource assessments convey a good deal more information than point estimates. Indeed much of the controversy about the relative merits of various resource estimates may be more a matter of difference in the confidence with which the estimates are held than anything else.

In cases where no confidence or probability figures are given, it would seem that there should be equal chances that the resource assessments are high or low. Yet, it appears that many resource assessments are intended to be high probability estimates.

The US Geological Survey, the Potential Gas Committee, the National Petroleum Council in its Future Petroleum Provinces report, and recently the Energy Research and Development Agency (Atomic Energy Commission) have used terminology intended to convey rough ideas of the confidence with which various portions of the estimates are held. This approach is certainly desirable. There may, however, be some confusion between measures reflecting the amount of informatior on which the estimate is based and measures of the probability of various resource amounts. There appears to be a tendency to bias estimates in unknown areas in a downward direction and at the same time to assign terminology which reflects low confidence. This may be double discounting. The poorer the information on which the estimate is based, the larger should be the variance of the estimate about the expected value. However, limited information on which to base the estimate should not itself lead to small expected values.

In our uranium report, we presented subjective probability curves for uranium available at up to $100 per pound of U_3O_8. Subsequently, we have attempted to define the three dimensional surface relating various costs, quantities, and probabilities. In the future we may well add technological and other dimensions creating an n-dimensional probability surface. While at present I consider this work as experimental rather than producing definitive uranium estimates, there is no doubt in my mind but that this is a useful approach. Among other things it requires a more disciplined approach on the part of the estimator. I am quite convinced that a desirable step in resource assessment is to present the conclusions in terms of probability distributions.

In terms of estimating efficiency and accuracy, there are unresolved questions as to which resource set should be estimated. Historically the resource type estimated, for example, crude oil or natural gas, has largely been determined by commercial considerations. This has been appropriate and such resource assessments will continue to be desirable. However, in dealing with national questions concerning the adequacy of long term supply, it is more important to know, with a given degree of accuracy, what the combined production of crude oil, natural gas, and natural gas liquids may be, than to know the individual components with an accuracy which, when the components are combined, gives less confidence about the total.

It seems that there may be advantages in terms of accuracy and reliability in estimating, for example, a combined total for crude oil, natural gas, and natural gas liquids as opposed to estimating them individually. Certainly, at the micro level there are limitations on our ability to predict whether a wildcat well will find predominantly oil or natural gas, whereas we can predict with somewhat greater accuracy that it will find one or the other or both. This may also be true at the macro level. It is at least worth examining whether attempting to estimate resources on a basis which gives more consideration to geological factors and less to market oriented factors might have advantages. This suggestion is made in full recognition that there are some differences in the conditions which produce oil and gas, for example, those related to depth and temperature. Even if there should be estimating advantages in making combined resource assessments, there would undoubtedly be a need to break the combined estimate down into components, which would, however, be of somewhat lower reliability than the overall total.

The possibility of including heavy, viscous crude oils in any combined estimate of US hydrocarbon resources would also need examination. The exclusion of data on such resources, of which roughly 100 billion barrels are known in the United States, may significantly distort resource assessments even though the known resources are accounted for separately. The question here, too, is basically whether the exclusion of such resources from our base data distorts the assessments or not.

It seems hardly necessary to say that the volume of earth for which the resource assessment is made should be well defined and well understood by users of the assessments. However, this is frequently not the case. In the United States, the well regarded "Future Petroleum Provinces" report by the National Petroleum Council excluded certain areas. While the report was clear as to the excluded areas, some of the excluded areas could contain significant amounts of petroleum. Some areas were said to have been excluded because of small potential. In view of the fact that the report was intended to be, and indeed was, used as a total United States estimate, it would have been appropriate for the authors to have added their best estimate of the resources in the missing areas rather than leaving the report incomplete. In making resource assessments, it is necessary to keep in mind the needs of the users and the uses to which the assessments may be put, even though this may force us to make some assessments which we would rather not include.

In the case of coal, in the United States, resource evaluations generally include only limited coverage of coal below 3,000 feet and no coverage below 6,000 feet. In view of the large size of United States coal resources, such limitations have little practical effect on the usefulness of the estimates. However, when projections are made that coal resources may be exhausted on the basis of such partial figures, and particularly when these calculations are supposed to have some sort of policy implications, then the exclusions present serious problems.

A final example of the failure to adequately communicate the volumetric limitations of resource estimates is provided by uranium. Estimates have frequently been made of United States uranium resources available at various prices and these estimates have been utilized to advocate the development of certain technologies. The footnotes in the reports generally reveal that the estimates apply only to the western United States (and more specifically, to only a fraction thereof). There is, however, largely unevaluated potential for uranium resources in Alaska and in the eastern United States. A greater insistence in the past on the incomplete nature of the estimates might well have prevented various abuses of the estimates and would have allayed suspicions that uranium resource figures were kept low to foster development of advanced technologies.

In one case, there is a legitimate difficulty in determining the volume to which the resource figures apply. This occurs where the estimates have been made by fitting mathematical or statistical data to historical data for a region containing substantial potentially productive volumes that have not contributed to the statistics. For example, this sort of analysis of petroleum resources for the United States raises questions of the extent to which Alaska and the offshore areas are automatically included in the derived results. To at least some observers, the same question applies with regard to less thoroughly tested areas and depths in the lower 48 states. The problem of definition of the volume to which mathematical-statistical analysis applies might be resolved by study and simulation. It appears that on the basis of a range of scenarios, believed to encompass the real distribution of the resources in nature, it should be possible to test, either analytically or by simulation methods, the asymptotic efficiency of various mathematical and statistical approaches to estimating resource endowments. This is an area for future research.

ESTIMATING PROCEDURE

The National Research Council of the United States National Academy of Sciences, in a controversial report published earlier this year, identified five different methods of estimating undiscovered resources, namely: straight volumetric, geologic basin analysis, probabilistic exploration/engineering analysis, analysis of historical production and discovery data, and analysis of discovery indices. Variations of these methods can also be distinguished.

It is not my purpose at this point to provide a review and critique of the various resource estimating procedures. To some extent this has been done, at least from one point of view, in the National Research Council study. My purpose is to deal more generally with the fundamental information which should go into the preparation of resource estimates if they are to be useful in the derivation of supply curves. A basic premise of our approach to resource estimating is, as indicated previously, that the fundamental purpose of macro resource assessments is to provide information useful in the development of supply curves.

Our current thinking is that it is desirable to separate the effort into three parts. The first step is to describe the resource endowment insofar as possible in physical terms, that is, in terms of expectations as to the number and distribution of deposits, their size, depth, grade, and any other characteristics about the resource that significantly affect the technology required for, and the cost of, recovery of the resource. Some of the resource analysis of the United States Geological Survey tends in this direction as did the work of the Potential Gas Committee and the National

Petroleum Council's report on "Future Petroleum Provinces." However, none of these reports have gone as far as may be desirable in describing the expected physical characteristics and distributions of the resources. The work of Gordon Kaufman at the Massachusetts Institute of Technology appears quite relevant in this respect.

The task of estimating the physical distribution and characteristics of resource deposits is not easy. Not only must we build on existing evidence but we must also conscientiously inquire as to how we can be sure that additional resources do not exist in areas that do not meet current criteria. Over at least the first 100 years of petroleum resource estimating in the United States, an approach of assuming widespread existence of petroleum and reducing the estimates only when it was conclusively shown that petroleum could not exist in quantity in a given area would have produced more meaningful resource estimates than those normally made. Obviously, at some stage we know enough about the occurrence of resources that good estimates of as yet undiscovered resources can be made on the basis of discoveries to date. Whether or not we are at that stage yet, for any or all of the energy resources, is not clear to me. Others believe that present knowledge is adequate for such projections. It would seem prudent to at least spend a fair portion of any evaluation effort searching for positive evidence that resources do not exist in a given environment instead of postulating their existence only when there is substantive positive evidence that they do exist.

This, of course, brings us back to the question of the probability of various resource endowments. The approach of presenting a resource assessment in terms of a probability distribution allows much more flexibility for dealing with uncertainties as to existence and quantity than current approaches. As pointed out in the discussion of input data, it is extremely important that attempts be made to compensate for the economic conditioning of historical data so that the estimates approach as closely as possible the true resource endowment in nature instead of replicating historically observed distributions. The extent to which the various methodologies described by the National Research Council are useful for our purposes depends, of course, on the extent to which they can indeed help estimate the natural resource endowment.

It is not, of course, necessary that resources occurring in different geological environments or even in different geographic areas all be estimated by the same technique. The methods for estimating uranium resources in sandstone deposits in the West may well differ from the method to estimate uranium resources in vein-type deposits. In each case, the most appropriate methodologies should be used with, again, due regard to the conditioning of the historical data used. Similarly, it may well be appropriate to utilize different methods to estimate uranium resources in Alaska, in the western United States, and in the eastern United States. It is, of course, highly desirable that all of the methods produce the same type of end product--estimates of the natural endowment of the resource in the area free of economic and technological constraints. If, as will usually be the case, different areas and volumes are estimated separately, it is important that all contributions from the varied geologic environments for the area being analyzed are considered. The analysis must be complete. Even areas where it is believed little of the resource exists should be included at zero level or at a low expected value with an appropriate distribution of possibilities.

The summation of the various volumes in a manner that takes proper account of the probability distributions for each resource type in each area constitutes the desired resource assessment. If the desired product is a supply curve or even simply an estimate of resources with certain economic and technological constraints, the next step is to make estimates of the cost of recovering the resources.

Whereas the estimating of the resource endowment requires geological skills, assisted perhaps by economic skills for adjusting historical data to account for the economic conditioning previously discussed, the estimating of the cost and technological requirements for recovery of the resource requires engineering and economic skills. Because the cost and technological factors, unlike the resource endowment, are not fixed in time, it will generally be advantageous to assume the technology of a recent year along with its associated costs in order to arrive at a cost function for the resources under a known fixed technology and base year economic parameters.

From this fixed base, it is, of course, quite proper to assume explicit learning curves for the technology along with such changes in the cost of equipment and labor as may result from the evolution of the technology. If desired, breakthroughs in technology can also be explicitly assumed. Like the basic resource estimates, the technology and cost figures should be expressed as probability distributions instead of point estimates. A final step is to make estimates of trends in labor and capital costs, in taxes, lease bonuses, royalties, environmental costs, and such other factors, along with their uncertainties, as may effect the evolution of the resource supply curve through time.

The resource estimating procedure outline here is a complex, expensive one. I believe, however, that it represents the trend of methodology, that it is basically within our capability, and that even attempting this sort of effort will advance the art and lead to more useful estimates. Any use of resource assessments to derive supply curves must do the steps suggested here either explicitly or implicitly.

To some extent the procedures outlined here were attempted by the National Petroleum Council in its recent studies of the "United States Energy Outlook." That approach was criticized by some economists. To some extent the criticisms were valid since the analysis did not take into account, through econometric and other types of analysis, the economic forces driving the system. I do not believe, however, that the basic cost oriented approach suggested here is inappropriate for long term supply analysis. There is no doubt, however, that in the shorter term, with which the National Petroleum Council analysis was concerned, supply may deviate from the levels suggested by the cost approach and that additional economic and econometric analysis will be necessary to deal with these deviations.

In conclusion, I would note that at a time when resources may be becoming a crucial limiting variable and when national policies may hinge on resource factors, it is appropriate that we exercise our professional skills to correct the "unsatisfactory state of affairs" in resource assessment.

PROBLEMS AND OPPORTUNITIES IN ADAPTING US GEOLOGICAL SURVEY TERMINOLOGY TO ENERGY RESOURCES*

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INTRODUCTION

This report summarizes a review that has been conducted over the past several months of the resource terminology adopted by the US Department of the Interior (USDI) on April 15, 1974. The objective of the evaluation was not to offer new terms or methodology but to identify problems that may be encountered in the general use of this terminology. Particular attention was paid to how these terms could be applied to energy resources. Within the energy resources group there was the question of whether or not the terms could be adapted to the renewable, or flow, resources.

The basic philosophy of the USDI terminology has been drawn from the work of its director, Vincent E. McKelvey. McKelvey presents his terminology in the form of a resources diagram (see Grenon's Figure 4) within which the USDI uses the following terms:

> Resource--A concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such form that economic extraction of a commodity is currently or potentially feasible.
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> Identified resources--Specific bodies of mineral-bearing material whose location, quality, and quantity are known from geologic evidence supported by engineering measurements with respect to the demonstrated category.
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> Undiscovered resources--Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

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Reserve--That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination. The term ore is used for reserves of some minerals.

Measured--Material for which estimates of the quality and quantity have been computed, within a margin of error of less than 20%, from sample analyses and measurements from closely spaced and geologically well-known sample sites.

Indicated--Material for which estimates of the quality and quantity have been computed partly from sample analyses and measurements and partly from reasonable geologic projections.

Demonstrated--A collective term for the sum of materials in both measured and indicated resources.

Inferred--Material in unexplored extensions of Demonstrated resources for which estimates of the quality and size are based on geologic evidence and projection.

Identified-Subeconomic resources--Materials that are not Reserves, but may become so as a result of changes in economic and legal conditions.

Paramarginal--The portion of subeconomic resources that 1) borders on being economically producible or 2) is not commercially available solely because of legal or political circumstances.

Submarginal--The portion of Subeconomic Resources which would require a substantially higher price (more than 1.5 times the price at the time of determination) or a major cost reducing advance in technology.

Hypothetical resources--Undiscovered materials that may reasonably be expected to exist in a known mining district under known geologic conditions. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as a Reserve or Identified-Subeconomic resource.

Speculative resources--Undiscovered materials that may occur either in known types of deposits in a favorable geologic setting where no discoveries have been made, or in as yet unknown types of deposits that remain to be recognized. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as Reserves or Identified-Subeconomic resources.

The initial difficulty that is encountered with the USDI's terms is that they do not conform to those that have been employed by mining geologists and engineers in North America for over 100 years in their appraisals of individual properties for investment purposes. Recently, the American Institute of Professional Geologists, American Institute of Mining, Metallurgical, and Petroleum Engineers, and Society of Economic Geologists adopted three other terms for use in the commercial evaluation of reserves:

> Proven ore--An ore reserve so extensively sampled that the tonnage, grade, geometry and recoverability of the ore within the block or blocks of ground under consideration can be computed with sufficient accuracy so that the uncertainties involved would not be a factor in determining the positive feasibility of a mining operation.
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> Probable ore--An ore reserve for which sufficient continuity of dimensions and grade can be assumed for preliminary financial planning but for which the risk of failure in continuity is greater than for Proven ore.
>
> Possible reserves--Mineralized material of which the dimensions and grade are based on geologic correlation between samples so widely spaced or so erratic that additional exploration is required to establish whether ore reserves are present.
>
> Coal--The above definitions of ore reserves can be applied to coal with appropriate modifications and with due regard to rank, grade, seam thickness, overburden, and recoverability.

In practice, the terms "proved," "probable," and "possible" have been used loosely and interchangeably with the terms "measured," "indicated," and "inferred." It is regrettable that industry and government could not agree upon common terms for use in North America.[1] However, the debate which has lasted over many decades may have at last ended with mutual recognition that industry will employ one set of economic evaluation terms while government, in conducting regional or national resource appraisals, will use another. Although some disagreement will still exist, most individuals tend to feel that comparable estimates are made under each set of definitions.

Blondel and Lasky (1956) and Netschert (1958) recognized the need for identifying the materials and energy contained

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[1] An interim document of Canada's Department of Energy, Mines and Resources concerning departmental terminology has also proposed the use of "measured," "indicated," and "inferred" as the subclasses of the reserves category.

in the earth's crust that exist but have little potential for actual use by society during any period of time that has present meaning. Netschert first suggested the term "resource base" as the sum total of the crude oil, natural gas, and natural gas liquids present in the earth's crust within a geographic area. He later (1960) enlarged this to include all mineral resources.

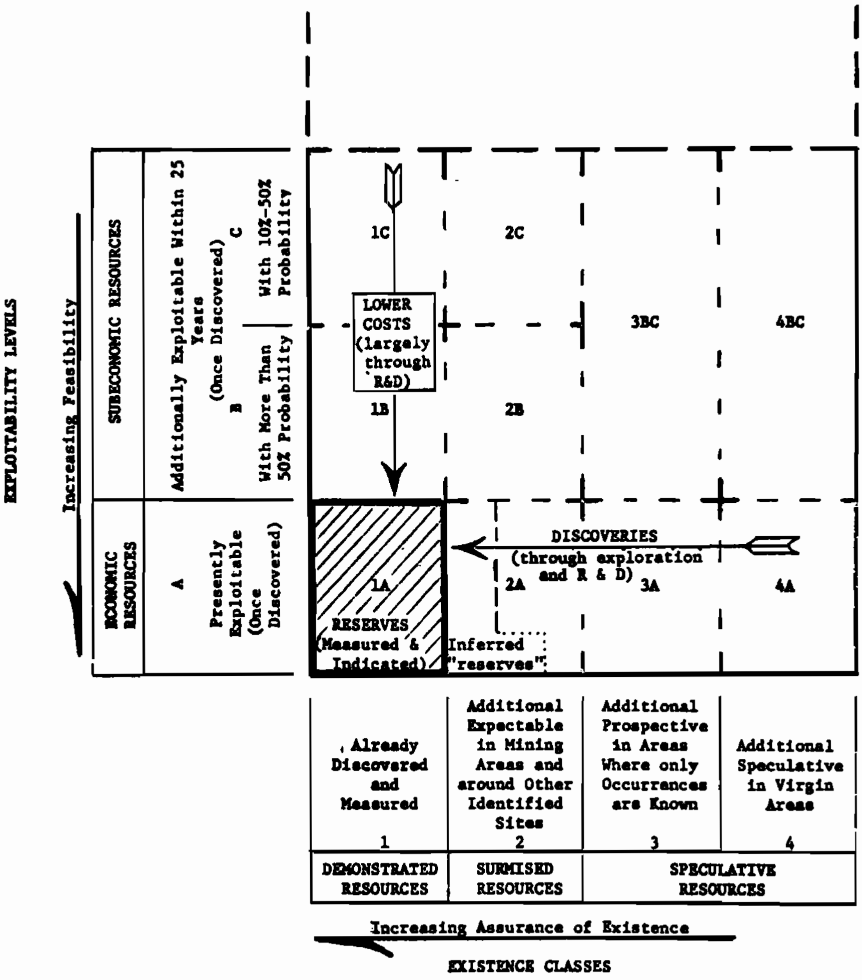
The USDI has not adopted the resource base concept and, although it implicitly includes all identified and undiscovered resources along the geologic axis, it does not define what is the lower limit of subeconomic resources, if any. Canada, however, recognizes the energy and minerals contained in a resource base and, as a consequence, has limited what may be classified as a resource. In so doing, they have not succumbed to the temptation to use price or cost, as has the USDI in separating submarginal from paramarginal. In preference, Canada has chosen to limit subeconomic resources on the basis of what may become exploitable during a specified period of future time (see Figure 1). Resources that through changes in technology or price have a probability of greater than 10% of becoming feasible for use are classified as a part of resources. Two other departures in the Canadian implementation of the McKelvey diagram are: 1) to introduce a classification called "surmised resources" which incorporates inferred "reserves" and other resources expected to be found in and around previously identified sites, and 2) to use a different identification for the two major classes of resources located in new areas.

The most challenging problem for the USDI in applying its terminology to the various mineral commodities will be to deal with energy resources and the industries that produce them. Energy resources have differences in characteristics and in past trade practices compared to those found in the metal resources that are reflected in the USDI terminology. Petroleum, coal, and natural gas have all customarily been estimated on a recoverable basis in North America as opposed to the "in place" used for metallic ores. Uranium offers a unique set of problems in that its terminology is a mix of terms drawn from both metals and energy practice as well as reflecting international terminology.

ADAPTATION OF THE USDI TERMINOLOGY TO THE MINERAL FUELS

Coal

The Bureau of Mines in trying to adapt to its past practice of dealing with coal resources on a depth/thickness/recoverable basis has proposed a set of terms for coal following the basic USDI pattern (see Appendix A). This presents the USDI with several problems. Among these are that they now have to cope with the recoverability problem and to determine whether or not thickness and depth match the geologic and economic criteria used to assign estimates to the various segments of the McKelvey diagram.



RESERVES (measured & indicated) = 1A (that is, demonstrated economic resources)
RESOURCES = RESERVES + all other numbered areas
RESOURCE BASE = RESOURCES + indefinite area beyond top of diagram

Note: It has been found impossible in practice to make distinctions between 3B and 3C, and between 4B and 4C.

Source: Canadian Department of Energy, Mines and Resources, "Departmental Terminology and Definitions of Reserves and Resources (Metals, Industrial Minerals, and Coal)," interim document, January 30, 1975 (Ottawa).

Figure 1. Departmental resource classification scheme.

Unfortunately, the Bureau of Mines' solution to the recoverability problem has been to propose a new term--"reserve base." Reserves under this scheme would be the recoverable portion and the reserve base would be the in place reserves. This involves three major shortcomings. One, it creates a new term. Two, there is the obvious possible confusion between a coal resource base and a coal reserve base. Three, the term reserves for all other minerals means in place, while for coal it would mean recoverable.

The Bureau's choice of depth and thickness as criteria or parts of definitions presents another set of problems. Depth and thickness are not actually relevant to whether or not coal should be classified as identified or undiscovered. These characteristics have had some influence on whether or not beds in actuality have been identified, but they should not be excluded from resource accounting once they have been discovered. Although it is unlikely that we have intentionally looked for and measured thin and deep beds of coal when there is so much coal available in thick beds near the surface, we do have the geologic capability to estimate how much coal is in these beds if they are known to exist. By attempting to exclude this coal within the general definition of what constitutes identified coal, USDI has created the paradoxical situation of having to state that beds of this description should be included in the resource totals if they are actually being mined, or could be.

It is likely that the USDI is attempting to avoid a possible problem of coal resource tonnages being inflated by inclusion of coal that has little potential for future use. Also, nuclear adds to the burden of calculations and leads to an inconsistency with past numbers. However, these tonnages will tend to fall into the subeconomic and undiscovered classifications or even be excluded because they fall outside the limits of what constitutes a resource. Also, this problem is further eased by the decision in both Canada and the United States that speculative coal (Classes 4A, B, and C in Canada) does not have any relevance in coal resource estimating and should not be measured.

Turning to the economic dimension, it is useful at this point for the USDI to set guidelines as to what combinations of thickness and depth of the various ranks of coal, that is, anthracite, bituminous, and lignite, are expected to qualify for classification as economic reserves or subeconomic reserves. Whether these are guidelines or should be formally included as criteria in the definition is moot. For example, it is expected that if there are beds of coal actually being mined, or that could be mined, that do not fit the stated criteria, the tonnages should be included in the proper category. On the other hand, coal which might meet the general criteria but is not minable owing to poor location, bad roof conditions, or poor quality (that is, sulfur content) should not be included in the quantities normally acceptable under these criteria.

The advantage of using the time dimension as a key factor in the subeconomic direction becomes obvious again with coal. Using a time limit means that the decision as to what depth and thicknesses of coal should be included does not have to be so narrowly specified. Economic reserves are those that can currently be mined regardless of their thickness or rank. The subeconomic classes include all coal that is of a thickness, depth, and rank for which there is an expectation that it could become minable in the next 25 years. This can be left either to judgment or to guideline criteria.

Uranium

For most of its history the Atomic Energy Commission (AEC) has been concerned with estimating the supply and demand for U_3O_8 from known deposits of usable uranium ore. This was an essential task since it was important for the nation to be apprised of its readily available uranium supplies. Little work was done on estimating resources of lower quality or undiscovered resources in other areas or types of deposits. In addition, the reserves were estimated on the basis of "forward cost" rather than price. This requires an engineering estimate of operating and capital costs and avoids an impression of stating what prices are appropriate. Thus, uranium resources were reported as tons of recoverable U_3O_8 at $8 per pound, $10 per pound, and $15 per pound. In more recent months attention has been given to tonnages at even higher per pound costs.

There has been some tendency in AEC publications to refer to all uranium as reserves or uranium ore regardless of cost. This is incorrect even though it is admittedly difficult to determine at what level of cost U_3O_8 is no longer a reserve. Current market activities indicate that new commitments for future uranium supplies are now above $20 per pound of U_3O_8. It would be helpful and less confusing if U_3O_8 at the various levels of forward cost could begin to be placed into the standard USDI economic and subeconomic classes. This would make possible in discussing uranium supplies the necessary distinction between economic reserves and subeconomic resources.

In the geologic dimension there are slightly more difficult problems with uranium. Initially, the AEC, in evaluating only known deposits and primarily at the $8 and $10 per pound cost level, was clearly producing estimates that would normally be considered as measured reserves. At the higher cost levels, AEC data were less precise and indicated resources would be a more appropriate designator. One confusing element in terminology for both Canada and the United States is that they both recognize the nomenclature adopted by the International Atomic Energy Agency (IAEA). Both countries try to equate domestic terms to international terms. Thus, we have "reasonably assured resources" in IAEA language. This offers no real difficulty. However, the IAEA term "estimated additional resources" seems to not only encompass inferred reserves but extends into undiscovered resources which are more properly a part of hypothetical resources in the United States system and surmised resources in Canada.

Recently the AEC became more interested in undiscovered resources than previously. As a result, it has further defined its classification of "potential resources" of uranium. As of May 1973, the AEC's potential resources would have been identical to the IAEA's estimated additional resources. However, the AEC during 1974 adopted for its use the terminology developed by the Potential Gas Committee for estimating undiscovered natural gas reserves (see Appendix D for a description of these terms). As a result, potential uranium resources are now identified as "probable," "possible," and "speculative." One notes that the AEC is classifying undiscovered resources using two of the old familiar engineering terms which for metals apply only to identified reserves (see Appendix B).

The present status of the AEC terminology compared to USDI and IAEA terms would appear to be approximately as shown in Table 1.

Table 1.

<table>
<tr><td>USDI</td><td>Measured</td><td>Indicated</td><td>Inferred</td><td colspan="3">Hypothetical</td><td>Speculative</td></tr>
<tr><td>IAEA</td><td colspan="2">Reasonably Assured</td><td colspan="3">Estimated Additional</td><td colspan="2"></td></tr>
<tr><td>AEC</td><td colspan="2">Reserves</td><td colspan="2">Probable</td><td colspan="2">Possible</td><td>Speculative</td></tr>
</table>

If this is a fair appraisal of where the AEC terminology last stood, it would seem that it is closer to being in accord with the USDI in where it draws the line for classifications but out of step in terminology. This problem may be more readily dealt with now that the AEC has been merged into the Energy Research and Development Administration (ERDA). However, the AEC terminology no longer matches very well with that of the IAEA.

One other problem that eventually will have to be faced concerning uranium resources is to bring them more into adjustment with the other energy forms. This is not only the problem of in place versus recoverable, which must be dealt with in all of the energy resources, but also a problem whether or not the uranium resources can be converted into a Btu equivalent that has been so useful in comparing different energy resources. The total Btu content per unit weight of uranium, assuming total conversion, is extremely large compared to other forms of energy. The proportion that is actually available either technically or economically varies tremendously depending on the technology being employed, for example, a light water reactor versus a light metal fast breeder reactor.

Petroleum

The petroleum reserve terminology offers very little immediate problem with respect to dealing with established industry terms. The American Petroleum Institute (API) has only two terms--"proved" and "indicated additional" reserves. The term "proved reserves" as applied to petroleum is comparable to the USDI's "measured" and the mineral engineers' "proven." In fact, it may even be more conservative than these in that the potential error, particularly for the actual reserves to be less than the estimate, is probably not as much as 20%. The API term "indicated additional reserves" is used to account for reserves that are expected to be produced from reservoir stimulation projects that will increase production but have not as yet been put in place or tested adequately enough to include the volumes in proved reserves. The reserves covered by this term would seem to fall either in the USDI's measured or indicated reserve classification, probably the latter (see Appendix C).

Beyond what the USDI would class as demonstrated petroleum reserves there is no formal oil company or industry effort to estimate for public purposes what would be considered inferred reserves. Internally, companies continuously evaluate all properties on the basis of their total future expected output. This is done shortly after a discovery well has been drilled and then refined as more data become available. Using materials balance calculations, volumetric methods, and comparative analysis it is possible to approximate what individual pools and fields will produce beyond what can be "proved" at any one point in time for existing wells. These data would be roughly comparable to the mineral engineers' "possible" reserves. Or, in the national aggregate, they would be equivalent to the USDI's "inferred" reserves. Unfortunately, it is difficult to estimate inferred reserves on a regional scale and the limitations on the use of proprietary data have so far precluded the estimating from being done on a property-by-property basis. There is a real question as to whether this latter approach is feasible. The Federal Energy Administration's current attempt to develop national data of this type should shed some light on this matter.

Natural Gas

As discussed previously and now to be reiterated here, there is no industrial or professional tradition to measure petroleum and natural gas resources in place. Therefore, to bring the oil and gas industry into conformance with the USDI practice of starting with "in place" data and then converting to "recoverable" will be extremely difficult. However, modern petroleum and natural gas evaluation practice does involve calculations of the in place hydrocarbons before the estimates are made for recoverable quantities at standard surface conditions of temperature and pressure so that in place calculations are technically possible to do.

The general situation in natural gas is slightly different from that found in petroleum. As is the case with petroleum, the American Gas Association measures proved reserves of recoverable natural gas using the API established definitions. There are also, as for petroleum, a number of estimates made from time to time of the ultimate production of natural gas after all reserves have been discovered and the economic limit of usable gas has been reached. These have the same limitations as those made for petroleum.

However, unlike the petroleum industry, the gas industry has made an industry effort through the Potential Gas Committee (PGC) to measure undiscovered natural gas reserves (see Appendix D). This encompasses extensions and discoveries in existing pools and field (probable reserves), new fields in productive provinces where characteristics are comparable to those in the productive areas (possible reserves), and new fields that might be discovered in areas that have not previously been productive (speculative reserves). As discussed previously in connection with the AEC's use of the PGC terminology, these terms are comparable, respectively, to the USDI's "inferred," "hypothetical," and "speculative."

In addition to the problem of the PGC terms being confused with those of the mineral engineers, there is a lack of precise definition as to the economic assumptions that are being applied. The equivalent USDI terms can be identified in the geologic dimension, but how far down the economic feasibility axis the PGC estimates extend cannot be ascertained under their assumption of adequate but reasonable prices and normal improvements in technology. On the basis of public statements by individuals connected with the PGC the gas resource estimate definitely extends beyond that which is expected to be discovered and produced under current prices. Their estimate appears to be based neither on some specified multiple of the present price nor on some assumption of what price and technology might reasonably be expected to do in the next 25 years. Whether or not PGC estimates are intended to include all that may become economically feasible to produce, which would be at the lower extreme of natural gas resources on the McKelvey diagram, is not determinable from their report.

The Flow and Renewable Energy Forms

A combination of perpetual supply and a lack of past importance seems to have limited the incentive to develop a formal terminology for the renewable energy sources. In contrast to the ever present question asked about the mineral fuels, "How much is there and how long will it last?" there seems to be little curiosity about what lies between the existing capacity to use energy flows and dramatic measures of ultimate potential illustrated by statements that the sun provides as much energy in three days as the total supply of fossil fuels.

Schurr and Netschert (1960) in Energy in the American Economy decided in their consideration of hydropower resources that it is not possible to adapt in direct fashion the reserves, resources, resource base terminology to the non-renewable or flow energy sources. No one has attempted to say otherwise.

However, this does not deny that the basic concept and need for examining the nonrenewable energy resource potentials in some comparable fashion are not feasible and useful. Schurr and Netschert suggested that there is a resource parallel in the estimates of hydropower potential that have been made for many years. The total hydropower potential based upon total water multiplied by the average head has been calculated as has the capacity of developed and undeveloped hydropower sites. Estimates have been made as to the amount of the undeveloped hydropower potential that could at some time in the future become usable. In concept, these calculations fit the McKelvey diagram. What is our current capacity (Developed Reserves)? What is currently economic (Reserves)? What is the total hydropower that we perceive will at some time be useful (Resources)? What is the total energy content of moving water (Resource Base)?

To be more specific, if we take the yearly average flow of water in the United States at mid-point in the watercourse times the gross head times the number of hours in a year, we have estimated the gross hydropower of the United States or resource base. If we then calculate what is technically usable at present or within some foreseeable future (this can be done either by subtracting losses from the resource base or adding together all the potentially usable sites according to river basins as done by the Federal Power Commission) you arrive at a measure of resources (see Appendix E). The portion of the technically usable potential which is currently (whether developed or not) competitive with alternative energy forms is our hydropower reserve.

Following this conceptual lead, any flow energy resource that can be confined to a specific site can be appraised. (It should be noted that since most renewable resources do not involve exploration and discovery any terminology reflects primarily economic potential. Moreover, the potential errors in estimating resemble those found along the geologic axis for the nonrenewable resources.) Terminology could be developed as follows:

Rated Capacity--Maximum (daily) output or nameplate capacity in kilowatts at existing sites.

Developed productive capacity--Average (annual) output in kilowatt hours at existing sites.

Undeveloped productive capacity--Average (annual) additional output in kilowatt hours at existing sites not yet fully developed.

Undeveloped economic capacity--Average (annual) output in kilowatt hours at undeveloped sites that are considered to be economic under current conditions.

Undeveloped subeconomic capacity--Average (annual) output in kilowatt hours at undeveloped sites that are expected to become economically usable within the next 25 years.

Undeveloped noneconomic capacity--That part of the resource base that is not expected to become economic in the next 25 years.

The renewable energy sources which cannot be confined to a specific site present a somewhat more complex problem in concept, terminology, and measurement. This is the case for the energy potential found in solar radiation, winds, or thermal gradients in the air or bodies of water.

The initial requirement in appraising solar energy resources is to map the various levels of energy concentration. For solar radiation and wind this would involve some integrated measure or coefficient combining average intensity, the range between maximum and minimum, and the diurnal and seasonal variations in flow. For solar energy found in the atmosphere or in large bodies of water a measure of the available temperature gradient would be adequate. These various measures of energy concentration or gradient could be evaluated according to what levels are currently competitive with other energy sources, what levels are expected to become economic in 25 years, and what gradients or concentrations are not expected to be usable during that interval.

The most difficult task will be to translate the total areas encompassed by the appropriate isopleths of energy potential into net usable areas. However, this may not involve a much greater degree of uncertainty and judgment than is required in estimating the amount of petroleum that may be discovered on the continental shelves. As an example, if we assume that all of Arizona is encompassed by a favorable solar concentration isopleth it would then be necessary to determine the economically and physically recoverable portion of that total resource potential. This would require estimating what amount of the surface could actually be covered by collecting surfaces, what would be the maximum technical recovery, what portion of the surface is currently available for this purpose, and what amount of land should be reserved for other future uses. Through this process it would be possible to estimate what is the maximum areal commitment that could be made to solar or wind energy. Of this total resource, the portion that is currently economic and developable as well as that portion that would become usable in the next 25 years could be estimated. Also, at the final stage of determining recoverability of the solar energy flow, consideration would have to be given to what would be the standards of acceptable environmental and ecological impact.

This illustrates how, based upon isopleths of solar concentration, it would be possible to first estimate Arizona's solar resource base solely on technical grounds. The estimated usable portion of that total, recognizing the competition from other land uses over the next 25 years, would define the resources. The amount which is currently economic would be the reserves. Finally, any considerations as to acceptable levels of recoverability could be introduced. In addition, any existing or proposed solar plants could be evaluated in terms of design capacity and their productive capacity based on average annual output in kilowatt hours.

The Special Case of Geothermal

The natural heat of the earth provides either a temperature gradient or hot water or steam that can be employed in the production of electricity. Direct use of geothermal heat for processing or space heating is possible but not expected to be a major use. In the case of natural dry steam, the steam can be employed directly for turning turbines. Naturally-occurring mixtures of hot water and steam can also be used by extracting the steam or by converting the hot water to steam before use in turbines. In the case of solid rock without natural circulating water, it is necessary to fracture the rock and introduce fluids into the rock crevices to extract the heat. In this latter "dry rock" circumstance, the geothermal resource is somewhat akin to air and water temperature gradients.

The natural heat gradient of the earth of approximately 2°F per 100 feet will provide usable temperature differences at sufficient depth. However, the more immediately attractive sources are natural steam or circulating hot water at high temperatures nearer the surface. To discover and extract this heat involves a process not unlike that employed for petroleum. A favorable geologic location is determined and then tested by drilling into the suspected geothermal zone. If adequate temperatures and fluid flow are encountered, then a sufficient number of holes are drilled to extract enough steam or hot water to operate a commercial-sized power plant.

An impression may be held by some that geothermal resources are vast blocks of uniform temperatures that can be exploited long into the future. In reality, geothermal zones tend to have discrete areal limits and may be limited in their usable vertical dimensions. Rapid extraction of the steam or hot water or removal of heat from dry rock can exceed the capability of the source to heat the circulating fluid through transfer of heat from the surrounding rock as rapidly as it is being extracted. Disposal of the water after the heat has been extracted also presents a problem of avoiding surface or ground water pollution or possible dilution of the heat source when subsurface disposal is employed. Thus, in appraising geothermal resources there is both a depletion as well as a recoverability factor to consider.

Geothermal energy is still an unfamiliar resource and the processes for its exploration, development and exploitation are in relatively primitive states. However, it is apparent that there is a geologic uncertainty involved and that exploration is necessary to discover usable resources and to define the limits of the discovery. Once developed, with heat being produced and sold to a power plant, it is then possible to measure the size of the resource. The resource may be depletable or renewable depending upon how it is exploited.

The resource terminology for geothermal energy can be related to both the McKelvey diagram and the hydropower model. In the geologic dimension, geothermal heat resources can be measured, indicated, inferred, hypothetical, or speculative. In the economic dimension, there are economic and subeconomic occurrences. If the heat reservoir is used in a fashion that causes it to be depleted to a point where it becomes unusable, then the reserves can be measured in terms of total heat to be produced during its expected lifetime. If, on the other hand, the heat flow is sustainable at a level where the lifetime is or would be expected to be extremely long or indefinite, then measurements would have to be made on the basis of rated capacity, developed productive capacity, undeveloped productive capacity, undeveloped economic capacity, and undeveloped subeconomic capacity.

Since geothermal plants already exist in this country and elsewhere, it is expected that terminology is already beginning to emerge among the professional and industrial groups. But no formally adopted language appears to have been accepted. It would seem advisable, before too many diverse terms are coined leading to opposition among various groups for the adoption of their own preferences, that the involved groups assemble and develop a uniform geothermal terminology as soon as possible.

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APPENDIX A

US Department of Interior Proposed Coal Terminology*

CRITERIA FOR COAL RESOURCE/RESERVE IDENTIFICATION

Coal resource and coal reserve classification is currently based upon three criteria: 1) thickness of the coal bed, 2) depth of the coal bed, and 3) the reliability of the data upon which the estimate was based. The criteria for each category are described below and summarized in Table A1 and will be used in preparing all Department of Interior coal resource/reserve estimates from January 1, 1974, until further revised.

> Identified Resources--Include beds of bituminous coal and anthracite 14 inches or more thick and beds of subbituminous coal and lignite 30 inches or more thick that occur at depths to 3,000 feet and whose existence and quantity have been delineated within specified degrees of geologic assurance as measured, indicated, or inferred. Include also thinner and/or deeper beds that currently are being mined or for which there is evidence that they could be mined commercially.
>
> Undiscovered Resources--Include beds of bituminous coal and anthracite 14 inches or more thick and beds of subbituminous coal and lignite 30 inches or more thick that are presumed to occur in unmapped and unexplored areas reasonably near the surface (to depths of 3,000 feet) or in deeper structural basins of depths between 3,000 feet and 6,000 feet. All undiscovered coal resources in the United States are considered to be in the Hypothetical category.
>
> Total Resources--Include in this category the sum of the Identified and Undiscovered Resources.
>
> Reserve Base--Include in place beds of bituminous coal and anthracite 28 inches or more thick and beds of subbituminous coal 60 inches or more thick that occur at depths to 1,000 feet. Include also thinner and/or deeper beds that currently are being mined or for which there is evidence that they could be mined commercially at this time. Include beds of lignite 60 inches or more thick which can be surface mined--generally those that occur at depths no greater than 120 feet.

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*Adapted from "Joint Geological Survey-Bureau of Mines Classification System for Coal Resources and Reserves," internal document, May 17, 1974.

Reserve or Recoverable Reserve--Include that portion of the reserve base that can be mined legally and economically at the time of classification.

Subeconomic Resources--Include all Identified Resources that do not fall into the Reserve category. Include in this category beds of bituminous coal and anthracite 14 inches to 28 inches thick and beds of subbituminous coal 30 inches to 60 inches thick that occur at depths to 1,000 feet. Include also beds of bituminous coal and anthracite 14 inches or more thick and beds of subbituminous coal 30 inches or more thick that occur at depths between 1,000 and 3,000 feet. Include lignite beds 30 inches or more thick that cannot be surface mined--generally those that occur at depths greater than 120 feet, and lignite beds 30 inches to 60 inches thick that can be surface mined. Include the non-recoverable portion of the reserve base.

The following criteria for measured, indicated, and inferred are applicable to both the Reserve and Subeconomic resource components:

Measured--Tonnage is computed from dimensions revealed in outcrops, trenches, mine workings, and drill holes. The points of observation and measurement are so closely spaced and the thickness and extent of coals are so well defined that the tonnage is judged to be accurate within 20% of true tonnage. Although the spacing of the points of observation necessary to demonstrate continuity of the coal differs from region to region according to the character of the coal beds, the points of observation are, in general, no greater than 1/2 mile apart.

Indicated--Tonnage is computed partly from specified measurements and partly from projection of visible data for a reasonable distance on the basis of geologic evidence. In general, the points of observation are about one mile apart, but they may be as much as 1 1/2 miles apart for beds of known continuity.

Inferred--Quantitative estimates are based largely on broad knowledge of the geologic character of the bed or region and few measurements of bed thickness are available. The estimates are based primarily on an assumed continuation for which there is geologic evidence. In general, inferred coal lies more than 1 1/2 miles from the outcrop or from points for which mining or drilling information is available.

Demonstrated Reserves--Include in this category the sum of the Measured and Indicated Reserves.

Table A1. Coal resource-reserve criteria.

	Depth - Feet	Thickness - Inches
Total Resources and Undiscovered Resources		
Anthracite and Bituminous	6,000 or less	14 or more
Subbituminous and Lignite	6,000 or less	30 or more
Identified Resources		
Anthracite and Bituminous	3,000 or less	14 or more
Subbituminous and Lignite	3,000 or less	30 or more
Reserve Base		
Anthracite and Bituminous	1,000 or less	28 or more
Subbituminous	1,000 or less	60 or more
Lignite	120 or less	60 or more
Reserves		
Criteria same as Reserve Base but with recoverability factor applied.		
Subeconomic Resources		
Anthracite and Bituminous	0 - 1,000	14 - 28
	1,000 - 3,000	14 or more
Subbituminous	0 - 1,000	30 - 60
	1,000 - 3,000	30 or more
Lignite	0 - 120	30 - 60
	120 - 3,000	30 or more

The Reserve Base includes some beds that are thinner and/or deeper than the general criteria permit, but that currently are being mined or are judged possibly commercially mineable at this time.

Identified Resources are classified as measured, indicated, and inferred according to the degree of geologic assurance as described in the text.

APPENDIX B

US Atomic Energy Commission† Terminology*

RESOURCE ESTIMATES

The relationship of resource quantities to cost and reliability of estimate is shown in Figure B1. Here, resources increase in size with increasing cost toward the bottom of the chart. They also increase in size, but with decreasing certainty, toward the right side of the chart. The shaded area indicates that portion of the resource spectrum of primary interest up to this time. Its vertical extent, representing cost, is relatively limited and extends close to the possible maximum competitive fuel cost for light water reactors.

Reserves

A uranium ore reserve is defined by the AEC as an estimate of the quantity of uranium in known deposits which can be produced at or below a stated cost per pound termed the "cutoff cost." Estimates are expressed in tons of ore and contained U_3O_8. The relation between reserves and potential is illustrated in Figure B1. Estimates qualify as a reserve only if there are sufficient data on the depth, thickness, continuity, and grade distribution of uranium for calculations on an engineering basis. The quantity, grade, and physical characteristics have been established with reasonable certainty by detailed sampling, usually by surface drilling, initially, and later supplemented by underground drilling and sampling. The density and method of sampling is determined by the size, depth, and geological characteristics of the deposit. Substantial capital costs have been incurred prior to establishing a reserve to the point where a determination can be made to proceed with mine and mill investment.

The term "reserves" is roughly synonymous with "reasonably assured resources" used by the Working Party on Uranium Resources sponsored by the OECD and the International Atomic Energy Agency, and the two terms are often used interchangeably. However, the estimates in both cases are less precise when applied to material in the plus $10 per pound cost category.

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†Now known as the Energy Research and Development Administration.

*Adapted from Nuclear Fuel Resource Evaluation--Concepts, Uses, Limitations (Grand Junction: May 1973).

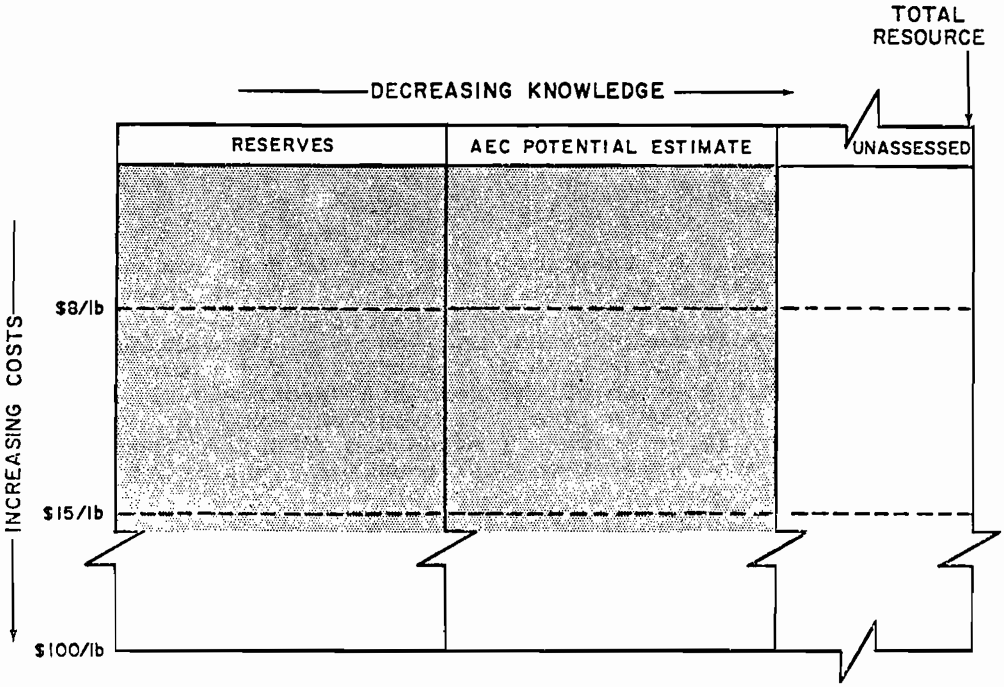

Figure B1. Uranium resources–range of cost and reliability.

POTENTIAL RESOURCES

Definition of Potential Resources

Uranium potential may be defined as a geologic judgment of the undiscovered tons of U_3O_8 present in minable amounts in areas that are relatively unexplored in detail, but about which enough is known of the uranium geology to permit prediction of the nature and extent of favorable environments or host rocks. The geographic locations of potential deposits may be definable only within broad limits. Providing the qualitative nature of potential is recognized and taken into account, potential plus reserves provide a more useful base for long-range predictions of domestic supply than do reserves alone.

The estimated potential resources of uranium are surmised to occur in 1) unexplored extensions of known deposits, 2) postulated deposits within known uranium areas, and 3) postulated deposits in other areas geologically favorable for uranium. The deposits are expected to be discoverable and exploitable within selected cost ranges.

Recognizing that the available data base (for example, pertinent geological and geophysical data and amount and results of exploratory work), and hence the reliability of the estimates, will vary greatly from area to area, the following classes of potential have been adopted for the preliminary evaluation.

Probable--potential resources are those estimates to occur in known uranium districts and are further postulated to be in extensions of known deposits, or in new deposits within trends or areas that have been mineralized as identified by exploration.

Possible--potential resources are those estimated to occur in new deposits in formations or geologic settings productive elsewhere within the same geologic province or subprovince under similar geologic conditions, or within the same geologic conditions, or within the same geologic province or subprovince under different geologic conditions.

Speculative--potential resources are those estimated to occur in new deposits in formations or geologic settings, not previously productive, within a productive geologic province or subprovince, or within a geologic province or subprovince not previously productive.

These definitions are patterned after those used by the Potential Gas Committee in its reports of potential natural gas resources.

APPENDIX C

American Petroleum Institute Terminology*

PROVED RESERVES OF CRUDE OIL

Definition

Proved reserves of crude oil as of December 31 of any given year are the estimated quantities of all liquids statistically defined as crude oil, which geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions. Reservoirs are considered proved if economic productivity is supported by either actual production or conclusive formation tests. The area of an oil reservoir considered proved includes: 1) that portion delineated by drilling and defined by gas-oil or oil-water contacts, if any, and 2) the immediately adjoining portions not yet drilled but which can be reasonably judged as economically productive on the basis of available geological and engineering data. In the absence of information on fluid contacts, the lowest known structural occurrence of hydrocarbons controls the lower proved limit of the reservoir.

Reserves of crude oil which can be produced economically through application of improved recovery techniques (such as fluid injection) are included in the "proved" classification if successful testing by a pilot project, or the operation of an installed program in the reservoir, provide support for the engineering analysis on which the project or program was based. Estimates of proved crude oil reserves do not include the following: a) oil that may become available from known reservoirs but is reported separately as "indicated additional reserves"; b) natural gas liquids (including lease condensate); c) oil the recovery of which is subject to reasonable doubt because of uncertainty as to geology, reservoir characteristics, or economic factors; d) oil that may occur in untested prospects; and e) oil that may be recovered from oil shales, coal, gilsonite, and other such sources.

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*Adapted from "Standard Definitions for Petroleum Statistics," Technical Report No. 1, July 1, 1967; "Organization and Definitions for the Estimation of Resources and Productivity Capacity of Crude Oil," Technical Report No. 2, June 1970; and "Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada and United States Productive Capacity as of December 31, 1973," June 1974.

PROVED DEVELOPED RESERVES

Definition

Proved developed reserves as of December 31 of any given year are proved reserves estimated to be recoverable through existing wells. Reserves in proved reservoirs penetrated by wells but currently not being produced are classified as "developed" if it is anticipated that such reserves will be recovered through existing wells requiring no more than workover operations.

PROVED UNDEVELOPED RESERVES

Definition

Proved undeveloped reserves as of December 31 of any given year are defined as economically recoverable reserves estimated to exist in proved reservoirs which will be recovered from wells to be drilled in the future. Reserves in undrilled areas are included in proved reserve estimates if they are considered proved by geologic analysis of the current well information.

INDICATED ADDITIONAL RESERVES

Definition

With the present state of industry technology, certain quantities of crude oil (other than those defined and reported as proved reserves) may be economically recoverable from the following potential sources: Known productive reservoirs in existing fields expected to respond to improved recovery techniques such as fluid injection where 1) an improved recovery technique has been installed but its effect cannot yet be fully evaluated; or 2) an improved technique has not been installed but knowledge of reservoir characteristics and the results of a known technique installed in a simular situation are available for use in the estimating procedure.

Crude oil potentially available from these sources is reported as "indicated additional reserves." The economic recoverability of these reserves is not considered to be established with sufficient conclusiveness to allow them to be included in proved reserves; however, if and when improved recovery techniques are successfully applied to known reservoirs, the corresponding indicated additional reserves will be reclassified and added to the inventory of "proved" reserves.

Indicated additional reserves do not include reserves associated with acreage that may be added to the area of a proved reservoir as the result of future drilling.

ORIGINAL OIL-IN-PLACE

Definition

The estimated number of stock tank barrels of crude oil in known reservoirs prior to any production is defined as "original oil-in-place." Known reservoirs include a) those that are currently productive; b) those to which proved reserves have been credited but from which there has been no production; and c) those that have been depleted.

Comments

Original oil-in-place is not to be confused with recoverable oil-in-place. Original oil-in-place is a gross quantity independent of recovery efficiency or economics of operation; recoverable oil-in-place is a net quantity which is dependent upon recovery efficiency and economics of operation.

The estimating of original oil-in-place is based on calculations using the volumetric method or the material balance method when sufficient factual data are available concerning reservoir rock, fluid properties, reservoir limits, and production performance. Where such data are not available, the estimating of original oil-in-place may be based on information and performance characteristics of reservoirs believed to be comparable. Oil-in-place estimates are limited to the reservoir area and volumes associated with proved reserves and past production.

ULTIMATE RECOVERY

Definition

Ultimate recovery represents the estimated quantity of crude oil which has been produced from a reservoir and is expected to be produced in the future if there are no substantial changes in current economic and operating conditions.

Comments

Ultimate recovery also may be expressed as the percentage of original oil-in-place which is expected to be eventually produced. This percentage will vary from one reservoir to another in accordance with the reservoir fluid, rock characteristics, and the producing mechanism or drive which is present.

Estimates of ultimate recovery from a given reservoir may be revised in subsequent years if 1) there is a successful application of an improved recovery technique; 2) there is an increase or decrease in the extent of the reservoir; or 3) there is information which indicates that recovery mechanisms are performing more or less efficiently than previously estimated.

NATURAL GAS--PROVED RESERVES

Proved reserves of natural gas as of December 31 of any given year are the estimated quantities of natural gas that geological and engineering data demonstrate with reasonable certainty to be recoverable in the future from known natural oil and gas reservoirs under existing economic and operating conditions.

Reservoirs are considered proved if economic productivity is supported by either actual production or conclusive formation tests. The area of a reservoir considered proved includes: a) that portion delineated by drilling and defined by gas-oil, gas-water, or oil-water contacts; and b) the adjoining portions not yet drilled but which can be reasonably judged as economically productive on the basis of available geological and engineering data. In the absence of information on fluid contacts, the lowest known structural occurrence of hydrocarbons controls the lower proved limit of the reservoir.

Reserve estimates are prepared for total recoverable natural gas, nonassociated gas, and associated-dissolved gas. Estimates do not include 1) gaseous equivalents of natural gas liquids expected to be recovered from reservoir natural gas as it is produced; 2) natural gas being held in underground storage; or 3) nonhydrocarbon gases.

Classifications of reservoirs by regulatory agencies are used as the basis for dividing total reserves between non-associated and associated-dissolved reserves. In the absence of classification by a regulatory agency, allocations are based on the natural occurrence of the gaseous hydrocarbons in reservoirs as determined by the operator.

NATURAL GAS LIQUIDS--PROVED RESERVES

Estimates of proved reserves of natural gas liquids on December 31 of any given year include a) reserves of liquids which are expected to be recovered from associated and non-associated gas produced from gas wells and processed through lease separators; and b) reserves of liquids expected to be recovered from associated-dissolved and nonassociated gas when processed in field facilities or gas processing plants. Estimates of proved reserves of natural gas liquids are based on 1) proved reserves of natural gas on December 31, and 2) rates at which liquids can be recovered from natural gas by using processing equipment of the type currently installed or planned as of December 31. Quantities of such reserves are expressed in liquid equivalents at the surface measured in terms of barrels of 42 US gallons at 60°F.

APPENDIX D
Potential Gas Committee Terminology*

DEFINITION OF POTENTIAL GAS

The phrase "potential supply of natural gas" as used by the Potential Gas Committee in making its estimates and in preparing its report, means: At a given date and underlying a particular geographic area, that prospective quantity of natural gas yet to be found and proved (as the term _proved_ is used by the American Gas Association Committee of Natural Gas Reserves) by all wells which may be drilled in the future under assumed conditions of adequate but reasonable prices and normal improvements in technology.

The definition of _potential supply_ specifies a relationship to proved reserves because the Committee's estimate at any given date is not to include any proved reserves existing as of that date but is to include such volumes as may become proved reserves in the future. Potential supply is a volume of gas which is in addition to existing proved reserves. An estimate of potential supply must take into consideration the criteria used by the Committee on Natural Gas Reserves of the American Gas Association in preparing its annual estimates of proved recoverable reserves. The Committee on Natural Gas Reserves defines proved recoverable reserves[1] as follows:

> The current estimated quantity of natural gas and natural gas liquids which analysis of geologic and engineering data demonstrate with reasonable certainty to be recoverable in the future from known oil and gas reservoirs under existing economic and operating conditions. Reservoirs are considered proved that have demonstrated the ability to produce by either actual production or conclusive formation test.

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*Adapted from Potential Gas Committee, _Potential Supply of Natural Gas in the United States_ (Boulder: November 1973).

[1] A.G.A. Proved Reserves Report, _27_, May 1973, p. 102.

> The area of a reservoir considered proved is that portion delineated by drilling and defined by gas-oil, gas-water contacts or limited by structural deformation or lenticularity of the reservoir. In the absence of fluid contacts, the lowest known structural occurrence of hydrocarbons controls the proved limits of the reservoir. The proved area of a reservoir may also include the adjoining portions not delineated by drilling but which can be evaluated as economically productive on the basis of geological and engineering data available at the time the estimate is made. Therefore, the reserves reported by the Committee include total proved reserves which may be in either the drilled or the undrilled portions of the field or reservoir.

The Committee on Natural Gas Reserves includes in proved reserves all gas estimated to be producible from tested formations under existing operating and economic conditions without regard to the size, use, or disposition of any production. Proved reserves in an undrilled area, however, must be so related to the developed or tested leases and to known field geology that its productive ability is assured.

CATEGORIES OF POTENTIAL GAS SUPPLY

Accuracy of the estimates of gas volumes included in the potential supply of a given area are dependent upon geological conditions and the extent to which the area has been explored and developed. Using available geologic data and the American Association of Petroleum Geologists classification of wells, the Work Committee divides the estimates into three broad categories. These categories are as follows:

a. Probable potential gas supply (associated with existing fields).

    1) Supply from known accumulations obtained by:

        a) Future extensions of existing pools, in known productive reservoirs.

        b) Future new pool discoveries, within existing fields, in reservoirs productive elsewhere within the same field.

    2) Supply from new pool discoveries obtained by:

        a) Future shallower and/or deeper new pool discoveries, within existing fields, in formations productive elsewhere within the same geologic province or subprovince, under similar geologic conditions.

        b) Future shallower and/or deeper new pool discoveries, within existing fields, in formations productive elsewhere within the same geologic province or subprovince, under <u>different</u> geological conditions.

b. Possible potential gas supply (associated with productive formations).

    1) Supply from <u>new field</u> discoveries obtained by:

        a) Future new field discoveries, in formations <u>productive</u> elsewhere within the same geologic province or subprovince, under <u>similar</u> geological conditions.

        b) Future new field discoveries, in formations <u>productive</u> elsewhere within the same geologic province or subprovince, under <u>different</u> geological conditions.

c. Speculative potential gas supply (associated with non-productive formations).

    1) Supply from <u>new pool</u> discoveries in formations not previously productive within a productive geologic province or subprovince.

    2) Supply from <u>new field</u> discoveries obtained by:

        a) Future new field discoveries in formations <u>not previously productive</u> within a productive geologic province or subprovince.

        b) Future new field discoveries within a geologic province <u>not previously productive</u>.

A <u>geologic province</u> is defined in the <u>Glossary of Geology and Related Sciences</u>, by the American Geological Institute, as "A large area or region unified in some way and considered as a whole." Hence, the Gulf Coast geosyncline and the Appalachian geosyncline often are referred to as <u>provinces</u>. Large provinces, such as those cited, are often divided into subprovinces to recognize geological homogeneity. Examples of subprovinces are the Mississippi embayment of the Gulf Coast geosyncline (province) and the Delaware basin within the Permian basin (province).

The term <u>basin</u> is avoided in the Guidelines because it has topographic and geomorphic meanings, as well as geologic. These meanings are often different and can lead to misinterpretations.

It is evident from the above that, as drilling progresses, gas volumes estimated to be in a particular reservoir will move from one category to another. Since any projection of potential supply lacks the accuracy of the proved reserve figures, particularly in the speculative category, it must be recognized that these estimates of potential supply will also be subject to upward and downward revisions when new geological and engineering data are provided by exploratory drilling. When gas is finally classified in the Proved category, it will no longer be included in the estimated potential supply.

APPENDIX E

Federal Power Commission Hydropower Resources Terminology*

FEDERAL POWER COMMISSION HYDROPOWER RESOURCES DEFINITIONS

Developed Projects

Information on developed hydroelectric projects was taken from reports made to the Commission by privately-, publicly-, and cooperatively-owned electric utilities and industrial establishments. The publicly-owned utility group includes Federal agencies, state power authorities, power and irrigation districts, and municipal electric utilities. The individual listings of conventional developed projects, along with undeveloped sites, are arranged by major drainages and river basins.

Undeveloped Sites

Information on undeveloped hydroelectric sites was taken from various river basin surveys and project investigations. The river basin studies encompass those by federal agencies, various federal-state entities operating under the aegis of the Water Resources Council, and others, including the water resources appraisal studies prepared by the Commission staff. Project investigations include those by federal and state agencies, electric utilities, and others, including studies made in connection with applications for Commission licenses and preliminary permits.

The available information has been adjusted or amended as necessary on the basis of review and analysis by the Commission staff. The estimates of capacity were based on natural streamflow, regulation of streamflow by storage, and available heads at the power sites. Allowance was made for depletions by irrigation and other consumptive uses of water. It was assumed that each site would be developed to achieve, in conjunction with the development of other sites, the best overall development of the water resources of the basin for power and other purposes. The estimates of generation represent average annual amounts, assuming average water conditions at project sites. Projects with proposed installations of less than 5,000 kilowatts are generally not included in the undeveloped listings.

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*Adapted from Federal Power Commission, "Hydroelectric Power Resources of the United States," January 1, 1972.

The estimates of conventional undeveloped water power aggregate the potential capacity of hundreds of individually identified sites. The possibility of developing a particular site depends on engineering, economic, environmental and other considerations which may vary considerably over time. Most sites included in this report have shown indications of engineering feasibility. Some of them have evidenced economic feasibility as well. Many sites have not been analyzed in sufficient detail to evaluate their economic or environmental costs and benefits but are included to give the reader an indication of the upper limit of the conventional water power potential of the United States. The estimates have been adjusted from previous years and will continue to be revised to reflect engineering, economic or other changes as they occur. It should be recognized, however, that economic and other factors may preclude the development of many of the potential sites listed.

CLASSIFICATION OF PETROLEUM RESOURCES AND RESERVES IN THE USSR AND ITS COMPARISON WITH CLASSIFICATIONS USED IN OTHER COUNTRIES[1]

M. Sh. Modelevsky and V. F. Pominov

Elaboration and uniform application of notions, terms and definitions are the essential part of primary energy sources estimating and development. However, this domain remains deficient in generally usable, scientifically sound principles approved on an international basis. Therefore, it seems highly desirable that a project be undertaken involving efforts from different countries, for the purpose of developing universal classifications and the corresponding terminology for resources of oil, gas, coal, oil shale, peat, uranium, water, wind and geothermal energies, as well as for other energy sources and carriers. Every energy source and carrier has its own distinctive features, and at the same time properties common to all the set.

The classification of petroleum reserves and resources in the USSR has been periodically changed and improved in accordance with new geological information and technical innovations in exploration and development of deposits. The latest variant has been in effect since 1970 (see study on Instructions on the Application, 1972).

The total amount of petroleum-in-place within a region (country, basin), irrespective of recovery possibilities, is called "the original potential geological resources" (OPGR). If oil and gas production have taken place in this region a part of OPGR remaining in the ground is called "the remaining potential geological resources". The OPGR may be divided into two major parts--explored and unexplored. The first of them is called "the original explored reserves" and includes the remaining reserves in known fields and amount of petroleum previously produced (cumulative production). The unexplored part of the OPGR is called "the unexplored reserves" and further divided into "prospective reserves" and "forecast (prognosis) reserves". The latter, in turn, consist of two subgroups (see Table 1).

The classification postulates the division of remaining explored reserves into two major groups--currently economically

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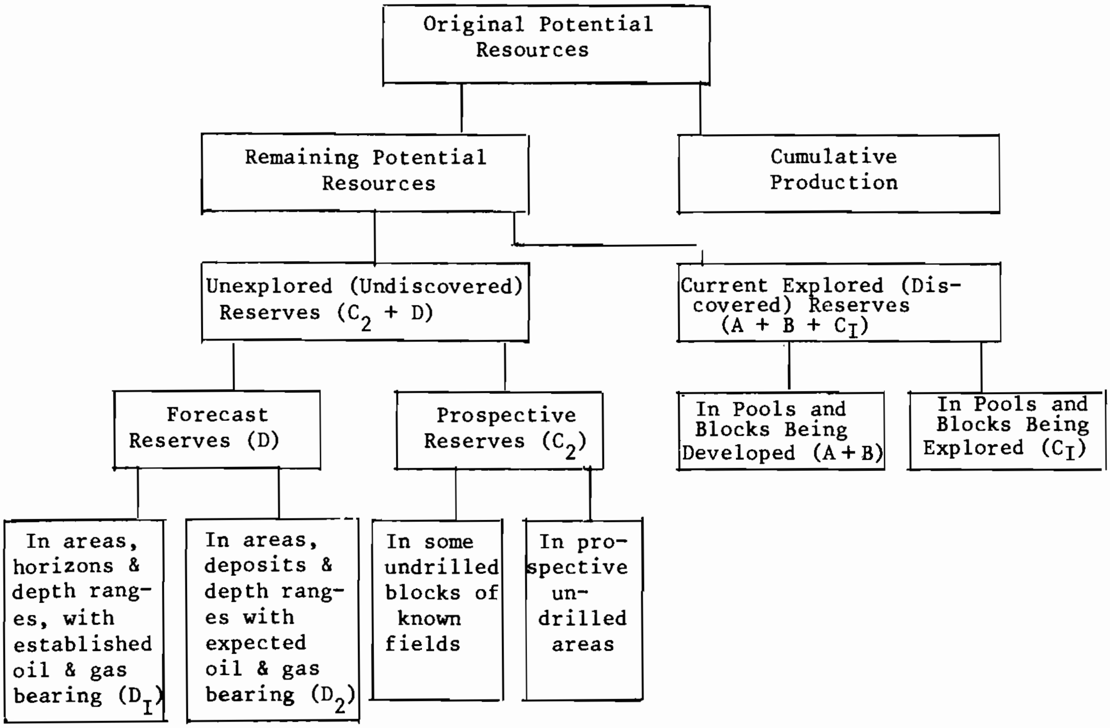
[1] The classification system is the same as used in most other socialist countries.

Table 1. Generalized structure of petroleum resources and reserves by classification adopted in the USSR.



recoverable and unrecoverable under current conditions (non-commercial). Recovery factors are estimated only for the economically recoverable quantities of oil and natural gas liquids. According to the state of geological knowledge the following three categories of explored reserves are singled out: A, B, C_1.

<u>Category A</u> is computed only during the process of exploitation of the fields and is studied to high a degree when all factors (conditions) influencing commercial production are fully determined, including reservoir properties and their changes, fluid chemical composition and saturation and also parameters determining the reservoir drive.

<u>Category B</u> is computed for reserves within the areas with commercial capacity proved by flow tests in wells which meet the reservoir at different hypsometric levels, and by favourable logging-coring data. The conditions of the petroleum occurrence, basic parameters, the drive-mechanism have to be studied

approximately. The prerequisite is a pilot exploitation of oil or gas wells and detailed knowledge of petroleum composition. The data are sufficient to start development designing.

Category C_1 is justified in known fields when some wells are proved to be commercial and others are characterized by favourable logging evidence and reservoir parameters. Also in this category are the reserves directly adjacent to blocks where the higher categories (A and B) are present in the same pool.

The accuracy of determining the basic parameters used in calculation of petroleum reserves by the volumetric methods may be in the range of 10%, 25% and 50% for the categories A, B and C_1 respectively (see studies by Mirchnik and Feigin, 1966; Trofimuk, 1964).

The category C_2 ("prospective reserves") is allocated for new areas (mainly for the anticline structures) delineated only with geological-geophysical methods (mainly with seismology), also for those blocks in known fields that adjoin the blocks with the higher categories and in deeper or shallower strata where the productivity is supposed to exist on the basis of only logging data. The noneconomically recoverable reserves are not applicable to the category C_2.

Petroleum reserves in new fields and pools are usually computed in the categories C_1 and C_2 (and only partly in B) immediately after drilling and testing the first lot of successful wells. So, the whole area with probable petroleum content is categorized at this stage, including a restricted zone where those wells are actually drilled. Such an approach makes possible an early determination, though approximately, of the commercial potential of new fields and it also permits an outlining of the plan of their development.

In addition to categories A, B, C_1 and C_2, forecast (prognosis) reserves (Group D) are calculated. These reserves are forecast in order to estimate the future potential of petroleum bearing provinces, regions and basins, and the calculations take broad geological considerations as a guideline.

Subgroup D_1 is calculated in inadequately studied traps and horizons, their petroleum potential being proved in other areas of this region (basin). The reserves of D_1 occur at depths reached by drilling in this region.

Subgroup D_2 includes petroleum reserves in regions inadequately studied by geological and geophysical investigations, in some distant (stratigraphic or parametric) wells and in regions with proved petroleum potential. Calculations for traps and promising horizons are only speculative, and the same holds true for depths not yet attained by drilling in this region.

The recoverable part of all groups and categories mentioned above may be found as a result of multiplying the volume of resources and reserves-in-place (geological) by a recovery factor (actual or expected by analogy with the other regions).

The Soviet classification of petroleum resources and reserves is characterized by a predominantly geological approach, the primary purpose being the calculation and subdivision of resources and reserves according to the degree of geological knowledge about pools, horizons, basins, etc. Usually rather high recovery factors have been taken, which would be a result of applying the most progressive methods of development in various types of fields. When calculating the recoverable portion of explored and unexplored reserves, the economic factors of their exploitation (including transportation and marketing) were rarely studied on a proper scale. Only in cases of quite small fields or when unprofitability of development is self-evident, such as when caused by specific conditions (for example, by some physical-chemical properties of the oil or gas), are the corresponding volumes of minerals singled out for the group of noncommercial reserves. However, recent years have witnessed a shift of emphasis, and the classification is becoming more and more economically oriented. For example, limits are set for the degree of exploration sufficient to justify the beginning of development and exploitation. This measure alone prevents unnecessary spending during the preliminary periods and hastens the process of bringing the minerals to the consumers.

In the USA, Canada, Latin America, Western Europe, Africa, the Middle East, South-East Asia and Australia a separation of reserves into certain groups is likewise greatly influenced by the degree of geological knowledge. Of no less importance, however, so far as available information is concerned, are economic and market factors, including considerations with regard to profitability of oil and gas production, transportation and selling, the character of land and mineral ownership, etc. Such an approach coupled with requiring stricter technical and economic conditions often leads to gross underestimating of remaining explored (proved) reserves (see Modelevskii and Pomianov, 1974).

The most widely accepted classification system in the majority of these countries is the petroleum reserves classification in use in the USA, though substantial departures are not uncommon because different authors put forth various meanings for some terms such as "proved", "probable", "possible reserves", "potential resources", etc. The scope of the present paper does not permit us to further expand on this subject. The following generalized set-up (see Table 2) is given to illustrate the gist of a comparative study of classifications used in USSR and other countries.

Table 2. Comparison of classifications adopted in the USSR and in other countries.

Groups of reserves in the US classification	Categories and groups from classification adopted in the USSR							
	USA and Canada	India	Iran	Malaysia	France	Netherlands	Federal Republic of Germany	North African Countries
Proved	A + B, partly C_I	A,B	A,B	A,B	A,B, partly C_I	A,B, partly C_I	A + B, partly C_I	A,B,C_I
Probable	C_I, C_2	C_I, C_2	C_I	C_I	C_I and partly C_2 in known fields	mainly C_I	C_I and sometimes C_2 in known fields	-
Possible	D_I, partly D_2	-	C_2 in known fields	C_2 in known fields	C_2 in prospective undrilled areas	C_2 in known fields	C_2 in prospective undrilled areas	-
Speculative	D_2	D_I	-	-	-	-	-	-

The US Geological Survey (USGS) and US Bureau of Mines (USBM) have recently adopted the classification of mineral resources proposed by V.E. McKelvey (1974). The all-embracing notion "total resources" used in this classification consists of two major categories--"identified reserves" (quantities of minerals recoverable under existing economic and technological conditions in known fields and prospective areas) and "identified and undiscovered resources" (established but currently uneconomic quantities in known fields and prospective areas and undiscovered quantities in new areas and basins).

In turn, the reserves are subdivided into three groups--measured, indicated and inferred. The first is essentially identical to proved reserves. The second comprises both probable and possible reserves (in the USGS and USBM definitions of this term); and the third term refers to known but unexplored deposits for which estimates of quantity and size are based on geologic evidence and projection.

Undiscovered resources consist of hypothetical and speculative groups, respectively in known districts and in a broadly favourable terrain where no discoveries have yet been made.

A preliminary comparison of Soviet and McKelvey's classifications is presented in Table 3. One should take into account that the classification destined for all the minerals would not necessarily reflect specific features of petroleum.

Table 3. Comparison of classifications of resources and reserves in the USSR and suggested by V.E. McKelvey.

Groups of mineral resources and reserves by McKelvey's classification	Categories and groups of recoverable petroleum resources & reserves in the USSR
Total resources	Original (ultimate) potential resources
Identified reserves	A B C_1 C_2
Measured reserves	A B, partly C_1
Developed reserves	A
Undeveloped reserves	B and partly C_1
Indicated reserves	C_1 and C_2 in known fields
Inferred reserves	C_2 in prospective areas and partly C_1 and C_2 in known fields
Undiscovered economic resources	D_1 D_2
Hypothetical resources	D_1
Speculative resources	D_2
Identified subeconomic resources	Noncommercial reserves of categories A, B and C_1 (noncommercial part of categories C_2 in the USSR not singled out)
Undiscovered subeconomic resources	Not singled out

The following conclusions can be drawn from a comparative study of the classifications used in different countries.

1) All the classifications have common elements.

2) Comparison is hampered by the lack of sufficient information about existing classifications, which is owing to the exceedingly general and flexible nature of the wording in some of them.

3) The classifications have positive as well as negative aspects (not touched upon here) and need to be further improved.

4) In connection with 3) a unified classification to be developed by experts from various countries will be very useful.

5) Definitions of main terms and terminological background deserve special attention.

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DISCUSSION

Rose: I support the statement that the McKelvey diagram can be adapted. We realize that it was derived early, from a mining concept, and had severe reservations at first about how it could be used for petroleum. But bending a few things here and there, changing certain definitions, it, in fact, does work, and we have adapted it successfully.

The second point I would like to make is that the US Geological Survey is not involved with the estimating of crude reserves. That work is carried out by the US Bureau of Mines, or simply by taking reserves information from the American private mining industry.

Grossling: What are those ordinates used in the first chart shown by Searl? One was the number of deposits for a given grade, and apparently the other was related to economics. Or was it the number of mines in actual exploitation?

Searl: The diagram shows a good linear relation between the average grade and number of deposits over a certain grade range. However, at lower grades the observed data differ significantly from the extended linear relation. This divergence is assumed to be due to economic factors--that is, higher costs of producing lower grade deposits.

Brinck: Concerning your graph of the number of ore deposits versus grade, you should make a difference between ore deposits of a given grade and the number of mineral deposits with this grade specification. Furthermore, it is a well known fact that both grade and size of US uranium deposits independently appear to be log normally distributed; Patterson (1974)* explained this from the fact that the low grade, small size tails are caused by the decreasing probability of the economic viability of these deposits, the high grade, large size tails, by the decreasing chance of their existence.

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*J.A. Patterson, 1974, "Outlook for Uranium", presented at the 17th Minerals Symposium, American Institute of Mining, Metallurgical, and Petroleum Engineers, May 11, 1974, Casper, Wyoming.

Clarke: I congratulate both authors on the attention drawn to the McKelvey diagram, and on the visualization of the way the two axes tie together. Earlier Fettweis drew attention to "mapping for a certain point in time", and Searl drew attention to the need to trust the use of professional skills of those who supply resource documents. The point is that it costs money to find out about resources by excavating, by putting holes in the ground. There is a high failure factor. It is by introducing your professional skills, making people aware of the supply position, that you actually illuminate the resource base, and I think one of the points of this Conference will be perhaps to show that the two axes of the McKelvey diagram are in a way interdependent. I am pleased with the observations of both gentlemen at this point.

Bowie: In uranium assessment we have a practical approach that has meant attempting to assess reserves and resources within different price categories. However, we believe in first things first and have concentrated on the less-than-\$30-per-pound U_3O_8 as the material likely to be used until the end of the century, although we have made some assessment of resources up to \$100 per pound of U_3O_8. High cost resources may never need to be used so their accurate assessment seems less important at the present time. Perhaps it is not very significant in 1975 to know what the ultimate resources of uranium are.*

Löennroth: I have a question for Grenon. Have you tried to adapt the concept of net energy content (that is, the energy content when the amount of energy needed for recovering the reserves has been subtracted) to the McKelvey diagram?

Grenon: We are in the process of investigating this possibility, and we are especially studying uranium shales and very low grade uranium ores. First results show that the figures for the tonnages to attribute to the various categories of resources of the McKelvey diagram can be considerably modified. Of course, this is also related to the economic scale of the McKelvey diagram, but such a relationship is not clear for the time being.

Hubbert: I have worked with the USGS and have had a close association with this McKelvey diagram since its inception. A logical difficulty with the system is that it violates a fundamental principle of scientific intelligibility expounded repeatedly by the philosopher of physics and Nobel Laureate, the late P.W. Bridgman: It is fundamental in physics that every concept that one uses must be definable operationally; otherwise one's analysis is unintelligible or, literally, nonsensical. The McKelvey diagram, expressed mathematically, is equivalent to the

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*This viewpoint is not shared at IIASA, where at least an idea of ultimate resources is looked for to help to better understand and to define long term energy strategies [the Editor].

following matrix:

$$Q = \begin{bmatrix} Q_{11} + Q_{12} + Q_{13} + \dots \\ + Q_{21} + Q_{22} + Q_{23} + \dots \\ + Q_{31} + Q_{32} + Q_{33} + \dots \end{bmatrix}$$

Unfortunately, no means exist for determining any of the terms Q_{ij}, except the first two or three. Hence, schemes of this kind violate Bridgman's criterion of intelligibility. An equation involving indeterminate or undefined terms cannot possibly yield a result of any higher intelligibility than the terms of its independent components. In my own studies, I have never found the McKelvey scheme to be of any use.

Grossling: I have four figures (see Figures 1, 2, 3, and 4 below) that might clarify something. Suppose we make a representation in three axes. On one is the probability p, the probability that something exists multiplied by the probability that it can be found; p is the probability of discovery. On the second axis is the unit price U. On the third we put a second derivative of the resource $d^2Q/dp\ dU$ where Q is the resource variable. (The reason for this is, of course, that a double integration will need resource amounts.) Then we could define a proper range of probabilities, for example 0.5 to 0.6 and a range of prices, and determine either by a computer model or by direct calculation the amount of that resource. We should do that for the full range of probabilities and prices. The second derivative defines a surface in the space of the three coordinates discussed. The McKelvey diagram is a way to classify this surface into compartments. If you take a slice in that surface and measure it--let us call it dR--then you can make a diagram, and deduce a resource for a price range. The integral of pdR of the resource base becomes simply the expected value. So the question is only one of semantics.

Fiala: I refer to your three dimensional diagram where you plot $d^2Q/dp\ dU$ against p probability and U price. What happens if you integrate over U? You should obtain the probability of existence of resources (geological probability). Integrating over this probability you should obtain the existing resources. Or you can look at it the other way around: starting from the inferred total of existing resources, you could use this total as a boundary condition for the twofold integration of $d^2Q/dp\ dU$ which would result in a calibration of the axis for $d^2Q/dp\ dU$. Did you use any of these considerations in designing your scheme?

Grossling: The variables I used in the diagrams are the probability p, the unit cost U, and the second derivative of the resources with respect to p and U, or its finite approximation $\Delta(\Delta Q)/\Delta p \Delta U$.

In Figure 1 we represent the resources corresponding to an element ΔP and ΔU, namely $\Delta(\Delta Q)$. If we plot in the vertical direction the quantity $\Delta(\Delta Q)/\Delta p \Delta U$ then the volume of the elementary prism is $\Delta(\Delta Q)$.

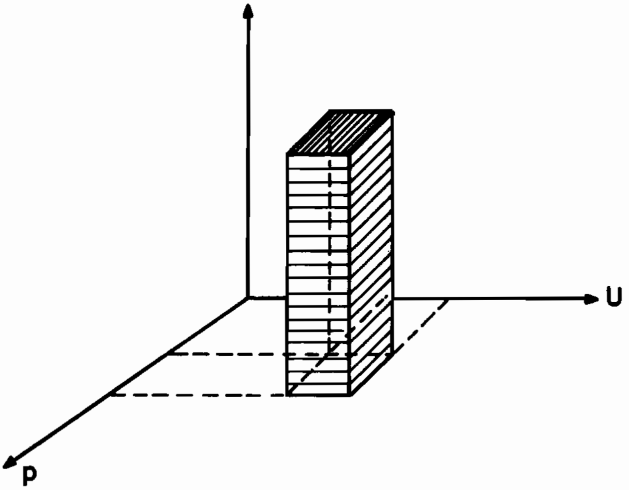

Figure 1.

The probability p in this case is the product of the probability that the resources exist somewhere in the region being considered, and the probability that they be found. Also, one could make the corresponding diagrams for the probability of existence pe and for p separately. The reason for using $d^2Q/dp\,dU$ is that with a double integration on p and U one obtains Q, the resource.

Now, if we assume that the process is applied to the full range of p and U and that $\Delta p \to 0$ and $\Delta U \to 0$, then we would obtain a surface such as that indicated in Figure 2. The volume under ABCD in Figure 2 would represent Q.

If we consider a certain interval Δp and integrate on U we get the slice ΔR of resources as indicated in Figure 3.

Finally, if we consider R as a function of p, which is the result of integrating the surface on U, we obtain a curve such as that represented in Figure 4. The resource base can, in this scheme, be defined as the expected value of R, namely:

$$B = \int_{C}^{D} p dR \quad .$$

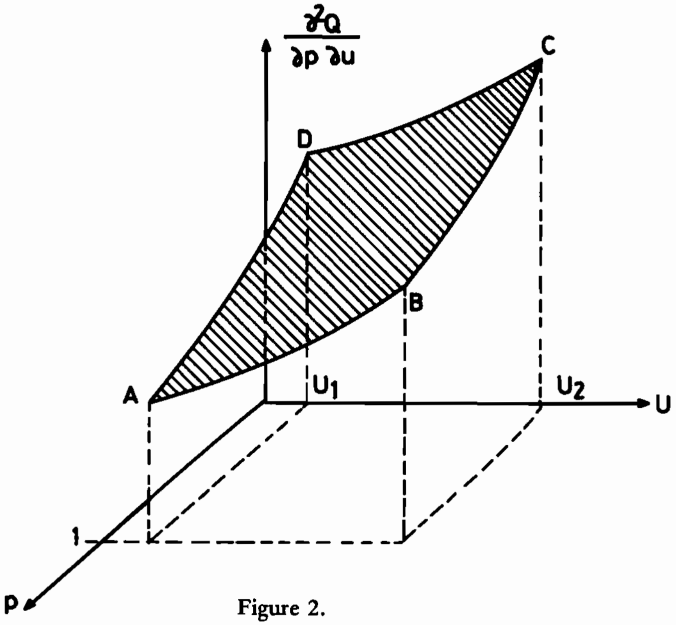

Figure 2.

Upon the above method of description of the resources, one could superimpose a partitioning of the space Q to facilitate resource classification. The McKelvey diagram is a classification of the projection of the surface upon the p and U plane.

<u>Häfele</u>: I have a question to both Searl and Schantz. You mentioned cost and geological probability as parameters, or constraints, for considering resources. If we would like to include more dimensions in such types of diagrams, what other categories, or constraints, are to be considered if a responsible policy, say of a government, is to be established? Is it pollution, production of waste, the issue of public versus private? What is it?

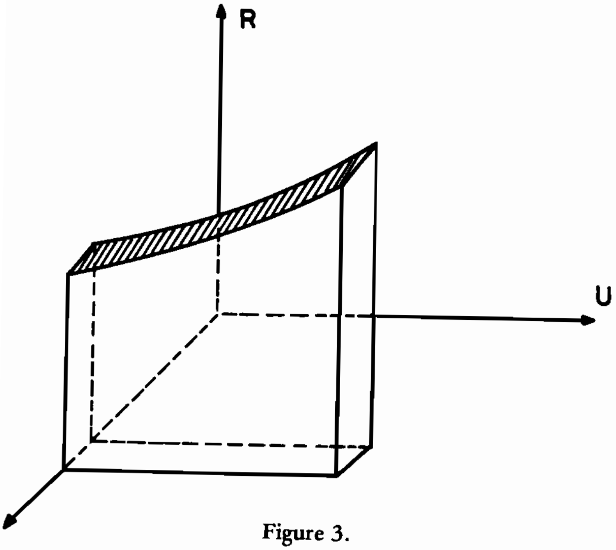

Figure 3.

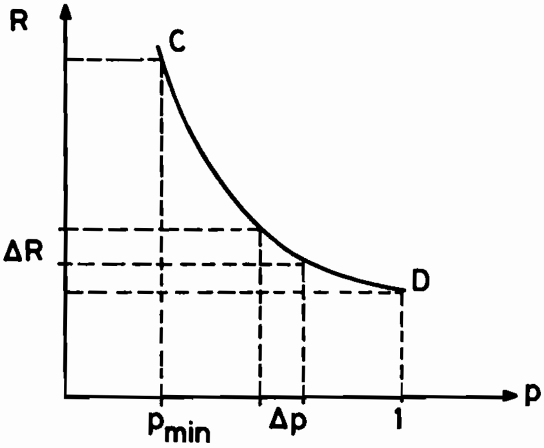

Figure 4.

Searl: Government policy toward resources exploration, exploitation and management would be my number one choice; technology, probably second.

Sickler: Since I am from Shell, I can attempt to answer this question from the industrial point of view. Taxation policy is the instrument with which the government tries to regulate what happens--at least in the Western world--and, of course, the government can encourage looking for resources, and they can do it in different ways. They can encourage you to look for marginal things, so the more costly things also come in. They can also encourage you not to do that, and only look for the large things. Rules on pollution, established practices, etc., can only be set by international cooperation and are not very effective if set by individual governments.

Odell: I think that governmental policy requirements depend on inbuilt attitudes of governments toward discovery and/or exploitation of resources. If, as in the USA or USSR, there is an "inherent belief" in autarchy, then this produces a different attitude to investment in resources evaluation compared with a region such as Western Europe, in which world trade in resources is taken to be a fundamental element in the accepted economic system.

Woite: We could make the following suggestion: define a net benefit for mankind as a yardstick for exploitability of resources. Let me explain this. This net benefit would have to be the balance of all direct and indirect costs, benefits, risks, and other hazards, including for example effects on health, environment (also aesthetics of environment), employment of people, social and political effects such as integrating or disintegrating people or regions.

This "exploitability" would have to vary with time, as the technology of mining and energy usage develops, and as weighting factors (for example between costs and health hazards) will vary with time. This "exploitability" will also depend on the socio-economic environment in the sense that other projects (for example agricultural, medical, educational, technical infrastructure) will compete with projects of energy resources exploitation for limited energy, financial, and manpower resources.

A strategy for the best use of all these resources will have to be developed. The above definition is intended to be comprehensive, but not necessarily practical.

Fettweis: I will give another answer to Häfele. I think it is also a question of ethics, and of the interests of different groups. And that is different in different countries.

Brin: For a government, the most important factors are the prices, and the security of the supply with respect to national independence.

Belototski: I should like to draw attention to the question of complex observation of resources and demand, and to underline the methodological difficulty as I see it. There is no use in investigating resources if not to compare them with demands in integrated mathematical models. An additional point is that the description of resources must be done with a characteristic of its price, as we have it, for example, with uranium resources.

Moreover, the time of calculation of resources and demand must be the same. We have quite useful econometric models on demands for a short period of time. What sort of models can meet these differences of calculation and what sort of additional preparations are necessary to improve the separated models--resources and demand models--for their close cooperation are important questions.

Kaufman: Would you please give us point estimates of the quantities in each of the categories in the USSR resources and reserves classification scheme, even if it is a personal projection, say a subjective estimate of the orders of magnitude?

Belototski: Several figures have been published, for instance in the 1974 World Energy Conference Survey on Energy Resources.

Clarke: Are there any special difficulties in allocating exploration resources between a prospect in category C_1 (with enough knowledge to say the prospect is rather poor) and a prospect in category C_2 where it is prospective, simply because there is not enough data to say it is not?

Belototski: There are no strict borders between categories B, C_1 and C_2. So there are, in fact, some difficulties in whether to use one category or another.

Styrikovich: This is especially true for a new region in which it is necessary to introduce a big infrastructure. Sometimes, you have a not-so-big A, B, and C_1, but a very big C_2. For example, in the north of Siberia several years ago we had only small amounts of gas in categories A, B, and C_1, but category C_2 was very big. So with these conditions, it is a question of risk. You must be prepared to make a big investment in infrastructure, and also accelerate drilling development, and so on.

METHODS FOR ASSESSING PETROLEUM RESOURCES

An assessment of world petroleum resources is probably one of the most important tasks in coming years. The continuation of our oil based economies and, still more important, the length of time we must allow for to achieve the transition to another energy resource (or resources) dominated economy depend on the possible quantity of ultimately recoverable oil and gas. To shift, say, to nuclear fuel too fast, or too slowly, can have dramatic consequences for many nations.

The world equilibrium and the balance of power depend on the geographic distribution of these ultimate oil resources. Curiously, there are few reliable estimates of world oil potential. We can even say that, to our knowledge, not a single method of assessment has been developed for performing such estimates. Most often, methods that have been developed for local or regional assessment, under given conditions (as shown, say, by the very interesting statistical analysis of King Hubbert for the US oil industry), have sometimes also been used for making world estimates, with obvious limitations.

No less curiously, many of these estimates have been made by industry experts. No doubt it is clear that much of the oil expertise lies with the world oil industry. But the reasons, the objectives for making resource estimates, and the subsequent utilization of such estimates obviously differ for a company and a national government. It is surprising to consider that the majority of governments--if not all of them--paid little or no attention to these estimates, or to the task of performing independent estimates of world oil potential, on which to base their own long term energy policy.

It is in this frame of mind that we plan to develop such methods at IIASA. By way of a start, we have begun a thorough analysis and detailed comparisons of oil and gas resource estimates and their methodology.

Judging by the number and the value of the papers presented at this Conference--as will be seen below--we consider that a first step toward this goal has been achieved. Papers and discussions have been divided into three parts.

In the first part, as in subsequent sections devoted to coal and uranium resources, a major paper by Sickler on the most recent estimate of world resources was presented and actively discussed. It is worth pointing out that our above comment on the weight of industry, or the influence of the objectives of industry, time horizon, and criteria also emerged in the course of the discussions.

The second part examines a few general points on modeling for petroleum resources or, as Kaufman's paper title indicated, "Models and Methods for Estimating Undiscovered Oil and Gas--what They Do and Do Not Do".

The third part is a clear review of some of the models that have been developed recently for the assessment of oil resources, such as "behavioristic", "analogic", "geologic", or "statistical" models, as they are sometimes referred to (classification mentioned by Rose).

A strong emphasis--confirmed by the lively discussions--was put on the so-called "probabilistic" models, as developed at MIT, the Geological Survey of Canada, Mobil Oil, Erasmus University, etc. In search of "objective" models, many discussions revolved on their "subjective" aspects, and the role of the judgment of experts in data gathering and assessment. The dialogue between opposite positions such as those of Hubbert and Odell is a clear illustration.

The last paper in this chapter is devoted to geothermal resources. Analogy between an oil field and a geothermal field has not yet been fully established. But we wished to include in this Conference at least one paper devoted to geothermal resources in order to show the link between these two types of deposits of energy resources.

WORLD PETROLEUM RESOURCES, PART 1:
METHODS AND MODELS USED TO ESTIMATE WORLD PETROLEUM RESOURCES

R. A. Sickler

Part one of this paper consists of two sections. Section 1 describes reserve estimating methods for known oil fields, and Section 2 describes them for hydrocarbons to be discovered in the future. Naturally, the methods and models used differ considerably between Sections 1 and 2.

1. RESERVES FROM KNOWN OIL FIELDS

Part 1 of this paper is only concerned with the conventional reserves of the oil and gas liquids from associated gas of known fields. It thus excludes oil reserves from tar sands, oilshales, synthetic crudes and also possible reserves associated with liquefaction of natural gas. The main objective is to present a consistent picture of the relationship between stock tank oil initially in place (STOIIP), ultimate primary recovery and expected additional supplementary recovery as function of time (see Figure 1 and Appendix to Part 1 for definition of terms).

For most areas, the ultimate primary recovery is reasonably well established, but large differences of opinion exist on how much oil might be expected from future improvements on existing supplementary recovery techniques and the development of new processes and when this additional oil might become available. As the future development of supplementary recovery for the various areas in the world outside centrally planned economies (WOCPE) can be expected to be different separate estimates have been made for the following eight areas:

North America (USA, Canada, Mexico),
Central and South America,
Europe,
Africa,
Far East and Australasia,
Iran,
Saudi Arabia,
Remaining Middle East.

The procedure which has been followed consists of the following steps:

a) Determination of the Ultimate Primary and Supplementary Recoveries at 1 January 1974 for the various areas from available sources.

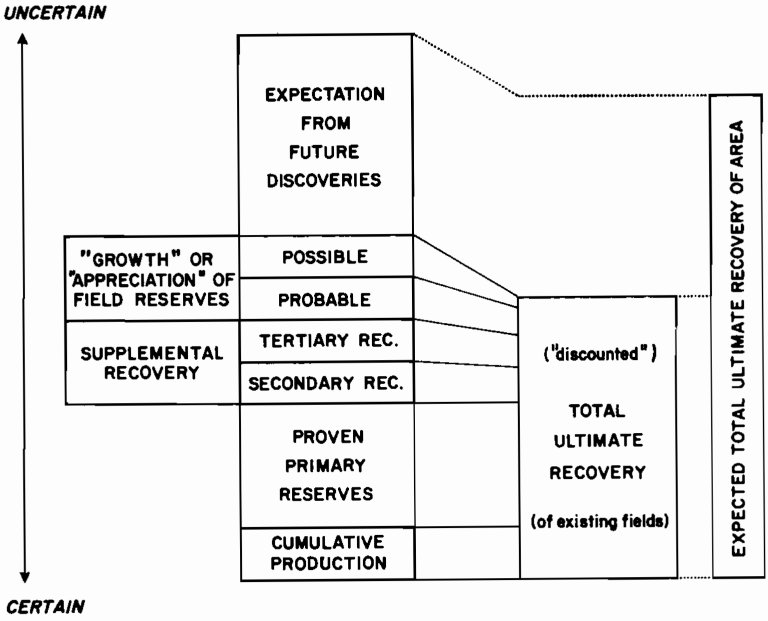

Figure 1. Crude oil reserves terminology.

b) Allocation of realistic primary and supplementary recovery factors, prevailing at 1 January 1974, taking into account the characteristics of the reservoirs and the fluid properties and only "full proven" supplementary recovery techniques.

c) Determination of the corresponding STOIIP figures.

d) Allocation of expected future average ultimate recovery factors, which might be achievable by 1 January 1985, 1 January 2000 and 1 January 2050, as a consequence of technical improvements and the development of new processes.

e) Determination of the corresponding expected ultimate recoveries at 1 January 1985, 1 January 2000 and 1 January 2050.

Since the USA and Canada are far ahead compared with the rest of the world in application of supplementary recovery techniques and the results are in general well documented, the estimate for North America has been used as a standard of comparison and will be discussed first. For the other areas, the available data are far less reliable and incomplete. Nevertheless the resulting estimates are believed to give a

Table 1. Estimated ultimate recoveries of fields, existing at 1 January 1974 for the world outside centrally planned economies (WOCPE) (Figures in 10^9 bbl).

	North America (USA, Canada, Mexico)		Central & South America		Europe		Africa		Far East & Australasia	
	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S
Status at 1 January 1974										
STOIIP(S)	550	100	265	100	55	100	215	100	100	100
Cumulative Production	130	24	38	14	3	5	17	8	8	8
Remaining Primary Reserves	8	1	26	10	16	30	34	16	16	16
Ultimate Primary Recovery	138	25	64	24	19	35	51	24	24	24
Additional Supplementary Recovery	66	12	6	2	1	2	6	3	-	-
Ultimate Recovery 1 January 1974	204	37	70	26	20	37	57	27	24	24
Expected Future Development										
Ultimate Recovery 1 January 1985	220	40	80	30	21	38	65	30	28	28
Ultimate Recovery 1 January 2000	248	45	93	35	22	40	75	35	32	32
Ultimate Recovery 1 January 2050	275	50	106	40	25	45	86	40	35	35

Table 1 (concluded).

Middle East

	Iran		Saudi Arabia		Remaining		Subtotal		WOCPE Grand Total	
	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S	10^9 bbl	%S
Status at 1 January 1974										
STOIIP (S)	440	100	530	100	475	100	1,445	100	2,630	100
Cumulative Production	18	4	20	4	32	7	70	5	266	10
Remaining Primary Reserves	52	12	142	27	114	24	308	21	408	15
Ultimate Primary Recovery	70	16	162	31	146	31	378	26	674	25
Additional Supplementary Recovery	-	-	23	4	18	4	41	3	120	5
Ultimate Recovery 1 January 1974	70	16	185	35	164	35	419	29	794	30
Expected Future Development										
Ultimate Recovery 1 January 1985	88	20	212	40	185	39	485	34	899	34
Ultimate Recovery 1 January 2000	110	25	238	45	208	44	556	38	1,026	39
Ultimate Recovery 1 January 2050	132	30	265	50	233	49	630	43	1,157	44

Table 2.

	STOIIP (S)[2] 10^9 bbl	Ultimately Recoverable Crude Oil 10^9 bbl	Ultimately Recoverable Crude Oil %S[2]	Ultimately Recoverable Gas Liquids 10^9 bbl	Ultimately Recoverable Gas Liquids %S[2]
USA[3]	438	138	31.5	22	5
Canada[3]	46	16	35	2	5
Mexico	(26)[4]	9	(32)[4]	(1)[4]	(5)[4]
Total	510	163	32	25	5

[2] "S" means STOIIP (Stock Tank Oil Initially In Place); see Appendix for definition.

[3] Data from Reserves of Crude Oil (1974).

[4] Parentheses indicate value is assumed.

reasonable idea of the order of magnitude of the expected future development of the reserves of existing fields in these areas (see Table 1).

The proven hydrocarbon liquids reserves on 1 January 1974 can be summarized in Table 2. In our estimate the proven STOIIP figure of 510 × 10^9 bbl to account for likely extensions in known fields.

Accepting the same total recovery factor of 32 + 5 = 37% for crude oil and gas liquids as given above for the proven, the present ultimate hydrocarbon liquids recovery is estimated at 204 × 10^9 bbl. The split in primary and supplementary recovery is based on the fact that, since 1950, the average "crude oil" recovery factor increased from 24%S[1] to the present 32%S. As before 1950 the share of supplementary recovery was only small (say 10%), the average primary crude oil recovery factor is probably some 22%S.

Allowing some 3%S for the average primary gas liquid recovery, the average total primary hydrocarbon liquid recovery factor has been taken at 25%S. For the future it has been assumed that the average total recovery factor will increase to 40%S by 1 January 1985, to 45% by 1 January 2000 and to 50% by 1 January 2050. For this last date the corresponding crude oil recovery factor is assumed to be 45%S and the gas liquids recovery factor to be unchanged at 5%S.

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[1] "S" means STOIIP (Stock Tank Oil Initially In Place); see Appendix for definition.

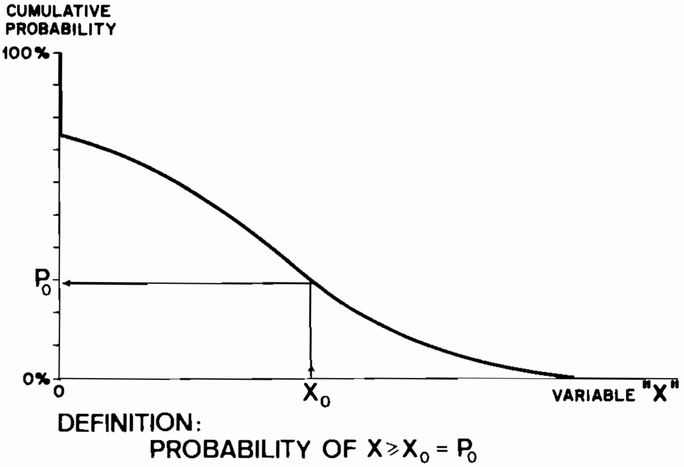


Figure 2. Expectation curve.

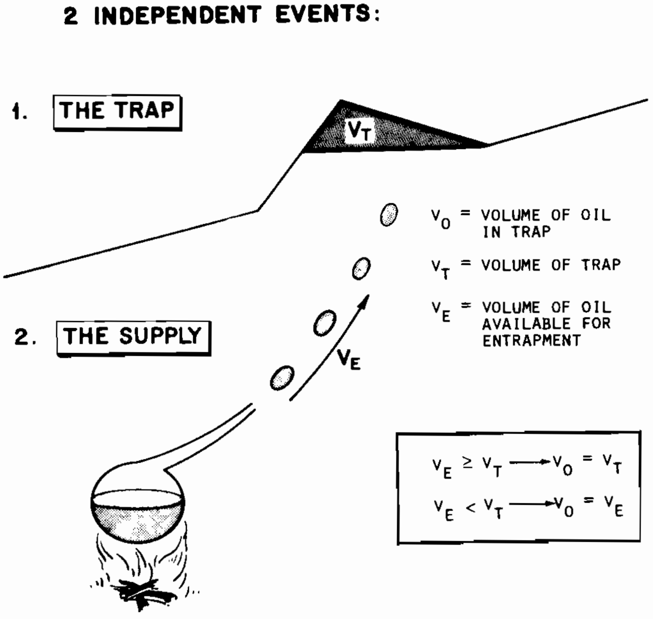
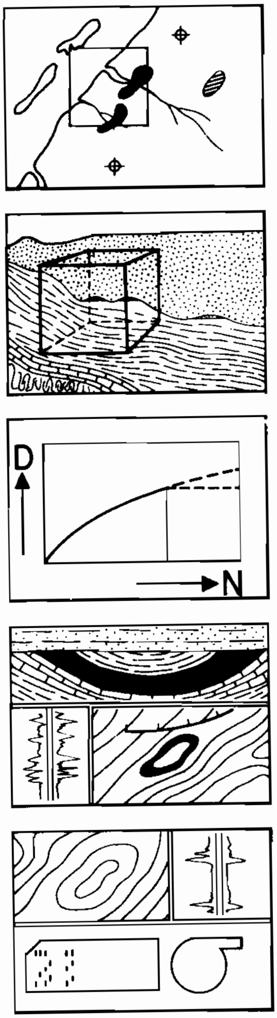


Figure 3. Exploration prospect appraisal.



AVERAGE BARRELS PER KM^2 OF SEDIMENTARY BASIN

AVERAGE BARRELS PER KM^3 OF SEDIMENTARY BASIN FILL

EXTRAPOLATION OF HISTORICAL TRENDS: DISCOVERY VERSUS EXPLORATION EFFORT

SUBJECTIVE ESTIMATES BY GEOLOGISTS FAMILIAR WITH AREA

"QUALITATIVE MODELS" THAT COMBINE A GEOLOGIST'S SUBJECTIVE STATEMENTS WITH WIDER STATISTICAL EXPERIENCE

Figure 4. Expectations from future discoveries, summary of estimating tools.

The value of 45%S for the crude oil recovery factor, which can be achieved with improved current and "soon-to-be-developed" technology by 1 January 2050, is in line with the general view expressed by various experts in the USA (for example, see Geffen, 1973).

Reserves From Other Areas

Ultimate Recovery on 1 January 1974

The assumed values for the average primary and average total ultimate recovery factor on 1 January 1974 used in the estimates as presented in the attached table are best guesses based on internal information on individual reservoir performance and local conditions.

Iran has the lowest recovery factor of only 16%S owing to the fact that the characteristics of the Asmari limestone reservoirs in Iran are unique. The highest recovery factors in the order of 35%S are found for Europe, Saudi Arabia and the remaining Middle East. Most reservoirs in these areas have a good permeability, are large, and are also rather homogeneous. For Central and South America, Africa and Far East/Australasia the recovery factors are in the range of 25%S.

The reservoirs are relatively small, heterogenous and also, in general, far away from industrial centres, making the economic environment for development less favourable than in the USA. The recovery factor for these areas is of the same order of magnitude as the ultimate primary recovery factor of 25%S for the USA.

Expected Future Ultimate Recoveries

The expected ultimate recoveries, in percents, that might be achievable by the development of new techniques have been related to the primary recovery as follows in Table 3.

Table 3.

	Ultimate Recovery %S			
	Primary		Total	
		1 January 1985	1 January 2000	1 January 2050
Iran	16	20	25	30
Far East/Australasia	24	28	32	35
Africa and Central and South America	24	30	35	40
Middle East outside Iran	31	40	45	50
Europe	35	38	40	45

Figure 6. Total world giant fields, year of discovery.

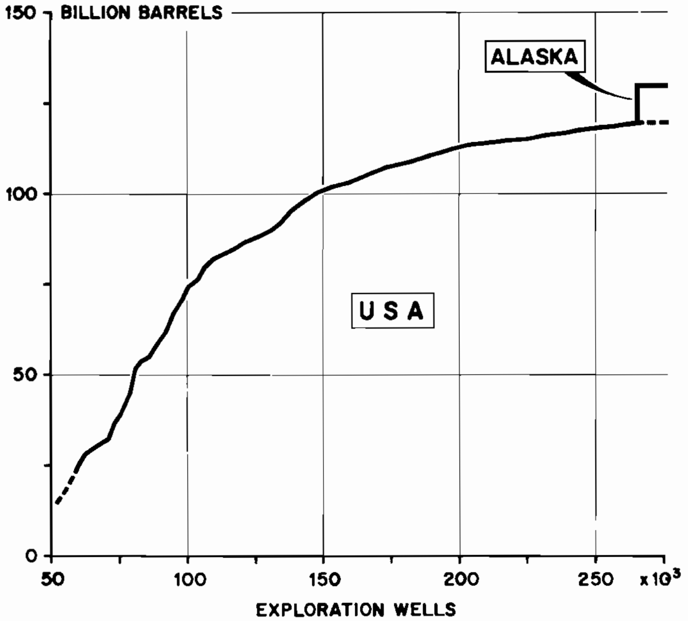


Figure 5. Cumulative recoverable oil discovered, total industry 1920-1969.

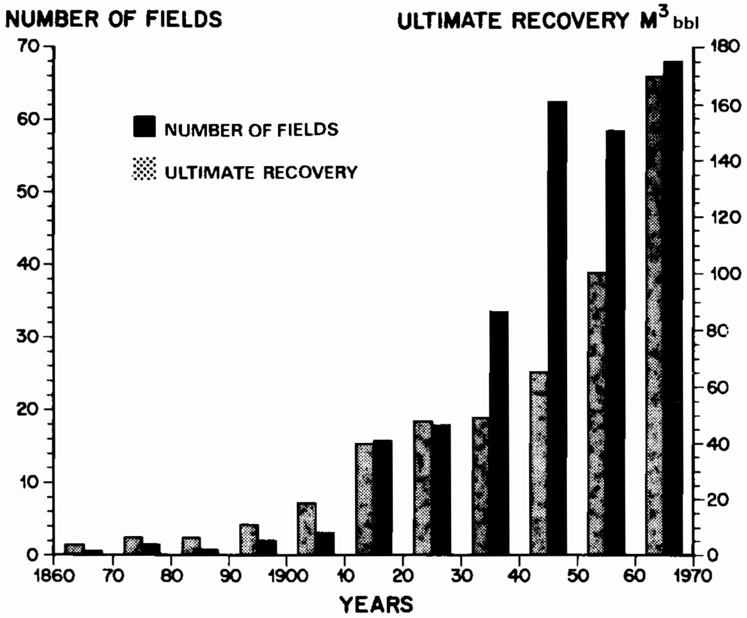


Figure 6. Total world giant fields, year of discovery.

For Iran, the final ultimate recovery is expected to be the lowest, only 30%S. However, since for the Asmari Limestones this still implies more or less a doubling of the present primary recovery by techniques which still have to be proven, this figure might already be optimistic.

For the Far East/Australasia, the final ultimate recovery of 35%S has been taken lower than the 40%S for Africa/Central and South America because the average fields are smaller and relatively more offshore fields are involved. For Europe, 45%S has been taken instead of 50%S allocated to the Middle East outside Iran because in Europe the major fields are located offshore.

2. EXPECTED FROM FUTURE DISCOVERIES

Introduction

Estimates of oil and gas reserves to be discovered in the future on a worldwide scale for land, shelf and deeper offshore (below 200 m water depth) areas differ widely, depending on the yardsticks used. In addition, expectation figures (see Figure 2) are often biased for a number of reasons. Unfortunately, no method has been developed yet which would enable the oil industry to predict with some degree of accuracy and confidence the volumes of hydrocarbons that will be found in sedimentary basins all over the world (see Figure 3). This is largely owing to the unknown factors in the evaluation game. One factor is lack of information on the subsurface configuration of many parts of the world, in particular the poorly accessible areas. Another factor is the uncertainty involved in qualitatively and quantitatively assessing all the factors that govern generation, migration, accumulation and preservation of hydrocarbons. In the following we try to point out the merits and disadvantages of the estimating tools currently in use (see Figure 4). We also add a few remarks on giant fields.

Estimating Tools

Average Barrels Per Km^2 of Sedimentary Basin

The hydrocarbon richness of a specific area can be expressed in barrels of reserves found per km^2 of hydrocarbon-bearing structure, sedimentary basin or larger units. Calibrated yardsticks are established in areas where most of the oil and gas have already been found. These yardsticks are then used to compare the hydrocarbon richness of individual hydrocarbon-bearing structures and entire hydrocarbon provinces, but also to develop yardsticks for undrilled basins.

But there are some disadvantages. The comparison of undrilled basins with known hydrocarbon provinces on a bbl/km^2 basis appears attractive at first sight. It is, however, deceptive since geological settings differ widely and no basin is strictly analogous to another. In addition, the difficulty often arises in defining the boundaries of a hydrocarbon province and, even more so, the boundaries of an undrilled basin. The simple bbl/km^2 approach also prevents us from taking into consideration the thickness of the sedimentary sequence in a basin.

Average Barrels Per Km^3 of Sedimentary Basin Fill

This method can be used to compare the hydrocarbon richness of entire hydrocarbon-bearing basins related to volumes of sediment. The disadvantages are the same as for the average barrels per km^2 of sedimentary basin. The sedimentary thickness, however, is taken into account.

Extrapolation of Historical Trends

Curves (see Figure 5) can be drawn to show the exploration effort in number of exploration wells drilled versus the ultimately recoverable reserves found. These curves usually show the following trend for a specific area:

a) Learning period. A number of wells are being drilled before hydrocarbons in commercial quantities can be located. The beginning of the curve is horizontal.

b) The first success is achieved. The explorationists know what to look for, and all sizeable prospects are being drilled, often with success. The curve rises.

c) The explorationists run out of sizeable prospects. Less obvious traps are being drilled and some additional, but usually small reserves are found. The curve flattens.

d) Deeper prospects are found or technological progress is achieved which makes the location of hitherto hidden traps possible or which enables the driller to go into deeper water. Additional reserves are found and the curve rises again.

e) The curve flattens again when most of the additional prospects have been drilled.

Extrapolation into the future by means of a flattening part of a curve provides an estimate of the expectations and the number of exploration wells required. Such extrapolations are only meaningful in a given province for specific objectives. New objectives (for example, unconventional traps) can significantly change the expectations.

Subjective Estimates By Geologists

Believe it or not, some geologists are usually quite good in assessing reserves to be found in certain areas based on thorough knowledge and professional flair. The value attached to such assessments depends on managerial attitudes and other factors usually beyond the strictly professional realm.

Qualitative Models

The factors which govern generation, migration, accumulation and preservation of hydrocarbons are known to some extent and are based on scientific theory. In known hydrocarbon provinces most of the factors that make up the hydrocarbon habitat are individually assessed in terms of excellent, favourable, ambiguous, etc. In vaguely known areas the same factors are assessed in qualitative terms based on some knowledge (for example, extraction of lithological sequence from seismic record before drilling).

A comprehensive data bank allows for the use of calibrated concepts of qualitative statements for comparison with qualitative statements made for vaguely known areas. Qualitative statements can also be translated into volumes (trap capacity and hydrocarbon available for entrapment) based on experience in well-known hydrocarbon provinces. The uncertainty and the range of possibilities are expressed in expectation curves. Mean values can be extracted and probability ranges shown.

The disadvantages include the fact that this method stands and falls with the intellectual honesty of the appraiser. The vaguer the knowledge of an area is, the vaguer and more "drawn-out" the expectation curves look. There is, however, no remedy to this situation. Insufficient knowledge cannot be compensated for by anything.

Giant Fields and Future Discoveries

We estimate that so far about 70% of the ultimately recoverable world oil reserves (including countries with centrally planned economies) have been found in giant fields (reserves about 500 million barrels per field; see Figures 6 to 9). The "recovery versus number of giant fields" curve already shows a slight flattening for the market economy countries. Most of the additional future reserves will probably be found in smaller sized anticlinal fields and in less conventional traps. Sophisticated technology is required to find them.

Giant fields could still be discovered in areas practically untouched so far (for example, Arctic areas and deeper parts of the oceans). High risk and high costs have prevented the industry so far from fully developing the tools necessary to cope with extreme geographic conditions, but most of the severe technological exploration problems will hopefully be solved in a decade or two.

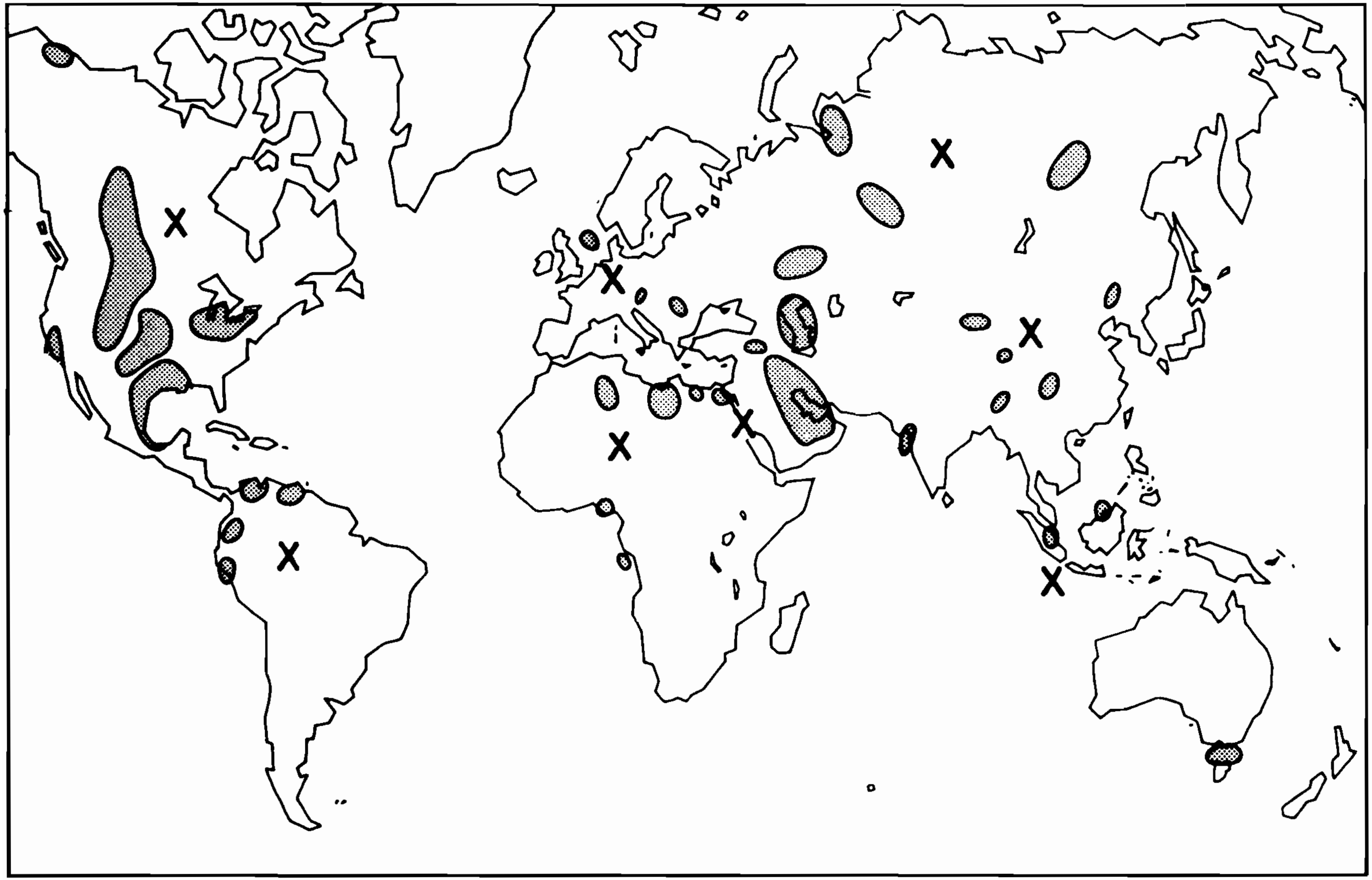


Figure 7. The location of giant oil fields.

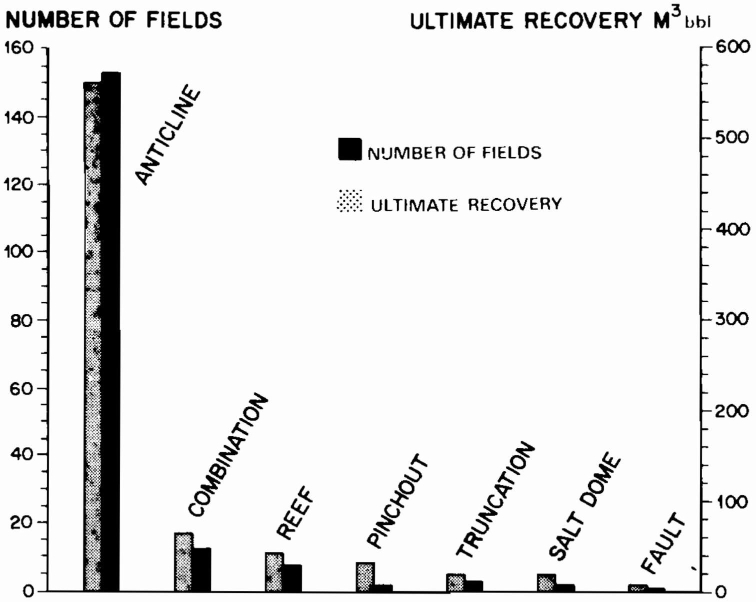


Figure 8. Total world giant fields, primary mode of trap.

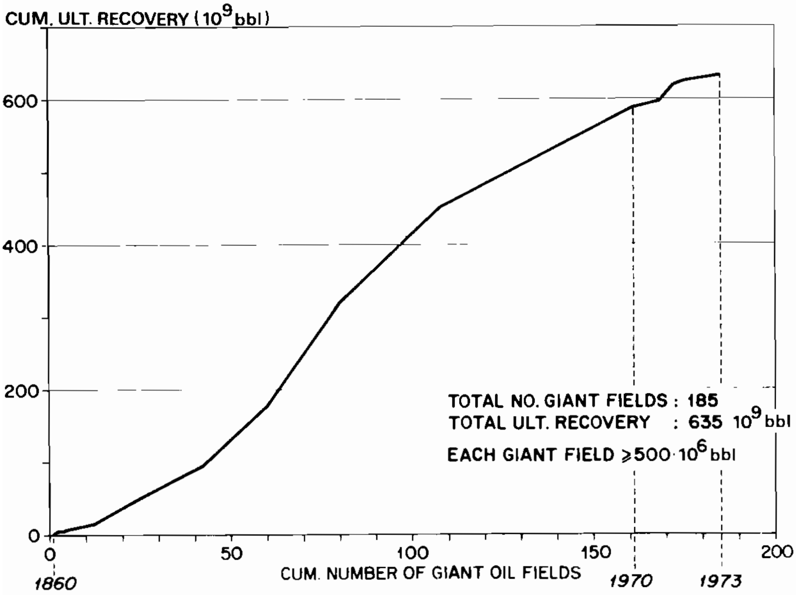


Figure 9. Total Western world giant fields, 1860-1973.

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Reserves of Crude Oil, Natural Gas Liquids and Natural Gas in the United States and Canada and United States Productive Capacity as of December 31, 1973 (June 1974), American Gas Association, American Petroleum Institute and the Canadian Petroleum Association, Vol. 28.

APPENDIX. TERMINOLOGY

The terminology used is in line with common oilfield practice, but for convenience a simplified definition of the most important terms is given.

STOIIP is the total quantity of stock tank oil initially in place within the reservoir or area considered. In the USA and Canada the term "Original in Place Reserves" is used but SIPM prefers to use the term reserves only in the sense of "remaining" recoverable oil at a certain date.

Ultimate Primary Recovery is the total amount of "stock tank" oil, that can be produced from a reservoir or area if only the available energy in the reservoir(s) is utilized for driving of the oil towards the producing wells.

Supplementary Recovery at a specified date is all additional oil above primary, that can be produced (at the specified date) by the expected "full proved" recovery techniques for supplementing natural reservoir forces and energy. As long as practically only water, gas and steam injection can be considered as "full proven", the additional supplementary recovery is about equal to the expected Secondary Recovery. Up to now this term has been used specifically for the additional oil, recoverable by the above indicated conventional methods, whereas the term Tertiary Recovery has been reserved for the additional oil, which perhaps in the future might be recovered by improved or new supplementary recovery techniques in case these processes become economically attractive. Historically the term tertiary refers to the fact that some of these techniques are applied after a "secondary" waterflood operation. In the future, gradually all the expected tertiary recovery will be absorbed in the term supplementary recovery. The distinction between secondary and tertiary will become meaningless, and the terms are therefore not used in this note.

Ultimate Recovery at a specified date is the sum of Ultimate primary recovery and (at that date estimated) the supplementary recovery.

Remaining Primary Reserves are the difference between the Ultimate Primary Recovery and the cumulative oil production as long as this value is smaller than the Ultimate Primary Recovery, otherwise the remaining primary recovery reserves (in this context) are zero.

Remaining Total Reserves at a certain date are the difference between the Ultimate Recovery at that date and the corresponding cumulative production. (These reserves are equal to the remaining primary reserves and the expected supplementary recovery.)

Primary Recovery Factor equals the Ultimate Primary Recovery expressed as percentage of STOIIP.

Total Recovery Factor at a specified date equals the Ultimate Recovery at that date expressed as a percentage of STOIIP.

WORLD PETROLEUM RESOURCES, PART 2: A SURVEY OF PETROLEUM RESOURCES IN THE WORLD OUTSIDE CENTRALLY PLANNED ECONOMIES (WOCPE) STATUS ON 1 JANUARY 1974

Part 2 of this paper, like Part 1, is concerned with conventional oil and gas reserves and thus excludes oil reserves from tar sands, oilshales, synthetic crudes and reserves associated with liquefaction of natural gas.

As the future development of supplementary recovery for the various areas in WOCPE can be expected to be different, separate estimates have been made for the following six areas (see Table 1):

North America (that is, the USA, Canada, Mexico),
Central and South America,
Europe,
Africa,
Middle East,
Far East and Australasia.

Owing to the unknown factors in the evaluation we have tried to produce a reasonable range (see Table 1) for the volumes of hydrocarbons to be found. A similar exercise has been carried out for gas reserves (Table 2), where a distinction is made between associated and non-associated gas reserves.

Table 1. Estimated reserves and future discoveries of crude oil as of 1 January 1974 for the world outside centrally planned economies (WOCPE). (Figures in 10^9 bbl).

	Reserves							
		Supplementary						
	Primary	Until 1985	1985-2000	Total	Future[1)] Discoveries	Total Known Reserves & Future Discoveries	Cumulative Production	Ultimate Recoverable Resources
Central and South America	26	16	13	55	20- 60	75- 115	38	113- 153
Europe	16	2	1	19	15- 45	34- 64	3	37- 67
Africa	34	14	10	58	20- 50	78- 108	17	95- 125
Middle East	308	107	71	486	50-100	536- 586	70	606- 656
Far East/ Australasia	16	4	4	24	10- 30	34- 54	8	42- 62
WOCPENA	400	143	99	642	115-285	757- 927	136	893-1,063
North America	8	82	28	118	50-100	168- 218	130	298- 348
WOCPE	408	225	127	760	165-385	925-1,145	266	1,191-1,411

1) Low value - 75% chance, high value - 25% chance.

Table 2. Estimated reserves and future discoveries of natural gas as of 1 January 1974 for the world outside centrally planned economies (WOCPE). (Figures in 10^9 Nm^3).

	Reserves			Future Discoveries	Total Known Reserves & Future Discoveries	Cumulative Production	Ultimate Recoverable Resources
	Associated	Non-associated	Total				
Central and South America	1,200	600	1,800	2,300	4,100	1,400	5,500
Europe	500	4,500	5,000	2,200	7,200	800	8,000
Africa	1,700	4,200	5,900	5,100	11,000	400	11,400
Middle East	10,900	6,700	17,600	16,400	34,000	1,100	35,100
Far East/ Australasia	500	2,900	3,400	7,100	10,500	200	10,700
WOCPENA	14,800	18,900	33,700	33,100	66,800	3,900	70,700
North America	-	-	8,400	12,000	20,400	13,000?	33,400
WOCPE	-	-	42,100	45,100	87,200	16,900?	104,100

DISCUSSION

Dunham: Would Sickler give us the cumulative production for the nonsocialist world up to now?

Sickler: Two hundred and sixty-six billion barrels total oil production.

Odell: This paper brings out the important issue to my mind, because if Sickler's figures are right, we have only one generation of oil and gas available and that necessitates the development of a very quick move to the nonfossil fuel economy. If other people's figures are right, then we have a two or three generation gap before we have to move to alternative energy economies.

Figure 1 shows the relationship between the estimates by oil company geologists and time. There are 23 estimates in this analysis. The first one was made in 1942, the latest in 1974. It looks as though the estimates of the ultimately recoverable reserves of oil are simply a function of knowledge. Knowledge, in turn, is a function of demand insofar as Shell and BP and all other companies are thinking about the utmost recoveries of oil in terms of what the likely demand for oil is going to be. I would suggest that Sickler's presentation today in fact is nothing more than what Shell thinks it is worth doing from its own point of view, as he said in the final remarks, up to the year 2000. If you read anything more into it than that, then we are running into a serious danger of underestimating what the "real" ultimate potential for oil is.

A second question is derived from the first. That is, at early periods the estimates of these different oil geologists were reasonably close together. Today, we are getting some estimates by BP of $1600\text{-}2000 \cdot 10^9$ barrels (and Clegg might have something to say to that) and from other people in the oil industry estimates higher by 50 to 75% at $2800\text{-}3200 \cdot 10^9$ barrels.

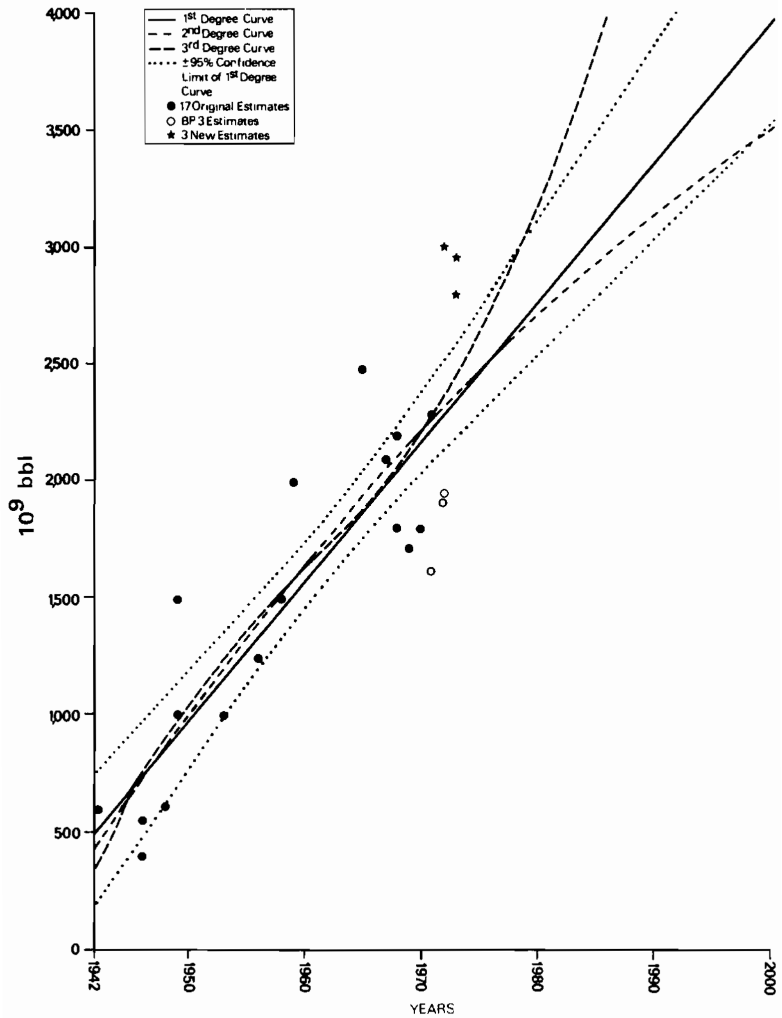

Figure 1.

Source: R. Odell and K. E. Rosing, "Estimating World Oil Discoveries up to 1999--The Question of Method", *Petroleum Times* (London), 79, 2001 (February 1975), 26-29. Reproduced with permission.

In other words, geologists are now coming up with such a broad range of figures that one wonders whether they are talking about the same thing. And if not, the rest of us ought to know, so that we do not run into the danger of using figures like Sickler's for planning future energy economies.

Sickler: Could you tell us whether this is the whole world, including the socialist areas?

Odell: Yes, it is.

Sickler: So, in order to make your figures comparable with mine, we have to knock off perhaps 1000 million barrels, which brings your figure down to around 2000 million barrels. Then I do not know if this includes gas or not? This is only oil?

Odell: Yes.

Sickler: So without the socialist areas my figure would be, say, 1500 million barrels. Secondly, I have looked at reserves in the climate that we think will prevail for finding and developing oil. We think that we would not be able or would not be allowed to start exploring the Antarctic before the year 2000, or the Arctic. Nor will there be much exploration from a political point of view in those countries where perhaps most of the oil is--the Middle East. So there are quite a lot of scenario-type constraints in my estimate. If one were to ignore these constraints I think one would come very close to a figure of 2500-3000 for the whole world. I hope that answers your question.

Odell: What about the idea that there seems to be a close relationship between the time of the estimate and the size of the estimate. We have on Figure 1 a first, second, and third degree curve, relating these to each other, with extrapolation suggesting upward of $3500 \cdot 10^9$ bbl by the year 2000.

Sickler: Sure.

Odell: Now, is there any reason why we cannot then assume that this extrapolation is reasonable?

Sickler: There is, and that is the reason estimates in the past were much closer together. It is in the techniques where we were fairly limited in the past. Nobody ever thought of reserves in the Antarctic or Arctic or in the deep ocean. Now, at this time we think we will be technically able to go after those reserves, and some people now include them because they think these reserves belong to the resource base. But we have excluded them explicitly because we do not think that we will go after them in the time period of our planning up to the year 2020 or so.

Häfele: I think this point of the meeting is very important. My picture of reality is such that I would not categorically doubt the possibility of exploring more than your 1000 billion barrels, maybe 2000, 3000, maybe even more than 3000. I think the right question--as I understand it--is not whether these reserves exist physically or not, but rather to understand the conditions and the scenarios for harvesting them.

Sickler: Exactly.

Häfele: There are many groups in the world that look into the medium and long range picture. At the same time, the decision makers are facing the questions of large scale investment with long lasting impacts in the future. I think it will undoubtedly be a major impact on ecology and on capital or on the globe as a whole if you were asked to harvest 4000 billion barrels. Then perhaps you do have to go to the Antarctic and to other places that you mentioned. The real question is not whether there is an energy option without difficulties, but rather which of these existing energy options has the least difficulties? Therefore this Institute is trying to push things to the extreme, and for methodological purposes we are trying to understand what happens if a society lives exclusively on coal, exclusively on nuclear energy, exclusively on solar energy. For instance, we are just about to start the Coal Task Force that we are building up.

Now would it perhaps be possible, with cooperation from some of you, to have at least a small Oil Task Force, describing a scenario for mankind depending on oil in a staged fashion? What does a situation look like if you live with 1000 billion barrels of reserves? How drastically would technology impact change? And how drastically would the picture change if you were after 3000 billion barrels? My question and suggestion are that right now, today, the oil experts in particular could perhaps contemplate with us whether we can start such a scenario project, a scenario venture. From the decision point of view it is needed now more than ever, and not everybody has understood fully that the availability of oil and the existence of resources are quite different things.

I do not know whom to address specifically, but I do want to say if one or two institutions familiar with the oil situation could cooperate with us beyond this Conference in identifying these scenarios, I think this would be a step forward.

Grossling: I would like to comment on Sickler's analysis, and especially to the bias or objective in making estimates, which are very legitimate from an industrial point of view.

In view of the uncertainty that exists--the bottlenecks--I would like to point out the situation in Latin America, where there is a prospective sedimentary area 2.6 times as large as that of the USA. Now in that area about 90 thousand wells (exploration and development) have been drilled, and in the USA about 2.2 million. The discrepancy is fantastic. What is holding Latin America back from developing oil? And why are the figures for Latin America very, very small relative to sedimentary areas?

Basically, it is not because of geology, it is not because sedimentary basins are unfavorable. It is an institutional problem; there are political factors. It has been the policy of the Latin American nations to restrain petroleum development. As an example, let us take Argentina.

Argentina is a rather prosperous nation with a greatly diversified economy. Its national policy has been to more or less keep the development of its oil resources in pace with its economic growth, and it is practically in balance. This is a nationalistic policy, the same as in the USA and I think in the USSR. Mexico has done much the same. But Brazil has been lagging behind. Brazil meets only about one-third of its oil demand with its domestic supply. But they have very large prospective areas. My forecast is that it is going to change drastically because of the new prices.

Now, the Latin American nations have become very aware of oil and, I think, you will see in the very near future that Argentina, for instance, will move to exploration. The same applies to Brazil and Mexico. Mexico really has started already. So I would think that Latin America, having about 20% or 25% of the prospective areas of the world, is going to have a much larger fraction of the oil resources of the world than believed until now. I know Latin America well, and I personally would multiply the figures for Latin America that you have given by a factor of two or three.

Sickler: I could answer perhaps to this that naturally, as I stated, we are looking to the years 2000-2020, or so. Now imagine that at this very moment Latin American countries suddenly open up and invite industry and people to go after exploration with experts and everything. Then it takes 10 to 15 years before the development, the understanding of the geological basin, before the whole thing falls into perspective. It is not done in a day. It takes 10 to 15 years. Look at the North Sea where they have been working for 15 years. Only now does the potential balance become available. Of course, before the 15 years are up some large oil fields will produce, but before you have a real impact of Latin America on the world situation you are past the year 2000--you are very much closer to the year 2020. So these resources may be available and they may be very large, but they will only be to the benefit of the people of Latin America in the years 2010 to 2050--not before that time. It is simply not possible.

Grossling: I think that Latin America will be in the picture within 10 years. It must fit into your picture within 10 years. Moreover, you have labeled the resources in your presentation with ultimately recoverable resources.

Sickler: But that is within the constraints set up here up to the year 2000.

Grossling: In that case, your label is wrong. They are not the ultimately recoverable resources. They have been constrained from a logistic point of view.

Sickler: I agree. It is the climate available now, and the scenario seen now, up to about the year 2000.

Roadifer: I would like to interject a word of caution about your extrapolation of the richness of the basins in South America. If you take the Amazon Basin, I agree it is very large; but I also know that many dry holes have been drilled there and I know the sedimentary history, the type of basin that it is, and that you cannot expect the richness that you can infer from North America, for example. This is just a word of caution, that this kind of straight analogy is a dangerous thing to do.

Sickler: One cannot compare basins just on the basis of the amount of hydrocarbons per square kilometer. In our opinion, the sedimentary basins in Latin America are in general far less prospective than those in the USA.

Clegg: I would like to comment relative to this point and to the question raised by Häfele on an oil-based economy. Surely the fundamental difference between oil resources and nuclear and coal resources is that in the latter we have a fair idea of where the raw materials are. We can say that there are large resources of coal, but there are logistic and practical problems whether we can produce these. There are also practical problems whether one can go the nuclear route; but as far as the raw material is concerned, we are pretty sure that it is there. For oil, this is pure speculation, and there is no guarantee that one would have the resources there. Even though your extrapolations and analyses might be absolutely perfect, you may still not find them where you actually drill.

In a paper presented to the *Financial Times* Conference on World Energy Supplies in 1973, Warman* analyzed the annual oil discovery rates for the market-economy countries that had been achieved over the past 70 years. This analysis differed from the usual approach in that it sought to allocate reserves back to their year of discovery rather than take the data published annually by a number of petroleum journals. To do this, a comprehensive study of the world's "giant" oil fields (about 70% of the world's known oil reserves) was made. This analysis has been updated and is illustrated in Figure 2.

The trends observed in the 1973 study have not been altered significantly over the past couple of years, and the discovery rate over the last 10 years has been less than half that achieved on average over the last 30 years (18 billion bbl/year). There seems no reason therefore to modify the view expressed in 1973 that it would be "unreasonable to plan on future finding rates exceeding 20 billion barrels per year".

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*H.R. Warman, "The Future Availability of Oil", paper presented at the *Financial Times*/BOAC Conference, London, September 18-20, 1973.

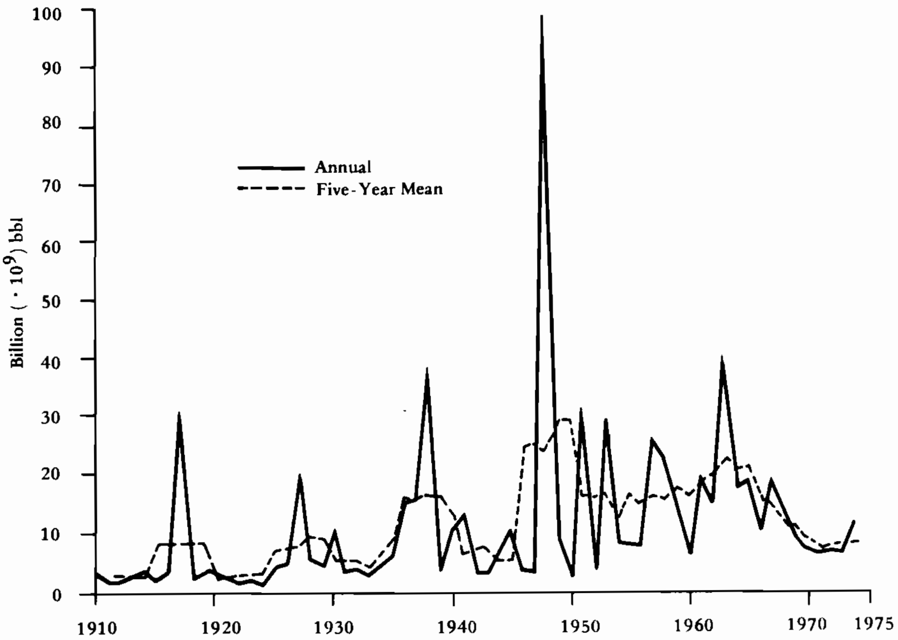

Figure 2. World oil discoveries (excluding the Socialist countries).

The effect of using this modified reserves discovery data on the behavior of the reserves remaining at any point of time and the reserves-to-production ratio is shown in Figure 3. From this it is seen that remaining reserves (that is, those discovered but not yet produced) actually peaked in the late 1960s and have since declined slightly--reflecting the fact that over the last 10 years or so the discovery rate has fallen below the annual production rate.

It is reasonable to postulate that the discovery rate should be related to the amount of exploration effort in some way, and that as more reserves are discovered in a particular area the search process becomes less rewarding. Some data for the Middle East have been collected on the number of exploration wells drilled each year over the last 20 years--a very crude measure of exploration effort. This shows that the number of wells drilled each year has varied between a low of 18 in 1954 to a high of 113 in 1973 (see Figure 4). At the same time discovery rate for reserves (backdated to the year of discovery) appears to be declining.

The statistical analysis of these observations is currently in progress and may lead to some (statistical) estimates of the possible range of total reserves in this region.

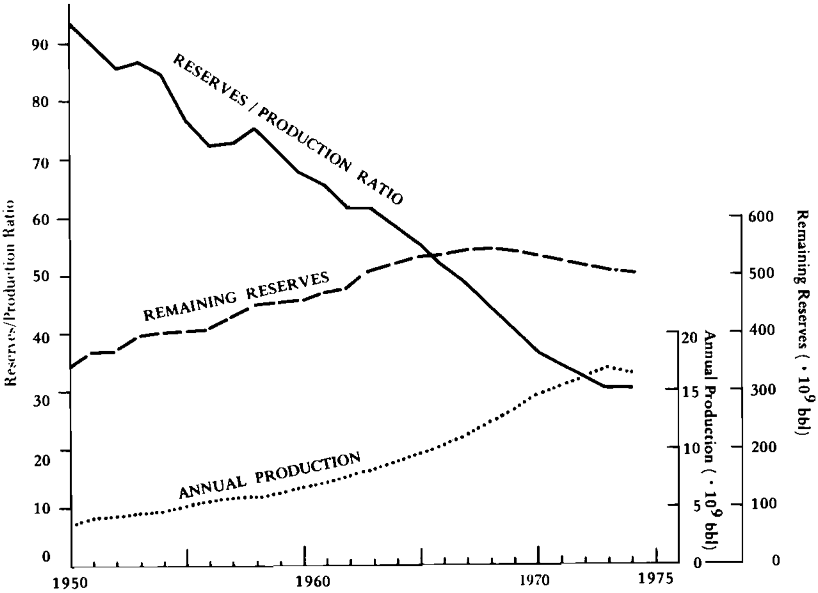

Figure 3. Annual production, remaining reserves, and the reserves-production ratio of the nonsocialist world.

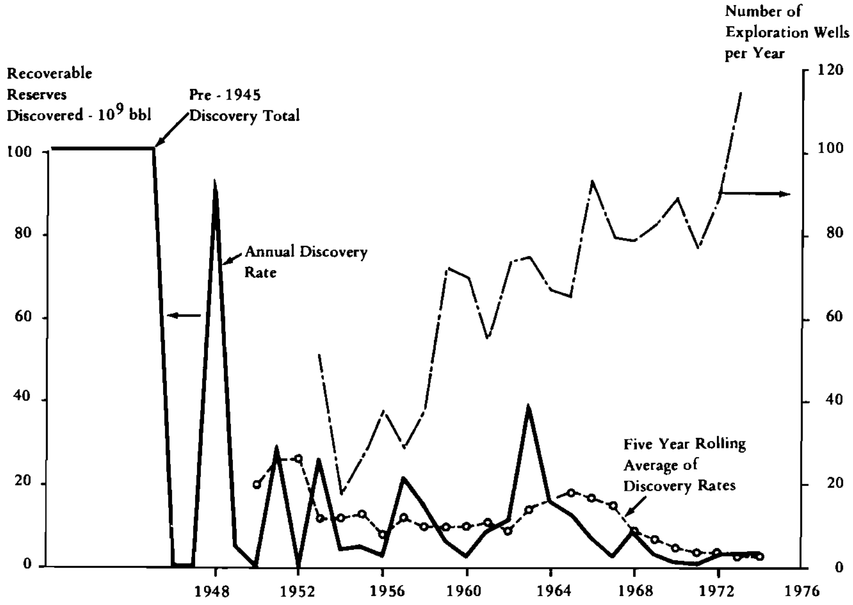

Figure 4. Middle East oil discovery rates and exploration wells drilled per year.

IN SEARCH OF A PROBABILISTIC MODEL OF PETROLEUM RESOURCE ASSESSMENT

B. F. Grossling

INTRODUCTION

Petroleum provides at present the major driving energy for national economies. The foreseen worldwide depletion of petroleum resources in a few decades, at a time of transition to new energy technologies, imposes hardships on many nations but enhances opportunities for those having a petroleum potential.

The petroleum prospective areas of the world consist of sedimentary basins and geosynclines not too intensely deformed tectonically, including the continental shelves down to 200 m depth, with a total area under national jurisdictions of about 26.1 million sq mi. Certain oceanic areas beyond the continental shelves--continental rise, continental slope--have petroleum prospects, but their eventual development may be some 10 to 20 years away.

The traditional geologic environment for petroleum has been the geosynclinal belt. Cratonic areas were reluctantly accepted by many geologists. It was the French who first discovered the important accumulations in Africa, actually in Algeria, in a previously deemed inadequate cratonic area. The occurrence of giant gas accumulations in the Western Siberian platform also did some violence to some traditional views of where petroleum should occur. In the same vein, large tracts of cratonic areas now believed to be covered by not too thick sedimentary columns ought to be considered a frontier in petroleum geology. Another petroleum frontier is the continental margins--shelf, rise, and slope.

The major areas that should be considered for petroleum exploration appear to have already been outlined in the world. Yet the appraisal of the extent of these areas is cautious, often underestimating what subsequent exploratory work reveals. For instance, estimates of the extent of the Great Artesian Basin of Australia can be seen to have greatly increased in the course of a decade. Similarly, I expect that the current picture of the extent of prospective areas in Africa and South America is conservative.

The extent of prospective area is very significant despite that experience in many basins shows that only a small percentage of the total prospective area is actually underlain by commercial petroleum accumulations.

The larger the tract of undrilled prospective area, the greater are the chances that thick sedimentary pods may occur here and there. Even when a few scattered pieces of evidence may indicate a thin sedimentary cover, prospects for generation and primary migration of petroleum may be enhanced by the large size of a prospective area. Such appear to be the circumstances, for instance, with respect to prospective areas in the interior of Africa and the Amazon basin. Of the total world petroleum prospective area, the non-OPEC, non-socialist developing countries control 48%; the developed countries, excluding the USSR, 30.5%; the USSR, 13%; the Middle East, 4.6%; China, 3.5%.

Next to be considered after the sedimentary area should be the total sedimentary volume in each region. Yet this information either is not readily available or has not been released as yet by companies or governments which have conducted exploration of certain areas. Moreover, many other geologic factors may be considered in a comprehensive assessment of the world petroleum potential.

The examination of the distribution of petroleum occurrences throughout the world, in basins with a significant amount of exploratory drilling, indicates that roughly one-half of the prospective basins and geosynclines do not yield any or much petroleum. And in those having petroleum deposits there is a great variety in the manner of distribution, size of deposits, and geologic conditions that control the petroleum accumulations. The situation could be described as a two-stage sequential decision game played by nature. First, it is decided with probability roughly one-half whether a particular basin or province will contain commercial accumulations or not. In the second stage it is decided with an underlying probability distribution the magnitude of the petroleum resources of the basin or geosyncline.

Ahead of exploratory drilling it would be difficult to ascertain which basins would contain petroleum. Of the many prospective basins and geosynclines in developing countries, for instance, roughly about one-half will prove disappointing with none or minor petroleum accumulations. This uncertainty of outcome at this stage is something that has to be accepted; only actual exploratory work, including drilling, can resolve the question.

Another element of surprise is the size of the petroleum accumulations. This is especially important because of the large contribution to petroleum resources of relatively few but very large fields. One can only speculate, ahead of drilling, that certain geologic conditions may prevail in a given basin or geosyncline which would lead to large accumulations.

Of the giant fields discovered so far those of the Middle East are mainly concentrated in oil, and those of the USSR in gas. The giants, in terms of millions of sq mi of prospective areas so far discovered, are as follows:

Field	Oil	Gas
Middle East	45	3.3
USSR	6	11.8
Conterminous US	3.2	7.9
Africa and Madagascar	3.2	0.6
Latin America	2	0
South and Southeast Asia, mainland	0	0 .

About two-thirds of all the past world drilling for petroleum took place in the United States. The bulk of the prospective area of the developing nations is grossly underexplored. An estimate of the total number of wells drilled per sq mi of prospective area in major regions is as follows:

Conterminous US	1.17
USSR	0.15
Argentina, Mexico, Venezuela	0.05
Middle East	0.01
Latin America, except as mentioned above	0.01
South and Southeast Asia and Indonesia	0.01
Africa and Madagascar	0.003 .

About the same relative values are obtained if either the number of exploration wells or the total footage drilled are considered instead of the total wells.

The projected drilling density in the conterminous United States provides an upper bound for the desirable drilling density. In the early development of the United States petroleum industry there was much unnecessary drilling. But even allowing for this factor, the drilling density would be roughly about 0.5 wells per sq mi of prospective area. In the Middle East drilling density is exceptionally low because of the giant dimensions of the fields and it cannot be considered representative of desirable drilling density elsewhere. In the USSR very active petroleum exploration has been carried out, but the exploration is far from passing the midpoint in overall development.

For areas of the order of one million sq mi or more, a desirable ultimate density of 0.3 wells per sq mi of prospective area seems a reasonable target. Then the drilling density should eventually increase by a factor of about 100 in Africa and Madagascar, and of about 30 in South and Southeast Asia, and also in Latin America aside of Argentina, Mexico, and Venezuela. Even in the latter three countries drilling density should eventually increase by a factor of about six.

The final exhaustion of worldwide petroleum resources is foreseen in a few decades. At the moment, the petroleum scene is dominated by one cartel. But looking beyond proved reserves, one finds that there are still a substantial number of completely or insufficiently explored lands which could wrest the control of the petroleum scene from the cartel.

The bulk of the prospective acreage available belongs to certain developing nations. The more important opportunities for petroleum development in developing countries, not already playing a major role, appear to be met in: Mexico, Colombia, Brazil, Peru, and Argentina in Latin America; Mali, Niger, Egypt, Mauritania, Chad, Tanzania, Somalia, and Mozambique in Africa. Vigorous exploration in many of the promising areas should result in the discovery of substantial amounts of petroleum, which could ease the pressures on prices. However, whether the present petroleum seller's market will go away will depend on who controls the new petroleum provinces.

The recoverable petroleum that with certainty can be said to have been found so far in a given country is the sum of the cumulative production plus the proved reserves. Moreover, the expected value in a statistical sense from discovered fields is somewhat larger. For this purpose I have introduced the concept of EVRD = Expected Value of Recoverable Discoveries, as defined below in this paper.

For the major regions which may be considered the EVRD per sq mi of prospective area has been

	Oil (bbl)	Gas (10^6 cu ft)
Middle East	496,000	510
Conterminous US	101,600	556
USSR	49,500	453
Western Europe	27,000	207
Africa and Madagascar	30,700	92
Latin America	24,200	52
South and Southeast Asia, mainland	2,500	60 .

The amount of petroleum initially in the ground in a given country or region and considered to be recoverable within foreseen technological and economic limits is the estimated ultimate recovery (EUR) of that country or region.

By considering certain best explored areas, excluding the Middle East, as benchmarks, I have selected for the ultimate petroleum recovery (EUR) from continental size regions, the following figures: 100,000 to 250,000 bbl of oil and 500 to 1,300 million cu ft of gas per sq mi of prospective area. The above figures do not include the eventual occurrence of Middle East size accumulations. The above provides another estimate for the world EUR, namely

- 2,600 to 6,500 billion bbl of oil, and
- 13,000 to 34,000 trillion cu ft of gas.

In addition, some further allowance should be made for the eventual occurrence of clusters of giant accumulations as in the Middle East. The extended reserves of the Middle East are 595 billion bbl of oil and 612 trillion cu ft of gas. The Middle East EUR's are probably at most equal to a few times these amounts, that is less than an order of magnitude larger.

Several petroleum companies are known to have pursued the search for "another Middle East". A consideration of the broad tectonic framework of various earth regions suggest certain likely places. Some of the places that I would choose are: north slope of the USSR, north slope of Canada, Gulf of Mexico, Argentine continental shelf, shelf between Mozambique and Madagascar, shelf between Australia and New Guinea. Of these six possibilities, four are in or nearby developing regions, namely: Gulf of Mexico, Argentine continental shelf, shelf between Mozambique and Madagascar, and shelf between Australia and New Guinea.

The EUR's that I propose for Latin America are

- 490 to 1,225 billion bbl of oil, and
- 2,450 to 6,370 trillion cu ft of gas;

for Africa and Madagascar:

- 470 to 1,200 billion bbl of oil, and
- 2,400 to 6,100 trillion cu ft of gas; and

for South and Southeast Asia:

- 130 to 325 billion bbl of oil, and
- 650 to 1,700 trillion cu ft of gas.

Because of the very limited petroleum development of these prospective lands, the bulk of the above EUR's remains in the ground to be discovered.

The above remarks reveal that there are large potential petroleum resources to be discovered in the world. For most areas we have a situation of incipient drilling. Methods of forecasting resources from projections based on historical production and reserve data (for instance, using Gompertz and logistic functions) are limited to mature areas such as the conterminous United States and the Maracaibo basin, for example. For the overwhelming majority of the world prospective areas we have a more speculative situation which calls for critical reviews of resource assessment methodology.

The estimates of prospective areas and of EUR's in this Introduction are taken from an unpublished report that I submitted to the International Bank for Reconstruction and Development, Washington, D.C., and provide an indication of the exploratory tasks ahead.

CONCEPTS AND PREMISES

Fundamental Concepts of Resources and Reserves

The span of the various resource and reserve terms for oil are shown in Figure 1. The situation for gas is similar.

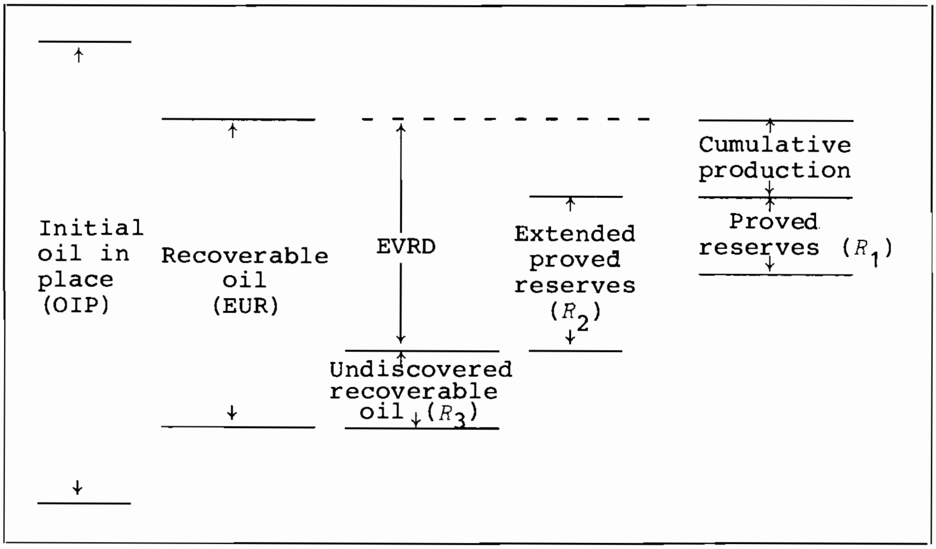

Figure 1. Span of the various resource and reserve terms for oil.

First we have the initial oil in place (OIP), that is, the amount prior to any exploitation which is to be found in undiscovered and discovered fields. Obviously, the OIP is difficult to estimate. As for the undiscovered (unknown) fields, an estimate has to be made based on the discovered (known) fields in relation to the geologic setting. This would not be too difficult if the unknown fields belonged to the same geologic groups as the known fields, or if both known and unknown fields belonged to a reasonable statistical population. However, actual exploration shows that often a certain discovery alters the concept of the petroleum accumulations to be found in a given area. Projections from an old model become obsolete. This logical difficulty is hard to overcome. Perhaps the best we can hope for with respect to the OIP value is to establish lower bounds for it, and to raise the lower bound whenever wider knowledge about the petroleum geology of the region considered justifies it.

Second comes the concept of recoverable resources, that is, the amount of oil which can be recovered, within technological and economic limits, both from undiscovered and discovered fields. This is often denoted as the estimated ultimate recovery (EUR). The relative amount of oil that is recoverable varies greatly, and has not been well established on a world-wide basis. With modern production practices primary and secondary methods have become well integrated and a sharp distinction is not justifiable. At the moment a figure of 40% probably represents a target figure for this phase of recovery. How much oil still remains in the ground even after the best production practices is not really known. Perhaps the recovery can be as high as 80% of the oil in place. Another factor that conditions the amount of recoverable resources is the economic limits. These will change with time, so the forecast of the recoverable resources should vary with the time span of the forecast.

Third, we have the concept of cumulative past production, that is, the total oil which has been produced from the discovered fields. It is the figure that can be ascertained more readily.

Fourth is the concept of proved reserves (R_1). Proved reserves, designed here as R_1, are defined as the amounts of petroleum which can be considered for certain to be producible from explored acreage within present economic and technological limits. To convey a qualitative sense to the above definition I would say that in known fields the amounts of petroleum that can be obtained with certainty, say higher than a 90% probability, can be estimated within ±25% or so. The main uncertainty in this estimating process would be covered by the span of the error (±25%). The increments of oil to be expected from known fields would fall off rapidly below a 90% probability. Essentially then we would have a rather narrow estimate distribution function for the proved reserves--the estimate of the magnitude of a quantity which is known to exist.

Fifth we have the concept of expanded proved reserves (R_2) that represents the expected amounts, in a statistical sense, of oil from revisions and extensions of discovered fields. We deal here with a different kind of uncertainty: the speculation that some petroleum may exist beyond the known parts of fields and as extensions of them. For most countries the following generalization can be made. An additional quantity equal to the proved reserves can be obtained with probability 0.8, and other equal additional quantity with probability 0.5. Hence the expected value of the expanded proved reserves, designated here as R_2, would be $(1 + 0.8 + 0.5)$ $R_1 = 2.3\ R_1$.

The recoverable petroleum that with certainty can be said to have been found so far in a given country is the sum of the cumulative production plus the proved reserves. The expected value from discovered fields is somewhat larger. For this purpose I have introduced the concept of EVRD = Expected Value of Recoverable Discoveries, defined as

$$\text{EVRD} = \text{cumulative production} + \text{expanded proved reserves } (R_2) \ .$$

Finally, the difference between the "recoverable resources" and the sum (cumulative production + expanded proved reserves) is the undiscovered recoverable resources (R_3). Hence an estimate of R_3 involves an estimating of the recoverable resources.

On the Appraisal of the Petroleum Resource Base

The main issue underlying the sudden increase of oil prices is a wide realization that the world petroleum resources would be depleted within a few decades. Yet how to appraise the extent of the remaining petroleum resources is a source of confusion. For long-range economic planning it would be useful to have rather accurate estimates of the total amount of recoverable oil in a given country. But because of the high degree of unpredictability of the actual location of petroleum deposits and the technological limitations in the search techniques it is not economically viable nor technically possible to discover, ahead of development, all the fields in the remaining resources.

Therefore, to appraise the long-range supply of oil and gas we need to go beyond mere projections from present trends. First, one should estimate the magnitude of the resource base, regardless of economics and uncertainty of discovery. Then one should subdivide the resource base according to various intervals of unit costs, in increasing order from present levels. Future technological developments or changed market conditions would allow the exploitation of certain resources which currently are uneconomical. Secondly, the resource base should be subdivided according to certainty of occurrence. Improvement of exploration techniques and increasing knowledge of actual geologic conditions would allow incorporating into the available supply some resources whose existence now is considered uncertain. Such a conceptual framework for the long-range appraisal of resources has already been proposed by McKelvey (1972). It provides a much more meaningful basis for long-range forecasts than before.

The language of mathematical statistics is required to define more rigorously the problem of appraisal of petroleum resources. The recoverable reserves for one fully developed oil field can be estimated with a relatively great accuracy (say within 25%); but the estimating for a new field, a petroleum district, a sedimentary basin, one nation, or the earth are exercises of increasing difficulty, and with correspondingly wider ranges of uncertainty. A few basically original estimates have been made of the world petroleum resources, but there is a vast amount of published data that in fact amount to "regurgitations" of somebody else's data, or somebody else's regurgitations of somebody else's, etc.

To carry the analysis a step further one can pose the question whether the amount of recoverable oil and gas for a given part of a region could be of a given magnitude. The answer can be given only in probabilistic terms. That is, we are faced here with the a priori probability density function of the recoverable amount of petroleum for an undrilled area. Such a probability density function is really not known, for example, for many undrilled areas in developing nations and most of the continental shelves, and it can only be surmised.

Conceptually, at a given time one could first classify the remaining resources R as to the probability of being found with continued exploration. This probability, say p, can be considered to be the product of the probability of existence of a field, p_e, and of the probability of actually locating the undiscovered field, p_d. The resources that at a given time we know with certainty are a certain amount. One could conceptually proceed to classify the undiscovered resources as incremental quantities $\mathrm{d}R$ corresponding to ranges of the probability p, down to some low value of the probability. The resource base, say B, could be defined as the expected value of the resources, that is, the integration of the incremental resource amounts multiplied by the probability of finding them:

$$B = p \, \mathrm{d}R \quad . \tag{1}$$

Upon this first classification scheme we have now to impose the constraints that result from economics. Only a fraction of the segment of resources within a certain probability range can be considered to be economically discoverable and recoverable, as per the conditions at the time when the assessment is made. In the future the economic limits may widen, although not necessarily so, thus permitting a larger proportion of each segment to be exploitable.

Moreover, it would seem that the a priori probability density function is not narrow, and would definitely become small only beyond the largest conceivable size of the recoverable amount of petroleum. Also the probability density corresponding to a very small size of the recoverable oil, or gas, is significant and different from zero. The probability density for, let us say, an amount of recoverable oil comparable on a unit area basis to a given known oil basin is significant and different from zero. As we do not know the shape of this probability density function for undrilled basins and as it appears to be quite broad, it is not proper to give only one value for the amount of recoverable oil or gas, nor to expect that its standard deviation is a small fraction of the magnitude of the recoverable amount. As a first approximation a uniform, or flat, probability density function could be taken for the petroleum estimates of an unexplored area. To give one figure for the petroleum resources of an unexplored area seems to be a futile undertaking.

Although the above scheme might appear to be conceptually clear, it is operationally very difficult. Below a given uncertainty value, say 60%, the situation becomes highly speculative. There is very little basis on which to construct the actual scheme. And yet the largest expected contributions to B should come from resources with low probabilities of eventually being found. However, one could strive to gradually perfect such a picture, considering the past record of discovery as a basis for estimating parameters of theoretical statistical models.

Perhaps one of the most perverse effects of the conceptual difficulties of petroleum resource assessment is the accuracy delusion. By that I mean the misconception that published figures for undiscovered resources have a somewhat narrow distribution function. That is, the possible values form a gaussian distribution about the published figure with not too great a standard deviation, say 20%. For new tracts of territory, as exemplified by the continental shelves, it is not possible yet to provide such a gaussian distribution. A team of company specialists might agree among themselves on a "most probable" value, but from team to team the "most probable" value will be found to vary substantially. The wide scatter observed in bids for offshore petroleum leases can well be attributed to this effect.

A better approximation to the underlying uncertainty function of resource estimates than the gaussian curve of the accuracy delusion is a modified uniform distribution function. It would extend with uniform probability from zero up to a resource amount somewhat greater than an amount corresponding to the richest known similar tract elsewhere, and then would drop rapidly to zero probability for larger resource amounts.

By analogy with other tracts and from knowledge of adjoining areas one might justify modifying the uniform distribution on the low side also, that is to drop quickly to zero probability for resource amounts smaller than a certain amount.

The estimated magnitude of the resource base, and its subdivision according to economics and degree of uncertainty in finding, sets targets for long-range petroleum exploration. In this we are not restricted to the high degree of certainty required by short-range considerations. This occurs because in the exploration of large unknown areas the uncertainties diminish as the exploration proceeds.

To appraise the petroleum resource potential of new tracts of territory one should consider the basic scheme (see Table 1) which underlies petroleum resource exploration and development. After the sedimentary basins have been identified, a pre-drilling potential estimate is made based on factors such as: area, maximum thickness of sediments, type of sediments, existence of structural traps, existence of stratigraphic traps, reconstruction of geologic history, occurrence of oil and gas seeps, adjoining petroleum provinces.

An exploratory well aims at a very specific target, which has been found from undrilled, unrecognized targets on the basis of prior data obtained in a region plus the specific geological and geophysical surveys in the particular prospect. The various targets that exist in the basin may be categorized in various groups--such as foreland anticlines, hinge belt anticlines, platform anticlines, fault traps, reefs, pinnacle reefs, domes over salt domes, regional pinch outs, shoestring sands, etc. Moreover, the geologic definition of the targets in each group could be quite specific.

When the petroleum industry in a given basin is pursuing a given "play" in fact it is running after targets in one of these groups. Before drilling, the actual existence of petroleum in one of these targets can only be ascertained with a given probability even after consideration of all the information that can be established. One could say, for example, that one out of four structures of a certain type on a certain part of a basin would contain oil. Moreover, the magnitude of the accumulation would be essentially determined by the group type, the actual size being almost unpredictable.

In this manner, the statistical success of drilling would be about the same almost to the very end of the play, except for the effect of the enhancement of knowledge because of interaction with previously obtained data. One could thus describe the outcome, in say barrels of oil or MCF of gas found per foot drilled, as a random sample from a normal distribution, having a certain mean and a certain variance which characterize the play. When several plays are being pursued the outcome would consist of random samplings from the various normal distributions corresponding to each group.

Table 1. Stages in petroleum resource development.

Geological and Geophysical Exploration

Existence of Sedimentary Basins Yes No → Out

↓

Pre-drilling Information:

- Area of basins
- Maximum thicknesses sediments
- Type of sediments
- Existence of structural traps
- Existence of stratigraphic traps
- Reconstruction of geologic history
- Oil or gas seeps
- Adjoining petroleum provinces

Pre-drilling Potential →

(End of First Phase of Appraisal)

Exploratory Drilling Campaign

Post-drilling Estimate of Petroleum Potential

(End of Second Phase of Appraisal)

Further Geological and Geophysical Work

Further Drilling

Development of Oil Potential

(Subsequent Phases of Appraisal)

In none of these models would there be a decreasing finding rate as a normal situation. The exploration would reach the limits of the resource with few warning signals on the finding rate, and bottom would be hit rather unexpectedly.

An analogy here may help to visualize the problem. Let us suppose an experienced hunter with a shotgun hunting rabbits in a large enclosed field. Let us further assume that there are 20 rabbits initially in the field, and that the hunter required three shots per rabbit, as per his early experience in similar fields. Then one would expect that on the average he will require three shots per rabbit from the first one he downs until the very last rabbit. But in the case of a series of exploratory wells in a given region the aim could improve. This occurs because of the enhancement of the geologic picture as the data from an increasing number of wells and exploration surveys become available.

Objective and Bias in Resource Assessment

When faced with the problem of estimating the magnitude of undiscovered petroleum resources one needs to analyze the objectives of such estimates. In situations which involve uncertainty one can rely heavily on the tools of mathematical statistics, as long as the statistical properties of the quantities involved are well defined. Such is not the case for most of the petroleum prospective areas of the world. We are not dealing with a single, well-defined statistical population of petroleum fields. As exploration encroaches upon the undrilled areas one needs to introduce new statistical categories of fields. Because of this, statistical methods have to be used with caution.

Of course, there is a whole range of situations which vary from well defined statistical properties (on size of accumulation and location) to very fuzzy situations. And unfortunately for most of the undrilled areas the situation is very fuzzy. Underlying each petroleum province there is a certain histogram of petroleum accumulation ranked according to a sequence of size intervals which range from zero to the largest conceivable value. This histogram, or its conceptual limit, the probability density distribution, can be estimated for certain limited regions. But we have very little to go on in constructing one for a sedimentary basin in the interior of Africa, for instance.

We are forced then to a blend of objective and subjective judgments. This has to be kept in mind because the mere fact that a probability density function is formulated mathematically does not necessarily mean that subjective elements have been removed. By ignoring these underlying logical difficulties, and also the various points of view which legitimately can be used in resource appraisal, much confusion and argument have arisen. There has been misuse of petroleum resource data by taking them out of context.

The amount of recoverable resources in a certain geologic domain can be viewed as a variate x, which could conceivably attain any value within a certain range $L \leq x \leq U$. By analysis of the outcomes of the same estimating process as applied to a suite of well explored geologic domains $\{\Lambda_i\}$, one could construct a probability function f(x) so that

$$P(x \geq 0) = \int_0^x f(x)\, dx \quad .$$

Alternatively, one could estimate $f(x)$ by using a model that involves subjective probabilities.

Another way of looking at the problem is to aim at the estimating of limits for x and for the range of x, within assigned probabilities. In practice, it would be more meaningful, as we have explained, to target on certain limits of x, rather than on $f(x)$.

What is to be done with a resource estimate is one of the crucial questions. Some of the possibilities which may be listed as examples are

- A bank is to decide on the financing of an exploration and development project.
- An oil company is to decide on beginning an exploration project.
- An oil company is to decide on continuing an exploration project.
- A government is to define a short-term national energy policy.
- A government is to define a mid-term national energy policy.
- A government is to define a long-term national energy policy.

It is to be noted that each application involves a decision maker who will use the resource estimate, and a specific decision to be taken depending on the resource estimate. Both are important in defining the nature of the resource estimate required.

For certain decisions, one needs a floor or lower bound for the resource estimate which has a high probability of being fulfilled or overpassed. A bank will require almost certainty, for instance. Using the language of mathematics this can be explained as follows. For deciding on the financing of a specific investment for resource exploration and development one needs to know the amount x_L of the resource such that the relationship

$$L \leq x \leq x_L$$

be fulfilled with a low probability α. This probability α determines the marginal risk of losing the investment. In conventional financing, moreover, one would require that the bulk of the investment be recoverable on the basis of an amount of resources which is almost certain to exist, and only that a marginal fraction of the investment be risked. Such an estimating problem could be described by a probability density distribution such that

$$P(x \geq L) = 1 \quad ,$$

$$p(L \leq x \leq u) = \int_{L}^{u} f_L(x)\,dx \quad .$$

A government, when analyzing the various outcomes on the energy posture of a nation, will need an indication on the minimum amount which with reasonable certainty can be counted on to be available from domestic sources.

An economic forecaster may want to center his discussion on a most likely value of the recoverable resources. Here a word of caution is in order. The most likely value should be sought in most circumstances, but seldom is it really available. What we often find is an intermediate value that has been nicknamed the most likely value.

In other cases one needs a roof or upper bound for the recoverable resources characterized by a low probability of being surpassed. When appraising, for instance, the possible impact of a new energy resource one may want to know how large its contribution to the total energy supply could be. It may be enough to know that the upper bound is at the most a few percent of the total energy supply. But if it turns out to be substantial, then a subsequent aim at a mid point of the likely outcomes may be in order.

An important bias arises out of competitive considerations. For instance, when appraising the petroleum prospects of specific undrilled areas throughout the world an oil company may not want to encourage its competitors by aiming at the upper range of the possible outcomes, but rather it may want to aim at the lower range while still falling within the range of what it considers viable.

Widespread recognition of the energy crisis has moved national planners to ask how much oil is left in a country. And they want to know this with precision, so as to make firm policy determinations. We meet here several problems, one of which is to make the planners understand that counting barrels of undiscovered oil in the ground is not as simple as counting sheep on the land. Let us examine what kinds of answer are both viable and useful to economic planners.

One needs to distinguish the various types of countries as to their initial petroleum posture, namely:

a) no exploration and no development;
b) unsuccessful exploration;
c) incipient exploration and incipient development;
d) limited exploration and limited development; and
e) intensive exploration and intensive development.

For the country groups a), b), and c) the first legitimate question for the planner is whether to act so as to permit exploration to proceed. In this decision problem one has to compare the two alternatives:

Go: that is, proceed with exploration; and
Not Go: that is, no exploration allowed.

This is not an unlikely situation. In fact it is the type of decision confronting national planners in certain developing nations having a petroleum potential. What needs to be balanced here is 1) the economic prize that might be obtained if exploration turns out to be successful, against 2) the costs of exploring plus indirect economic losses because of having proceeded with the exploration. In this case, an estimate at the center of the range and the upper bound would be useful to make the decision.

However, for country group d) it may be that the limited exploration and development is constrained by an estimate that has aimed at the lower end of the range.

A country with intensive exploration and development may want, in the first place, an estimate of the minimum of recoverable resources which are left in order to proceed cautiously. For a comprehensive contingency planning beyond this minimum one would need the most likely outcome and the upper bound.

The requirements on which resource appraisal methods should be judged are several:

- consistency with observations;
- degrees of objectivity, and its counterpart, of subjective judgment;
- stability of forecast;
- reproducibility; and
- adequacy as to the true answer.

Often forecasting methods have been advanced because they satisfy some of these criteria, but fail to demonstrate adequacy. Objectivity and reproducibility, for instance, are not enough. The final criterion is adequacy, which is difficult to achieve and more difficult to demonstrate.

PROBLEMS WITH HISTORICAL PROJECTION MODELS

The Linear "Drilling Input--Petroleum Output" Model

A linear input-output model of petroleum exploration and development may be used to gauge the economic impact of the finding rate. The input to the model is a schedule of exploratory drilling per year, and the main output is the amount of oil or gas discovered per year. Such a model has been used in the United States, for instance, by the National Petroleum Council (1973) and Project Independence Task Forces (November 1974).

One assumption is that the amount discovered per year is simply proportional to the drilling per year. The amount of oil or gas discovered per foot drilled can be taken to be a parameter that is a function of the cumulative drilling, and varies from region to region. Another basic assumption is that the production per year is a constant fraction of the proved reserves.

The calculation starts with the reserves as of the beginning of the period of projection and updates them year by year as the result of the drilling discoveries and the yearly production withdrawals. A separate tally would be kept of primary, secondary, and tertiary reserves.

The basic equations for this model would be as follows:

$$\Delta R_n = \mu_1 m D_{n-\lambda} + \Delta R'_n + \Delta R''_n + \Delta R'''_n + \varepsilon \quad , \tag{2}$$

$$P_{n+1} = f R_n \quad , \tag{3}$$

and

$$R_n = R_{n-1} + \Sigma \Delta R_n - P_n \quad , \tag{4}$$

where

ΔR_n = (recoverable) proved reserve established during n-th year in a region,

$D_{n-\lambda}$ = exploratory drilling footage undertaken during $(n - \lambda)$ year,

m = finding rate in bbl of oil or mcf of gas per ft drilled, where m is a function of ΣD_n,

μ_1 = primary recovery factor,

λ = lead time in years,

$\Delta R'_n$ = revisions and extensions of earlier primary proved reserves on n-th year,

$\Delta R''_n$ = actual increment to secondary proved reserves on n-th year,

μ_2 = secondary recovery factor,

$\Delta R'''_n$ = actual increment to tertiary proved reserves on n-th year,

μ_3 = tertiary recovery factor,

ε = revisions to prior computations of $\Delta R'$, $\Delta R''$, and $\Delta R'''$,

P_n = production in n-th year,

f = fraction of the current reserves to be produced each year,

R_n = recoverable proved reserve as of the end of the n-th year.

The starting conditions are the set of the R_0 values as of the beginning of the period of projection. The parameters μ_1, μ_2, μ_3, m, f, and λ are assumed known in the model, and would be estimated by studying the historical data for the region. The schedule of primary, secondary, and tertiary recovery factors is also given to the model. Then an exploratory drilling schedule is assumed for the region, that is, the amounts D_n to be drilled in each region in each year.

Equations (2), (3), and (4) correspond to the approaches used by the National Petroleum Council (1973) for oil and gas calculations. The oil model assumes that a certain proportion of associated and dissolved gas is found per barrel of oil reserve discovered, and this gas is passed to the gas model. A constant fraction of the total amount of exploratory drilling is assumed to be allocated to gas exploration.

The unresolved question up to this point is the role of the market price in inducing the assumed drilling schedule. Actual economic costs of various oils vary in a wide range. Some producers would lose money with the average price, and would not have undertaken the corresponding exploration and development. The market price required to yield the assumed drilling schedule should be higher than the average cost. Or, said another way, the actual drilling schedule and petroleum outcome would be smaller than indicated by the above model for a market price the same as the average cost.

What is needed is a way to estimate the supply curves for oil and for gas, that is, the amounts of oil and gas which would be available as a function of their market price. This requires consideration of the variety of individual development projects ranked as to their profitability.

The exploratory effort D_n in a given province in a given year n can be viewed as the initial point of an investment decision. Let us define this as an "n-project". The exploratory effort D_n would result in the discovery of a proved reserve $\Delta P_{n+\lambda}$, where λ is an exploration lead time, but only if the industry actually decides to make the necessary investments. An entrepreneur would decide whether to undertake the project depending on his assessment of the project's financial outcome. For this decision the discounted cash flow method, with an assumed discount rate r, can be used. The above is the procedure adopted, for instance, in Project Independence (US Department of the Interior, Oil Task Force Report, November 1974), and it can be used to develop a mathematical formulation.

Let $\Delta P_n(\tau)$ be the annual production to be obtained from an n-project, τ being the time counted from its initial year n. For a given discount rate r, there would be a minimum unit price $p_n(r)$ of the oil, or gas, that the entrepreneur would require for deciding to make the investment in the n-project. This unit price is a function of the discount rate r, and also of the specific n-project considered. As a basic characteristic of an n-project we can take the finding rate m. Hence we can write

$$p_n(r) = p(m,r) \quad . \tag{5}$$

That is, given the finding rate and the discount rate, the minimum required price can be calculated.

Consider now the supply situation in a given year n as being the result of all prior n-projects that have been undertaken. For a unit market price U we can ask which would be the supply P_n of oil, or gas, that would be available. The supply P_n would be the sum of the productions for the year n of all prior n-projects that would be undertaken. The supply for a given year would thus consist of the addition of the contributions drawn various years after discovery from a set of n-projects, that is of several "vintages". So the question is which n-projects would have been undertaken.

If the future-price expectation of all entrepreneurs prior to year n had been U, then all those n-projects for which

$$U(m,r) \leq U \tag{6}$$

would have been carried out, and the supply would be

$$P_n = \sum_{\tau=n}^{\tau=L} \delta_{m,p} \Delta P_n(n - \tau) \quad , \tag{7}$$

where the operator $\delta_{m,p}$ is equal to 1 if (6) is satisfied, and equal to 0 if it is not.

The finding rate is defined as the ratio

$$m = \frac{\Delta R_{n+\lambda}}{D_n} \quad . \tag{8}$$

For a given region this finding rate may vary in some manner as a function of the cumulative drilling, that is $m = f(\Sigma D_n)$.

Now I would like to discuss whether the value P_n above, as a function of U, would provide an estimate of the supply curve. The most critical piece of input data to the calculation of this estimate of the supply curve appears to be the finding rate. We have

$$\Delta R_{n+\lambda} = mD_n \quad . \tag{9}$$

First, the future-price expectation in the past may be different from the actual price at a later time. If the future-price expectation in the past had been higher than the actual current price, then the actual current supply would be higher than indicated by equation (7) because more entrepreneurs would have decided, some mistakenly, to carry out their n-projects. On the other hand if the future-price expectation in the past had been lower than the actual current price at a later time then the actual supply would be lower than indicated by equation (7) because fewer n-projects would have been carried out. But if it is assumed that the future-price expectation of entrepreneurs is correct, then the above difficulty disappears.

Second, an n-project would generally encompass several petroleum fields of various degrees of profitability. Yet all of them are linked in this simple model as one project. This naturally tends to blur the significance of the supply curve as calculated above.

Now we assume that the production rate obtained from $\Delta R_{n+\lambda}$ decreases exponentially with time and that the decay constant is T_1, so that

$$\Delta P_n(\tau) = (\Delta R_{n+\lambda} / T_1)\, e^{-\tau/T_1} \quad . \tag{10}$$

Hence

$$\Delta P_n(\tau) = m(D_n/T_1)\, e^{-\tau/T_1} \quad . \tag{11}$$

The development and exploitation of an n-project gives origin to a sequence of annual investments, expenditures, and incomes throughout the life of the project. In the discounted cash flow method the cash proceeds and cash outlays are discounted to the initial time. If the discount rate is assumed, then the unit required price to make the present value of the proceeds equal to the present value of the outlays can be calculated.

For the discounted cash flow of a given n-project, and given the US type of taxation as an example, we can use the expression

$$F = (1 - \alpha)(1 - \beta)U\sum_{\tau} \Delta P_{\tau} e^{-r\tau} + \gamma(E_a + E_b) - E_0 - \sum_{\tau} E_{\tau} e^{-r\tau}$$

$$- \sum_{\tau} \gamma \{(1 - \alpha)(1 - \beta)p\Delta P_{\tau} - E_{\tau} - \eta - \theta\} e^{-r\tau} \quad , \qquad (12)$$

where

F = present value of the discounted cash flows,

U = unit price of oil (or gas),

P_{τ} = production per year on τ year of project,

α = ad valorem tax,

β = royalty rate,

E_a = expensed items: dry holes + δ% of successful wells + lease rentals + overhead,

E_b = tax credits: ε% of successful wells + environment and safety + gas plant + lease equipment,

γ = corporation tax rate,

E_0 = initial cash expenditures,

E_{τ} = cash expenses on τ year of project,

η = effective depletion rate for τ year of project, as a fraction of the net revenue,

θ = depreciation for τ year of project, and

r = annual discount rate .

The first term in expression (12) corresponds to the present value of the net revenues; the second term corresponds to tax credits; the third corresponds to the initial expenditure; the fourth corresponds to the present value of the annual expenses; and the last term corresponds to the present value of the income taxes.

Equation (12) is to be solved for U, namely

$$U = \frac{{}_0 + \gamma\sum_{\tau}(E_{\tau} - \eta - \theta)\, e^{-r\tau} - \gamma(E_a + E_b)}{\gamma(1 - \alpha)(1 - \beta) \sum_{\tau} \Delta P_{\tau} e^{-r\tau}} \qquad (13)$$

Some of the quantities in the numerator of equation (13) correlate strongly with D and others with ΔR. But the predominant effect appears to be a linear dependence of E_0 on D. Moreover,

$$\Delta P_{\tau} = m(D/T_1)\, e^{-\tau/T_1} \qquad (14)$$

because of equation (11), and thus ΔP_{τ} is also proportional to D. Therefore the factor D tends to cancel out in equation (13), and the price U would turn out to be inversely proportional to the finding rate m, namely

$$U = \frac{c}{m} \quad , \qquad (15)$$

where c is a constant which depends on the investment and operating expense coefficients, tax rates, and production decay constant T_1.

The Drilling Finding Rate

The density of drilling, that is the number of exploratory wells drilled per square mile of prospective area, is a useful indicator of what needs to be done in young petroleum provinces, as for instance in most developing countries. Because of this it is necessary to review the relationship between wells drilled and petroleum found. Total footage is a measure of the amount of drilling.

A common assumption is that the average amount of proved reserve found each year is proportional to the amount of exploratory drilling in that year. Moreover, it has been assumed that this finding rate, in bbl of oil and mcf of gas per ft, decreases as the cumulative drilling increases. Offhand this appears to be a reasonable assumption.

Why should the finding rate decrease steadily as the cumulative drilling increases? It cannot occur simply because the oil resources in a region are being depleted as the exploratory drilling increases. For it could happen that the finding rate remained constant or even increased during most of the exploratory phase of a region and then dropped rapidly to zero as the limits of the resource base are finally approached.

It has been claimed that the finding rate should decrease because the larger fields would be discovered first. Of course this is what one would like to do, but the record of exploration in basin after basin reveals that this is not so. The discovery of giant fields typically occurs some 30 years after exploration begins in a region. And there does not appear to be a dominating "pickle-barrel effect" to thus justify a decrease of the finding rate.

Maximum depth of drilling has been increasing worldwide. For given basins and time lapses of 10-20 years the average drilling depth may show a trend of increase. This would introduce a decreasing trend of the finding rate with time. The year to year fluctuations of the finding rate, however, can be considerably larger than the effect per year of this basic trend.

As an example, let us examine how the finding rate behaves for the National Petroleum Council (US) regions, which rate is reproduced here in Table 2. For the period 1956-1970 the finding rates for regions 1, 2, 2A, 6, 6A, 7, 8, 9, 10, and 11 vary rather randomly from year to year and do not demonstrate any trend of decreasing values with increasing drilling. On the contrary, for regions 1, 2A, the aggregate of 8, 9, and 10, and 11 the basic trends indicate that the finding rate increases with the cumulative drilling. Only for regions 3, 4, and 5 is a declining trend indicated.

On the Economic Role of the Finding Rate

To gauge the quantitative importance of the finding rate function on the supply curve let us assume a linearly decreasing function, namely

$$m = m_0 - hQ \quad , \tag{16}$$

where m_0 is the finding rate at the initial point considered, Q is the cumulative exploratory drilling measured from the initial point, and h is a constant.

The supply S is obtained by integrating the outcome of the drilling effort, namely:

$$S = \int_{o}^{Q_1} m\,dQ = \int_{o}^{Q_1} (m_o - hQ)dQ \quad , \tag{17}$$

or

$$S = m_o Q_1 - \frac{gQ_1^{\;2}}{2} \quad . \tag{18}$$

Table 2. New OIP added per foot of exploratory drilling.[1]

	Region										
Year	1	2	2A	3	4	5	6	6A	7	8,9,10	11
1956	0	191	33	93	94	201	86	1,239	97	106	0
1957	0	163	13	188	115	254	92	1,027	79	90	0
1958	0	186	38	227	107	274	80	4,037	61	90	0
1959	214	143	34	113	86	329	103	17,451	65	132	0
1960	3,968	222	522	159	100	314	87	-	75	112	0
1961	2,178	151	774	138	99	273	146	-	76	68	0
1962	0	545	365	69	54	249	135	751	92	75	22
1963	43	263	1,206	71	42	213	81	460	72	84	0
1964	366	1,360	163	56	52	149	102	323	76	82	138
1965	2,975	226	1,063	40	71	184	93	257	83	69	569
1966	2,256	40	1,262	80	40	134	62	487	55	81	0
1967	4,492	93	1,867	112	69	136	71	282	46	106	0
1968	11,233	411	640	68	75	95	41	391	41	144	16
1969	128	43	1,695	45	25	87	59	415	51	149	129
1970	463	77	0	44	41	121	77	1,423	78	175	72

[1] "US Energy Outlook - Oil and Gas Availability" (National Petroleum Council, 1973), pp. 212-222.

The cutoff point of the drilling, namely the Q_1 value, would depend on the economics. The cumulative amount of drilling Q determines m by equation (16), and m determines the minimum required price from equation (15), Thus

$$\frac{c}{U_1} = m_o - gQ_1 \tag{19}$$

$$Q_1 = \frac{m_o - cU_1}{g} \quad . \tag{20}$$

So the supply S is

$$S = \frac{m_o^2}{2g} - \frac{c^2}{2gU_1^2} \quad . \tag{21}$$

Equation (21) demonstrates that the supply function S has an asymptote. No matter how large the price U_1, the quantity S would be no larger than $m_o^2/2g$. As U_1 increases, S increases at a slower and slower pace to its ultimate asymptotic value. The asymptotic value of S varies with the square of the initial finding rate, and also is inversely proportional to the downward slope of the finding rate line.

A quantitative assessment of the role of the finding rate function, as I have done briefly here, reveals that the finding rate plays a major role in defining the supply curve for petroleum. A decreasing finding rate, even a mild linear decrease with cumulative drilling, imposes a definite roof (asymptotic value) to the supply curve. No matter how high the price goes the supply does not go above it. As the price increases, the supply increases at a more and more sluggish pace.

Note on the Logistic Method of Projection

The application of the logistic function to the estimating of petroleum resources has been done by M.K. Hubbert in an extensive series of papers since 1956 or so (see, for instance, Hubbert, 1969). A similar approach is the use of the Gompertz curve as done by C.L. Moore (1965). These methods have the advantage of their simplicity and of being based on published statistical data. They are intended to be used in areas when exploratory drilling has reached a mature stage.

These methods have been called mathematical because they use a formula to fit the cumulative production and proved reserve data. Yet they are in fact empirical because there is no theory which justifies the use of the logistic or Gompertz function.

The difficulty of recognizing when the final maximum has been reached remains in these methods. The historical oil production curves of several countries exhibit well defined maxima. Had the logistic, or Gompertz, projection method been used, there would have been a gross underestimating of the undiscovered oil resources. For instance, the annual oil production curve for Mexico in the period 1918-1932 exhibits a maximum in 1921; for Austria in the period 1946-1961 a single maximum in 1955; for France in the period 1946-1973 a maximum in 1965; for Rumania in the period 1918-1947 a maximum in 1936; for the USSR in the period 1918-1945 a maximum in 1941.

They provide a firm estimate of the minimum amount of petroleum which ought to be found if the industry continues doing what it has been doing in the past--what is already in the bag, so to speak. But they cannot predict new plays in a basin. The application of these methods is limited to mature petroleum regions, and thus cannot be used in the majority of the prospective petroleum areas of the world.

Note on Random Search

In petroleum resource appraisal there are two basic questions to be answered:

- how much petroleum is there?
- where is it?

If we assume the answer to the first of these questions, we have a problem of search only.

Some random drilling models purport to show that the outcome of past exploration is to be explained by random drilling. However, even a superficial acquaintance with petroleum exploration reveals that such is not the case. The overwhelming majority of exploratory drilling decisions are made on the basis of all information which is available to the decision maker, and the choices of exploratory sites are those that currently appear to be most promising. The aggregate nature of the data used and the naiveté of some decision models used might explain why this exercise seems to prosper.

A major logical difficulty in the modelling of past exploration is the introduction of a postmortem point of view. When exploration begins to tackle a new province it does so with no assurance that there are commercial accumulations and with no assurances as to their size. If in fact there are, let us say, 100 fields in a province at the beginning of the exploration, a search strategy cannot assume this but must assume the variety of possible ultimate outcomes: 0 field, 1 field, 2 fields, ... , n fields. On the other hand, if we assume that at the beginning of the exploration we have a statement saying that there are somewhere in the basin

100 basins, and that we ought to find them, the situation would be different. Then we could engage in a systematic campaign of grid drilling, with closer and closer grids, until the fields are found. Thus a model of random, or grid drilling, loses meaning when examined against the exploration that has to unfold the plot.

In order to explain the outcome of exploratory efforts one must take into consideration both the search strategy of pre-drilling surveys (geology and geophysics), and the exploratory drilling strategy. By trying different composite strategies the petroleum industry has come to settle on quite different strategies for the above two phases of exploration.

Pre-drilling surveys, not being so much hindered by logistic limitations as drilling, can systematically cover wide ranging areas. The purpose of this pre-drilling phase is to find likely traps. A probability of trap recognition could be associated with the outcome of each pre-drilling exploratory method. Whether the behavior of pre-drilling surveys could be simulated by a random search is not clear.

Exploratory drilling, on the other hand, cannot roam freely over the prospective area. Logistic considerations of the exploratory activity itself constrain its freedom of movement. Moreover, logistic considerations of the petroleum industry itself also condition the areas of more intensive exploratory drilling. As soon as a discovery is made a reassessment has to be made about the exploratory/development drilling strategy. Because of the above considerations it would be uneconomical to assume a random exploratory drilling strategy. Exploratory drilling is focused on specific traps; and as soon as a discovery is made is concentrated on traps that belong to the same geologic family, or what is called a play.

Yet, while searching systematically for a given type of trap, unforeseen conditions are met which can lead to a random disturbance, which may trigger another sequel of exploratory drilling. The result of this dual strategy can be gauged by a simple model. Let us assume that a number dn_i of exploratory holes is drilled after traps of type i, then the number dT of traps discovered is

$$dT = \alpha_i dn_i + \sum_j (1 - \alpha_j)(N_j - T_j) \frac{\Delta S_j}{S} dn_j \quad , \qquad (22)$$

where

α_i = probability of correct recognition of trap type i,

α_S = probability of correct recognition of trap type s,

ΔS_j = average area of trap type j,

S = total search area,

dn_j = number of exploratory holes drilled after traps of type j,

N_j = total number of traps type j, other than i, which exist in the regions,

T_j = cumulative number of traps of type j discovered.

If n_i and n_j are independent variables, then the solution of equation (22) is

$$T = \alpha_i n_i + \sum_j [N_j - k \exp\{ - \frac{\Delta S_j (1 - \alpha_j)}{S} n_j \}] + c \quad , (23)$$

where c and k are constants of integration.

The above formula reveals the two elements of the exploratory drilling outcome, namely a hit with constant probability α_i represented by the first term on the right side, plus a term with a negative exponential represented by the second term.

If we were to focus only on the rate of discovery of traps type j, accidentally while running after type i, one gets

$$\frac{dT}{dn_j} = \frac{k\Delta S(1 - \alpha)}{S} \exp\{ - \frac{\Delta S(1 - \alpha)n}{S} \} \quad . \qquad (24)$$

Menard and Sharman, in a recent paper soon to be published, propose a model of search which in effect takes into account only the second term of equation (22). That is, they assume a pure random search.

SKETCH OF A PROBABILISTIC MODEL OF PETROLEUM RESOURCE ASSESSMENT

The world prospective regions consist of a set of sedimentary basins $\{B_i\}$. Each basin may be segmented in a number of geologic compartments, $\{V_{i,j}\}$, characterized by a homogenous probability space as to size and location of a given type of petroleum trap $T_{i,j}$. The $V_{i,j}$ may overlap in part with each other, and the union of the $\{V_{i,j}\}$ may be smaller than the space occupied by B_i.

The exploration strategy aims at identifying these geologic compartments that provide lanes for further discoveries. The probability of discovery of a field is enhanced when the definition of the geologic compartment is established. Exploration then can move to a higher probability path.

Some of the statistical distribution functions of the $T_{i,j}$ may be correlated or functionally dependent on those of other $T_{i,k}$; but there are many which are totally independent. Therefore, the statistical properties of some $T_{i,k}$ may be inferred statistically from those of known $T_{i,j}$; but there are others for which the known $T_{i,j}$ will provide no information.

For a given B_i, the domains of some of the $V_{i,j}$ may have been defined in part or in total by the exploration effort. That is, an element $v_{i,j}$ of $V_{i,j}$ would be known. The ultimate recoverable resources $r_{i,j}$ from $v_{i,j}$ may be estimated from field production data, success ratios, and even logistic or Gompertz type projections.

For those already-identified $V_{i,j}$ having a known element $v_{i,j}$, an estimate of the recoverable resources $r_{i,j}$ in $V_{i,j}$ may be made:

- by scaling $r_{i,j}$ in terms of the significant dimensional parameters of $v_{i,j}$ and $V_{i,j}$, or
- by an econometric analysis based on the dimensional parameters, which would permit expressing the results in terms of their statistical significance, or
- by formulating a field of probability occurrences over $V_{i,j}$ based on an extension of what may be known in $v_{i,j}$.

For those already-identified $V_{i,j}$, but having no known element, an estimate of the recoverable resources would have to be made by comparison with other $V_{i,j}$, and by introducing a subjective judgment of the field of trap occurrences throughout $V_{i,j}$.

For the remaining parts of B_i where no $V_{i,j}$ have been identified, a broader range of estimates would have to be made based on more subjective judgments as to the likelihood of occurrence of fields, and the statistical properties of their size and locational parameters.

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MODELS AND METHODS FOR ESTIMATING UNDISCOVERED OIL AND GAS--WHAT THEY DO AND DO NOT DO

G. M. Kaufman

INTRODUCTION

Oil price increases initiated by the OPEC cartel have fueled an explosion of interest in forecasts of amounts of undiscovered oil and gas. Perhaps the most striking feature of published forecasts of undiscovered oil and gas is their range. Cook (1975) lists 17 published point estimates of aggregate recoverable oil in the United States beyond known reserves made from 1965 through 1974. The highest is 15 times the lowest. Differences in the amount and quality of geological information employed and in its interpretation, differences in the economic and technical scenarios implicitly or explicitly assumed, and differences in the methods employed for computing forecasts account in part for this enormous range. Few authors discuss in detail how their forecasts can be used in analysis of the relative merits of policy alternatives, even though the end use of a forecast should shape its form. The notable exceptions are econometric modellers (cf. MacAvoy and Pindyck (1973) for example.

A forecast of undiscovered oil and gas is enhanced in quality if designed with a clear conception of the policy alternatives it is meant to address. Once accepted, this premise suggests that whenever possible, geologists and their scientific collaborators should work backward from a specific statement of what alternatives are to be analyzed and in what fashion, shaping their forecasts to conform analytically with policy analysis. This is not a comfortable intellectual posture for many geologists, who by training and inclination think in a descriptive mode dictated by the historical development of their profession. For example, many geologists regard their forecasting job as done when they have produced a point estimate of the aggregate amount of recoverable oil or gas in an unexplored region of interest; such an estimate is useful as background information for evaluating the region as a potential source of recoverable petroleum. However, estimates must be made of the number of deposits, their location and sizes, and of the risks involved in exploring for them in order to determine what amount of recoverable oil will be elicited within a given time frame if a particular mix of land leasing, price, and tax policy is assumed.

Several of the contributions to this conference provide important evidence of change in this traditional posture, and also of a proliferation of mathematical models for generating estimates of undiscovered oil and gas. While no single method of forecasting is universally suitable at all levels of geological aggregation from sedimentary unit or play to nationwide and at all stages of exploration, it may be possible to relate features of some of the models discussed here so as to create new models with wider domains of application and greater forecasting precision. To this end we compare attributes of a sample of models in a simple fashion that sets the stage for a critical evaluation of their strengths and weaknesses.

Desirable features of a model designed to generate estimates of undiscovered oil and gas include:

1) the output in a form useful for policy analysis; in some instances this means it can be employed in the construction of an economic supply function;

2) a scientifically credible model; that is, it is based on explicitly stated postulates which can be validated or invalidated by statistical testing of observed data;

3) measures of uncertainty of estimates and of model parameters which can be computed;

4) expert judgement which can be explicitly incorporated as personal (subjective) probabilities and blended in a logical fashion with objective evidence as the latter accrues.

There are many modelling styles currently in fashion, so to ease comparison we classify them into five types: 1) black box extrapolation, 2) geological-volumetric, 3) subjective probability, 4) econometric, and 5) discovery process.

Table 1 is a display of descriptive properties of each model type suggested by these questions:

1) Is the model deterministic or probabilistic?

2) If it is probabilistic, is it an objective model of a data generating process, a subjective probability model, or a combination of both?

3) Does the model provide a mechanism for logical weighting of subjective judgement and objective evidence as the latter accrues?

4) What methods are employed to estimate model parameters?

5) Is the model's structure a logical consequence of set of postulates or assumptions about the physical process by which data are generated?

6) If so, can each assumption be empirically validated or invalidated by statistical testing?

Table 1.

2) Model type	1) Probabilistic	3) Logical weighting of expert judgement & objective data possible	4) Methods used to estimate parameters	5),6) Statistical tests of model assumptions possible	7) Economic variables explicitly displayed	10) Lowest level of aggregation
Black Box Extrapolation:						
Hubbert	NO	NO	subjective interpretation of data and graphical curve fitting	YES: If probabilistic character of error components identified	NO	Nationwide US
Moore	NO	NO	least squares		NO	Nationwide US
Geological-Volumetric:						
ANOGRE	NO	NO	subjective interpretation of data	NO: But empirical behavior of f can be determined by retrospective analysis of data.	NO	geological zone or stratigraphic unit
Subjective Probability:						
USGS RAG	YES	NO	elicitation of personal probabilities	Indirectly. Tests of dependence, independence of uncertain quantities, for example, possible by analogy with objective data from similar zone.	NO	geol. province
GSC	YES	NO			NO	geol. zone
Exxon	YES	NO			NO	geol. zone
Econometric:						
MacAvoy-Pindyck	YES	YES	two stage least squares	YES	YES	FPC production districts
Discovery Process:						
Odell-Rosing	YES	NO	subjective interpretation of data, personal probabilities	YES	YES	geological province
Barouch-Kaufman	YES	YES	stat. estimating MLE & non-linear least squares	YES	-	geological zone

7) Are the effects of economic variables on rates of new discoveries measurable?

8) What kind of input data does the model accept?

9) How does the model generate output data and in what form?

10) What level of geological and geographic aggregation is employed?

By an objective probability model, we mean one that describes in full detail a probability law governing the generation of data. The parameters of this probability law may not be known with certainty, but the functional form of the class of probability distributions corresponding to it is. The model presented by Rosanov is an example. A subjective probability model is by definition composed primarily of judgemental probabilities elicited from experts. Three examples are the model employed by the Resource Assessment Group (RAG) of the US Geological Survey, that employed by the Geological Survey of Canada, and Exxon's speculative supply model.[1] In assessing additions to reserves from growth of existing fields, enough historical data are generally available to allow use of an objective model whose parameters may be estimated by a combination of expert judgement and data analysis with most weight given to the data. Forecasts of the amounts remaining to be discovered from plays in which a moderate to large number of discoveries have been made can be treated in a similar fashion. Subjective judgement has a dominant role in appraisal of speculative plays--one conceived to exist in a sediment sparsely drilled and in which no discoveries have been made. Consequently, most models currently in use to assess the potential of frontier areas are composed of a set of subjective probability distributions and logical relations among them.

Bayes' theorem tells us how to weight observed data generated by an objective probability model against subjective opinion expressed in the form of personal probabilities for parameters of a data generating model which are not known with certainty. (Baecher and Gros apply Bayes' theorem to a regression model describing geologically-trending bodies to do this.) However, it is oftentimes more natural for geologists to express their opinions about observable quantities such as the areal extent of an oil pool or the number of prospects in a geological zone rather than about parameters of a probabilistic data generating process. In such instances there is a non-

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[1] A description of Exxon's speculative supply model as used to forecast onshore Louisiana gas potential is given in Studies in Geology No. 1, an AAPG memoir volume due to be published in October 1975.

trivial mathematical problem to solve if Bayes' theorem is to be applied: under what conditions and by what methods can a (subjective) distribution for parameters be recovered? We shall discuss this problem in more detail.

There is an important difference between a model whose output is a logical consequence of relations among a set of primitive assumptions describing the process by which data are generated and one in which the "law" governing the mathematical form of its output is the primitive assumption. An example of the former is the model of Barouch and the present author; the models of Hubbert and Moore are instances of the latter. The user will generally have more confidence in forecasts generated by a model that passes tests of the validity of primitive assumptions from which it is structured independently of tests of the predictive quality of its output.

A discovery process model is an objective probability model built on assumptions about specific geological, technological, and economic attributes of the process of exploration in a petroleum basin. Econometric models currently in use consist of sets of stochastic equations describing the time rate of drilling wildcat wells, successes and failures, and additions to known reserves of oil and gas, and so are superficially similar to discovery process models. They differ in that these equations are constructed in accordance with traditional econometric practice rather than derived from primitive assumptions about the deposition of hydrocarbon pools and the way in which they are discovered; that is, they are linear or loglinear regression equations.

While the model types we have cited differ in many ways, there are a number of logical relations between them that may be exploited to create new models with a wider domain of application. Consider, for example, the application of three model types to a single, sparsely explored petroleum zone: geologic-volumetric, subjective probability, and discovery process. Figure 1 below shows in a rough way how typical output variables generated by each model type are related. All three models incorporate observed objective data on drilling successes and failures, number of and size of discoveries either explicitly or implicitly, so we display only input variables characteristic of each type. It is possible in principle to transform the inputs into a subjective probability model (expert judgement expressed as personal or subjective probabilities about the number of and sizes of deposits) and into a (subjective) probability distribution for the parameters of a discovery process model. The output of the latter then becomes a logical mixture of objective data and expert judgement. We shall examine this idea in our discussion of subjective probability models. Perhaps the most important output variable of a geologic-volumetric model (total amount of undiscovered hydrocarbons) can be calculated from the outputs of both discovery process and subjective probability models. These are only hints at logical links between model types, a topic deserving considerably more analysis than we shall provide here.

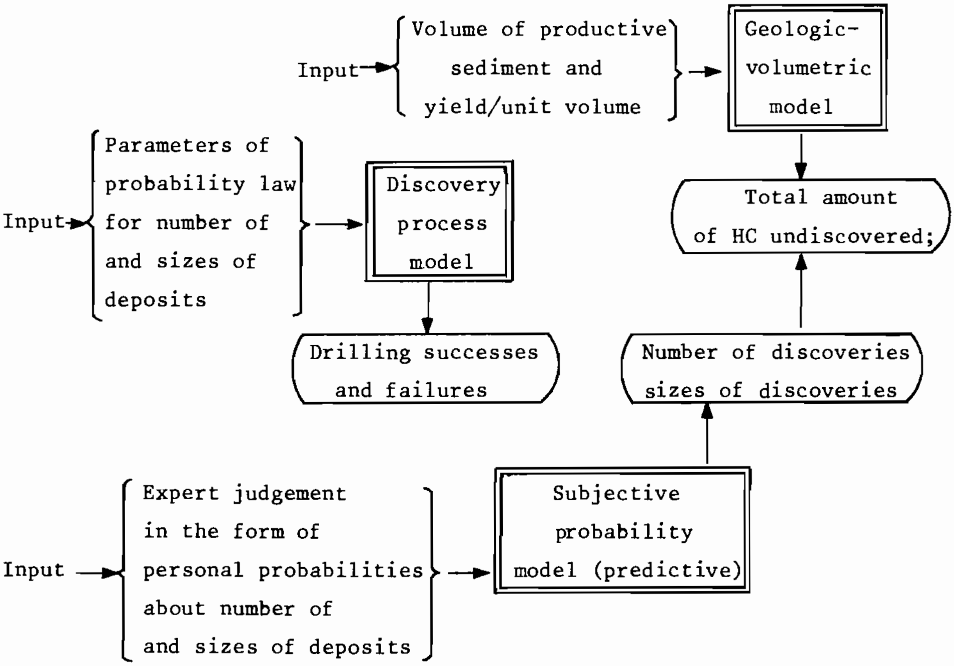

Figure 1.

The levels of geological and geographical aggregation assumed by the models in Table 1 vary from individual geological zone to nationwide US. At the extremes, a forecast of total US undiscovered recoverable oil, for example, can be generated by modelling each geological zone in each US petroleum province and then aggregating, or by using a model of the Hubbert type. The former requires immensely more input data than the latter--and in addition, a set of explicit rules for combining the micro-forecasts for individual zones. Hubbert's model has the added advantage of being analytically simple and easy to interpret--two qualities not to be undersold.

DISCUSSION

Black Box Extrapolation

A black box extrapolation model is one whose structure mirrors the past behavior of data without direct appeal to the underlying physical or economic principles describing how the data were generated. Such models are widely used to characterize the structure of both deterministic and probabilistic data generating processes. (Among the latter are time series and regression-like models.)

The models of M. King Hubbert (1962) and C. L. Moore (1965) are classical examples of this type. Both models are deterministic in that they describe the trend of data but not the error component about the trend.

Hubbert was the first to explore systematically the application of a fundamental hypothesis about growth to aggregated US oil and gas industry time series data: on a scale of time, the rate of growth increases slowly at first, accelerates to a peak, and then declines. He produces an extrapolation of cumulative proved discoveries and cumulative production of oil for the US as a whole, of rates of proved discoveries, and of a number of related quantities on two scales: a time scale and a scale of exploratory effort measured in wells drilled. This is done by fitting a logistic function to observed data. Once chosen, the logistic function fixes the qualitative properties of the trend as a function of time or of exploratory effort: the graph of cumulative proved discoveries is S-shaped and the graph of its derivative is symmetric.

Much controversy has surrounded Hubbert's forecasts because of the seemingly arbitrary choice of functional form (see J. M. Ryan (1965; 1966) reply; also Hubbert (1965)). Arguments for and against Hubbert's forecasting method have been extensively aired and so we will not review them here. In another context, Feller (1966) comments pungently on the logistic distribution function

$$F(t) = \left[1 + e^{-\alpha t-\beta}\right]^{-1} \qquad \alpha > 0,$$

as a model of growth:

> An unbelievably huge literature tried to establish a transcendental "law of logistic growth"; measured in appropriate units, practically all growth processes were supposed to be represented by a function of the (above) form with t representing time. Lengthy tables, complete with chi-square tests, supported this thesis for human populations, for bacterial colonies, development of railroads, etc. Both height and weight of plants and animals were found to follow the logistic law even though it is theoretically clear that these two variables cannot be subject to the same distribution. Laboratory experiments on bacteria showed that not even systematic disturbances can produce other results. Population theory relied on logistic extrapolations (even though they were demonstrably unreliable). The only trouble with theory is that

> not only the logistic distribution but also the normal, the Cauchy, and other distributions can be fitted to the same material with the same or better goodness of fit. In this competition the logistic distribution plays no distinguished role whatever; most contradictory theoretical models can be supported by the same observational material.

Feller is arguing that the data alone are generally not sufficiently rich in detail to allow us to distinguish among competing models of growth with precision; that is, it is difficult to design a discriminating test of competing structural hypotheses about the growth of, in this case, cumulative production of petroleum over time. The danger in choosing an "incorrect" choice of functional form for the growth curve is that it can lead to wildly inaccurate predictions.

However, this does not seem to be the case with Hubbert's forecasts, principally because he uses an artful blend of expert subjective judgement and analysis of the time series data to arrive at a choice of parameters for the logistic function rather than relying solely on an objective procedure for computing parameter estimates from the observed data.

Geological-Volumetric Models

The ANOGRE system proposed by Mallory (1975) is typical of geological-volumetric methods for estimating aggregate amounts of undiscovered oil and gas in a petroleum province. As Mallory says, "Commonly, the proponents of this class of methods build inventories of prospective rock and then attribute to these rock volumes a reasonable quantity of hydrocarbons. The methods are fundamentally geologic in approach and do not depend on technological, economic or political extrapolations to determine quantities. Time and industrial performance are only involved incidentally insofar as they influenced in the past the rates and quantities which yield the hard statistical numbers upon which attributions of undiscovered quantities are based."

Reasoning by geological analogy, it is assumed that the amount of hydrocarbons found in the volume of rock already drilled within a stratigraphic unit is functionally related to the amount of hydrocarbons in the volume of rock within that unit not already drilled. (A key assumption is that the volume of rock condemned by a dry hole is a specific fixed number for a given stratigraphic unit.)

Defining

$V_{drilled}$ = the volume of rock tested by development wells in known pools, and the volume of rock drilled and found barren;

$V_{potential}$ = the volume of rock which seems capable of producing but has not been drilled;

HC_{known} = volume of hydrocarbons discovered;

$HC_{unknown}$ = computed volume of hydrocarbons yet to be found;

Mallory assumes that

$$\frac{V_{drilled}}{HC_{known}} = \frac{V_{potential}}{HC_{unknown}} \cdot f \quad .$$

The "factor" f is generally chosen subjectively. (Mallory suggests a number between 1.0 and 0.5; others suggest a lower value.) Given f, $V_{drilled}$, HC_{known}, and $V_{potential}$, this formula yields a point estimate of $HC_{unknown}$.

In fact f is a function of two variables indexed by two physical parameters; for example, the parameters might be chosen to be the aggregate volume of rock in the unit and the aggregate amount of hydrocarbons--although neither parameter may be known with certainty. So regarded, f varies in a systematic way as the exploratory process unfolds. It would be useful to examine the empirical behavior of f by retrospective analysis of well explored regions.

While valuable as background information and as a crude benchmark to determine whether a stratigraphic unit has any remaining potential, a point estimate of $HC_{unknown}$ cannot readily be used for detailed investment decision making or for government policy analysis. No measures of uncertainty of $HC_{unknown}$ are computed, and only when the behavior of f is expressed as a function of variables whose values are generated by the exploratory process can statistical testing be done.

Subjective Probability Models

Personal probabilities elicited from experts are being more and more widely used and, as their use expands, it becomes increasingly important that experts whose opinions are being elicited be trained to avoid hidden biases arising as a result of the heuristics most of us use to translate subjective judgements into probabilities. Tversky and Kahneman (1974) give an excellent account of how systematic errors may happen.

In conformity with our intuition, predictions should be made by use of a formal mechanism through which expert judgement largely determines what predictions are made when little objective evidence is available; but as the amount of objective data grows this data should assume more and more relative weight, ultimately overwhelming initial subjective judgements. None of the subjective probability models cited in Table 1 incorporate such a mechanism. Without a formal model of the discovery process, the only way in which subjective assessments can be updated as objective evidence accrues is by repeating the assessment procedure; however, given an explicit description of the manner in which new discoveries are generated (a stochastic model of the discovery process), it is possible to update in a logically rigorous way without repeating the assessment procedure.

If we view observed data such as number and size of discoveries and drilling successes and failures as being generated by a process representable as an objective probability model, then many of the component distributions of the subjective probability models presented here may be interpreted as predictive in the following sense: suppose that there are N pools in a geological zone whose sizes $A_1, \ldots, A_N$ are uncertain quantities that are probabilistically independent and identically generated according to a probability law (the objective model) representable by a density $f(\cdot|\Theta)$ with parameter $\Theta \varepsilon \Theta$. Suppose also that Θ is not known with certainty and that subjective opinion about it is expressed in the form of a cumulative distribution function $H(\Theta) \equiv P\{\tilde{\Theta}<\Theta\}$. Then the predictive density for a generic $\tilde{A}_i$ prior to observing any of the $\tilde{A}_i$s is

$$K(A) = \int_{\Theta} f(A|\Theta)dH(\Theta) \quad .$$

In order to update K in the light of a sample of observed values of the $\tilde{A}_i$s we need to know H. If only K(A) as defined above is given, then H must be first recovered by "solving" the above integral equation for H given K and f. Mathematically precise versions of this problem tailored to specific subjective probability models deserve attention.

Econometric Models

MacAvoy and Pindyck's econometric model of supply and demand for gas in the US is an excellent example of how econometric analysis can be used to predict the effects of specific energy policy alternatives. It examines the impact of regulatory policy on gas reserves, production, supply, demand, and prices over a 10 year span. A key ingredient of their model is a set of regression equations which relates the rate of exploratory drilling, of successes and failures, and of amounts discovered to economic incentives, previous discoveries, and success ratios. While these equations are linear and do not explicitly incorporate features of the discovery process, they can be regarded as a crude approximation derived from qualitative reasoning about how discoveries are generated.

The output--probability distributions of wells drilled per unit time, number of successes and failures, additions to reserves--is used to predict the response over time of production, supply, and demand to a changing regulated field price; that is, they do policy analysis.

The simulation results depend critically on the accuracy with which the supply of new reserves has been modelled. While statistical testing of both the direction of influence of individual variables and of the predictive accuracy of the model have been done, all parameters are estimated from historical data so that the model in effect sums up the past. If the system is subject to structural changes of large magnitude within the model's time horizon, it is particularly important to have a means of introducing expert opinion about these changes in a systematic way. A key research question then is "How can expert opinion about undiscovered oil and gas expressed in the form of personal probabilities be introduced into econometric models of supply and demand for oil and gas?"

Discovery Process Models

Odell and Rosing's model of exploration and development of the North Sea oil province is an ambitious attempt to integrate geological, engineering, and economic features of the search for and development of oil reserves in this province. Since a detailed description of it will be given by P. Odell at this Conference, we restrict our attention to a comparison of certain of the assumptions on which the model is built with those underlying the model of Barouch and myself.

The Odell-Rosing model is rich in ab initio assumptions specifically tailored to the North Sea province. The time rate of wildcat drilling, the probabilities of success per well per year, and the probabilities of discovering fields of given class sizes are fixed at the outset. Probabilistic time patterns for reserve appreciation of discovered fields and for depletion rates are assumed. A static economic scenario is posited; however, the impact of a "run of bad years" on the average of initially declared reserves is incorporated by reducing the mean of average initially declared reserves until a "run of good years" obtains.

Most of these assumptions are based on the modellers' subjective interpretation of available data expressed in the form of point estimates for parameters such as the probability that a well of a given "class" will be successful, and in the choice of a normal distribution to characterize the variability about the mean of additions to initially declared reserves. This latter assumption seems logically out of joint with the set of assumptions governing probabilities of discovering fields of given class sizes, for given the probability that a well will discover a field of a given size in a given year and given the number and type of well drilled ("class" well or "other" well) the probability law for total initially declared reserves in that year is predetermined. In view of the large number of assumptions and the complicated way in which they interact, it would be useful to conduct a sensitivity analysis of the model, that is, do a series of Monte Carlo runs designed to determine which parameter values must strongly influence the probabilistic forecasts produced by the model.

The model constructed by Barouch and myself is of a completely different character. It is much less rich in descriptive detail than the Odell-Rosing model and uses data in a different way. That is, the assumptions are based on observed statistical regularities of the size distribution of fields or pools and of the order in which they are discovered. The joint probability law for successes and failures and for sizes of discoveries evolves dynamically as drilling effort proceeds, for it is an explicit function of past drilling history. It is possible to test the validity of the basic assumptions using standard methods of inference, and this is currently being done.

Concluding Remarks

While there is a large published literature devoted to each of the model types discussed here, comparatively little effort has been devoted to systematic development of ways to interface structurally distinct models. Hopefully this topic will be pursued with more vigor by all of us, because there are potential bonuses: wider domains of application and increased forecasting precision. This presentation has only scratched the surface--underneath lies a set of fascinating research questions whose answers may have considerable practical value.

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SUBJECTIVE SAMPLING APPROACHES TO RESOURCE ESTIMATION

Gregory B. Baecher

1. INTRODUCTION

Resource estimation techniques can be broadly grouped into two classes: macroanalytic approaches which model empirical relationships in aggregated discovery or production data and microanalytic approaches which model structural relationships in the exploration process. Perhaps the best known examples for each of these are Hubbert (1969) and Allais (1957).

The present paper addresses microanalytic approaches. In particular, it sets about broadening present sampling theory techniques to encompass more of what we know about the exploration process and to include prior geological opinion. This broadening is seen as necessary if estimates based on microanalytic methods are to be comprehensive and valid.

The main purpose of this paper is not to mathematically solve formulae associated with the broadening, but to indicate directions toward which continuing work should be moving.

2. MACROANALYTIC VERSUS MICROANALYTIC APPROACHES

Macroanalytic models, which in essence are trend extrapolation procedures, assume an unspecified "uniformity-of-nature." They assume that exploration and production operate within a fixed (or at most, gradually changing) environment which leads to aggregate behavior according to simple relationships between important variables. Taking this to be true, empirically fitted relationships may be extrapolated into the future, either in time or along some other dimension (for example, cumulative drilling length). Macroanalytic approaches do not use structural relationships among facets of exploration and production, and lump together economic, geological, and exploratory variables.

Arguments for and against macroanalytic approaches appear in the geologic literature (Ryan, 1973a; Hubbert, 1969; Moore, 1966) as well as in the literature of other disciplines where similar tools are used for estimating or forecasting (for example, economics). Specifically, two properties limit their usefulness for resource estimation. First, they lead to deterministic predictions, the uncertainty of which is difficult to judge (for example, changing from one family of curves to another, or from one method of fitting to another, drastically changes estimates--see Hubbert (1969), Moore (1966)). Second, they depend on a substantial history of discovery and production. While this history exists for areas like the United States, for sparsely explored areas the analysis often <u>begins</u> by predicting total resources some other way, and <u>then</u> calculates time streams of production (Hubbert, 1969).

Microanalytic approaches also suffer drawbacks, which again are generic to the approach and not limited to resource estimation. First, they require detailed data on a region by region basis of geologic and geometric properties, numbers and sizes of discoveries, and amounts and patterns of exploration allocations. Second, they require orders of magnitude more computation effort than microanalytic approaches, as gross estimates are formed by first making regional estimates and then aggregating. These requirements make microanalytic approaches difficult and laborious to apply. Third, although not necessarily a shortcoming, microanalytic approaches do not account for economic or production factors. They deal purely with geological and statistical variables. Economic variables must be considered separately using the geological/statistical analysis as input (for example, MacAvoy and Pindyck, 1974).

On the other hand, microanalytic approaches have four very favorable properties which recommend them from the present perspective:

1) they allow inclusion of geological input on a regional basis;

2) they may be applied to regions which have been only sparsely explored;

3) they often allow quantification of uncertainty;

4) their output can be readily incorporated in strategy optimization for local or regional exploration.

3. MICROANALYTIC MODELS

Microanalytic approaches proceed by making resource estimates for small regions which are assumed geologically homogeneous, then aggregating over all regions. As the aggregation is straightforward, attention is drawn to making estimates for each region. In a traditional, judgmental way this has always been done by exploration geologists. Based on experience geologists subjectively judge the similarity of the region to better known regions, and in combination with geological theory make predictions of resources (for example, upper and lower bounds). This is a very basic microanalytic approach, and is the approach that Harris (1973) attempts to quantify.

A second approach is to correlate geological variables with resources either by regression or factor analysis (Harris, 1965; DeGeoffroy and Wignall, 1971; DeGeoffroy and Wu, 1970). This is a straightforward approach with which there is experience in many applications. However, it suffers well known limitations in that it is a correlation and not a causal model. Factors which are highly correlated with mineralization or deposition in one context are not necessarily those which would be correlated with it in others. As these methods are normally applied to known deposits rather than resources, regression and factor analysis confound geological and nongeological variables. This leads to the not too surprising results of Griffiths and Singer (1971) that "mineral potential" is most highly correlated with degree of development.

A third approach treats estimation as a problem of inference from sampling. The size distribution and spatial dispersion of deposits are modelled by families of probability functions, and parameters for these distributions are estimated assuming known deposits to be a probability sample of the total in situ population (Allais, 1957; Uhler and Bradley, 1970; Kaufman, 1974; Slichter, 1960; Griffiths, 1966). Total resource estimates are made by evaluating the random sum

$$R = a_1 + a_2 + a_3 + \cdots + a_N \tag{1}$$

in which a_1 is a random variable drawn from the distribution of deposit sizes, and N is a random variable representing the number of deposits within the region (Uhler and Bradley, 1970).

Criticism of the sampling approach has been based primarily on the observation that known deposits are not a simple random sample of in situ deposits, the necessity of choosing families of distributions to model the size distribution and spatial dispersion of deposits, and lack of geological input in the model.

The observation that known deposits are not a simple random sample of in situ deposits is not so much an argument against a sampling approach as an argument against uncritical application of that approach. For example, Kaufman (1974) has presented a more rigorous analysis of the sampling approach in which in situ deposits are treated as a finite random sample from some "super-population" (see also Ericson, 1969). Then, the parameters of that super-population are estimated by assuming known deposits to be a sample of the in situ population selected with probability proportional to size and without replacement (see Figure 1). Very different estimates of super-population parameters are obtained using this assumption than using the simple random assumption. A point we will return to in Section 3 is that similar special considerations must be made in estimating parameters of the spatial dispersion function. In particular, that the probability of finding n deposits within a subregion is nonlinearly related to the amount of exploration effort allocated to that subregion and to the distribution of deposit sizes.

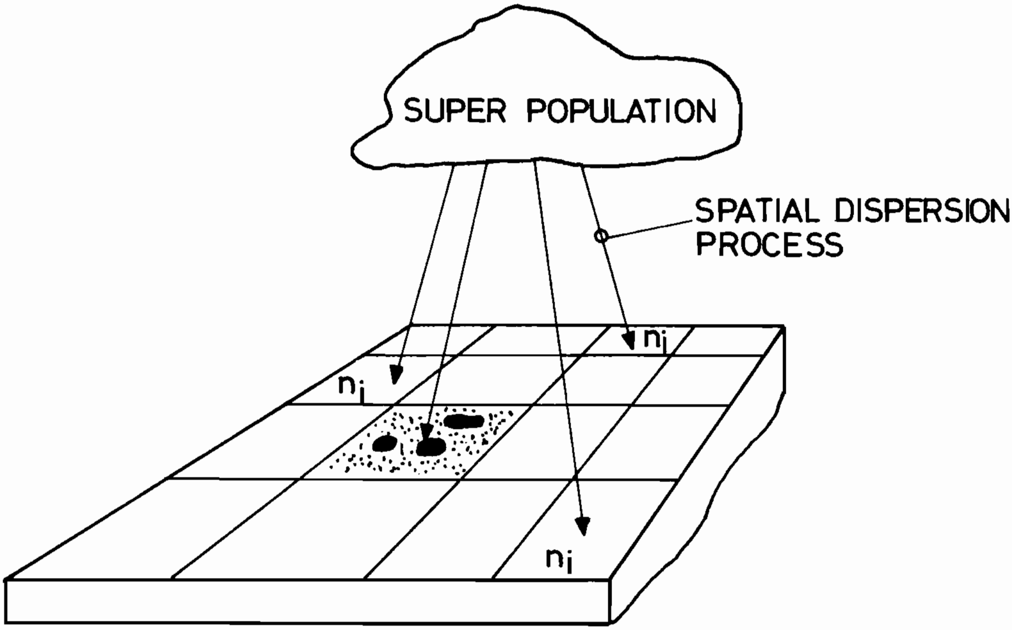

Figure 1.

The problem of selecting a family of distributions to model the super-population and spatial dispersion of deposits is common to all analyses (in that mathematically simple functions must always be chosen somehow). In the present context, however, there is considerable empirical evidence to suggest that lognormal super-populations do accurately model geometric properties of many geological populations (Slichter, 1960), and that the negative binomial distribution may adequately model spatial dispersion, but this is not as clear. (We will also return to this spatial model in Section 3). Furthermore, one suspects (see, for example, Uhler and Bradley, 1970) that total resource estimates are fairly robust to changes in the form of the super-population, and even more so to the form of spatial dispersion.

An interesting direction of future work would be to quantitatively evaluate the sensitivity of resource estimates to the form of these distributions. A refinement following such analysis may be to form so-called composite Bayesian distributions as suggested by Wood (1974) and Box and Tiao (1973), in which distribution models are themselves random variables.

The most important criticism of sampling approaches is that they generally neglect prior geological information. This is certainly true of the "frequentist" approaches to inference, and even the Bayesian analysis have remained tied to "uninformed priors." In making estimates of natural resources we have considerably more information available than merely the number and sizes of already discovered deposits. This prior information comes from regional geology, experience in similar regions, and basic concepts of geological processes. Comprehensive estimates must account for this information. It is only when the available data set is so large that inferences become insensitive to prior information that the latter can be neglected. Given the small amount of information which comes from finding or not finding deposits (relative to the inferences about regional geology and structure which are made), this is seldom the case. Given human biases toward neglecting prior information in the face of new, "hard" data (Tversky, 1974) inclusion of geological information must be explicit.

4. REQUIREMENTS FOR A COMPREHENSIVE SAMPLING APPROACH

To this point we have discussed macro- and microanalytic approaches to resource estimates, and indicated advantages and disadvantages of each. From this discussion it seems apparent that sampling approaches offer a methodological framework within which a comprehensive and realistic model of exploration and estimation might be developed. We now turn toward necessary modifications of the sampling approach.

Two requirements which present sampling approaches do not entirely satisfy, but which they must to be comprehensive and realistic are that:

a) prior geological information and opinion be accounted for;

b) the real likelihood of deposits being discovered be reflected.

Logically, these facets of inference are separable and may be combined by Bayes' Theorem,

$$f'(\underline{\Theta},\Omega|\text{data}) \propto f^{o}(\underline{\Theta},\underline{\Omega})\ L(\text{data}|\underline{\Theta},\Omega) \quad . \tag{2}$$

Here, $\underline{\Theta}$ and $\underline{\Omega}$ are taken to be geological parameters describing the size and spatial distribution of deposits; f^{o} $(\underline{\Theta},\underline{\Omega})$ and $f'(\underline{\Theta},\Omega|\text{data})$ are the prior and posterior probability distribution of the parameters, respectively; and $L(\text{data}|\underline{\Theta},\underline{\Omega})$ is the likelihood of *observing the data* were $\underline{\Theta}$ and $\underline{\Omega}$ the true parametric value. *Prior geological information* is contained in $f^{o}(\underline{\Theta},\underline{\Omega})$; characteristics of the exploration process are contained in $L(\text{data}|\underline{\Theta},\underline{\Omega})$.

4.1 Prior Information and Subjectivity

One enters nearly all inferential situations with some prior information or suspicions. A region seems favorable for exploration because it is similar to known areas of deposition or because it has geological properties associated with deposition. However, each individual has different experiences and concepts of geology and thus assesses favorability differently. This is the traditional role of the exploration geologist. Geological structures are highly complex, and *comparatively* few observations are made in exploration. Therefore, experience and judgment are important. This is the reason geologists are called upon to make resource estimates rather than other people (see Robinson (1963) for an illustration of the importance of subjective concepts in interpreting exploration data).

A geologist considers the results of exploration in the context of his prior feelings. To the extent the two are consistent he gives more or less credibility to his feelings. However, this inferential process, and thus exploration as a whole, is purely subjective. Hence exploration cannot be adequately modelled without introducing the concept of subjective probability (Baecher, 1972). The useable results of exploration are hypotheses. These hypotheses arise subjectively and are given credence subjectively; "hard" data only enters in modifying the degree-of-credibility given to hypotheses. Uncertainties associated with exploration are those associated with hypotheses, so uncertainties, too, are necessarily subjective. Only when the amount of data becomes so large that inferences cease to be affected by prior feelings can exploration be spoken of as "objective." This occurs for only the most intensively explored regions.

So, the sampling approach we would like to develop must be based on subjective probability. This is not unique to the exploration literature, although a thorough attempt at a rigorous fundamentally subjective approach may be.[1] Kaufman (1974) bases his analysis on a Bayesian approach, but does not address using geological information to assess priors (adopting "uninformed" priors instead). Harris (1971) and Harris et al. (1970) use subjective probability in a one-step procedure for making resource estimates without exploration data (that is, using only geological maps). However, this is a degenerate case of resource estimation, and they seem to use subjective probability merely as a pragmatic tool when other data are not available.

4.1.1 Assessing Subjective Probabilities

Applicability of subjectivist theory rests ultimately on our ability to adequately assess probability distributions. Adequacy here means the ability to quantify an individual's true personal feelings in a probability measure. There is not room here to review the literature on behavioral decision theory and quantification of subjective probabilities. However, this work is extensive and rather consistent. Feelings can be reliably quantified if a careful, rigorously based technique is employed. People do exhibit bias in quantifying their feelings (Tversky, 1974), but these biases may not be great. Individuals may exhibit consistent conservative biases in updating their prior feelings by sample data (Edwards, 1968), but in highly complicated, real problems this conservatism seems to diminish or even disappear (Winkler and Murphy, 1974). In some meteorological experiments measured subjective probabilities of experts have been shown to be better forecasters of natural occurrences than structural models (Murphy and Winkler, 1974). In short, we can adequately assess subjective probabilities, but these assessments should be carefully made in the context of past research. As with any technology, haphazard application leads to unreliable results.

4.1.2 Coalescing Geological Opinion

Adopting a subjectivist philosophy of course leads to the problem of differing expert opinion, and speaking of "good"

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[1] Grayson's (1960) well-known application of statistical decision theory to oil and gas drilling decisions is, of course, a rigorous and early application of subjective probability to geological exploration. However, for whatever reasons, subjectivism has never been adopted by "geostatisticians" and thus the resource estimation literature remains nonsubjectivst and (with the exception of Kaufman) non-Bayesian.

and "bad" assessors ceases to make sense. Probabilities reflect only individual feelings, which in turn may not reflect reality. These differences are no surprise, however, as the literature contains wildly differing resource estimates already, and policy makers have always had to deal with differing expert opinions.

The traditional way to coalesce differing subjective probabilities has been the Delphi method, which is a discussion and averaging process. This procedure has received considerable criticism, but is widely used (Pill, 1971). Actually, it is more consensus seeking than a true coalescence. Harris (1971) uses this approach in his mineral potential estimates of Sonora.

A more rigorous method based entirely on Bayesian philosophy has been recently proposed by Morris (1971, 1974), and this approach could be adopted for coalescing geological opinion. It assumes that the ultimate policy analyst can himself assign some prior subjective distribution to the extent of deposition or mineralization. Let these estimates be expressed in terms of two sets of parameters which correspond respectively to the size distribution of deposits ($\underline{\theta}$), and to spatial dispersion ($\underline{\Omega}$). These prior probabilities could be taken as uniform. Opinion is taken individually from several geologists in the same terms, that is, in the form of probability distributions on the parameters $\underline{\theta}$ and $\underline{\Omega}$. To the analyst or policy maker these probability distributions (representing expert opinion) are <u>information</u> and he may coalesce them by the normal Bayesian argument, using his own feelings as a prior probability:

$$f'(\underline{\theta},\underline{\Omega})\text{ experts' opinion)}$$

$$\propto f^{o}(\underline{\theta},\underline{\Omega})\ L(\text{experts' opinion})|\underline{\theta},\Omega) \quad . \qquad (3)$$

This formulation offers a rigorous relationship for coalescing expert opinion. The difficulties of evaluating "credibility" of experts are concentrated in (some might say transferred to) developing a likelihood function for their opinion conditioned on what the actual parametric values $\underline{\theta}$ and $\underline{\Omega}$ might be. While this is straightforward, it becomes untidy when the likelihoods of individual experts' opinions are not independent.

But how can the likelihood function be estimated? As Morris argues, no matter how one proceeds with a statistical analysis, likelihood functions are always established subjectively. For convenience, we may assign families of distributions to those as we do to other things (for example, a normal likelihood) but always this is judgmentally done. Just as we assess subjective probability, so also we may assess likelihood functions based on the policy analyst's or decision maker's feelings relative to his experts' credibility. This reflects the central argument in favor of all quantitative decision analysis: quantitative analysis does not make decisions for the decision maker, rather it allows him to decompose a decision (or estimation), treat each part in isolation, then reaggregate in a logically consistent manner to draw deductive conclusions. Always, the conclusion drawn rests on the judgment of the person who draws it. To deny this is misleading.

A strength of this approach is that it allows the analyst also to establish the expected value of expert opinion (or the marginal expected value of an additional opinion). This process is established exactly as the "expected value of sample information" is evaluated in any Bayesian Decision Theoretic application.

4.1.3 A Proposal for Including Geological Opinion in Resource Estimates

Entering a new estimation task there are four types of prior information to be included: individual experience, documented experience, geological theory, and local characteristics. Were there only documented experience and local conditions, priors could be generated by regression or related techniques. However, individual experience and theory serve to modify direct correlations with the "hard" data of previously explored areas by degrees to which the region under consideration is or is not similar to previous areas, and the ways in which it seems anomalous in terms of basic geological processes. In combining these sources of information the geologist functions somewhat as a subjective information processor (Figure 2).

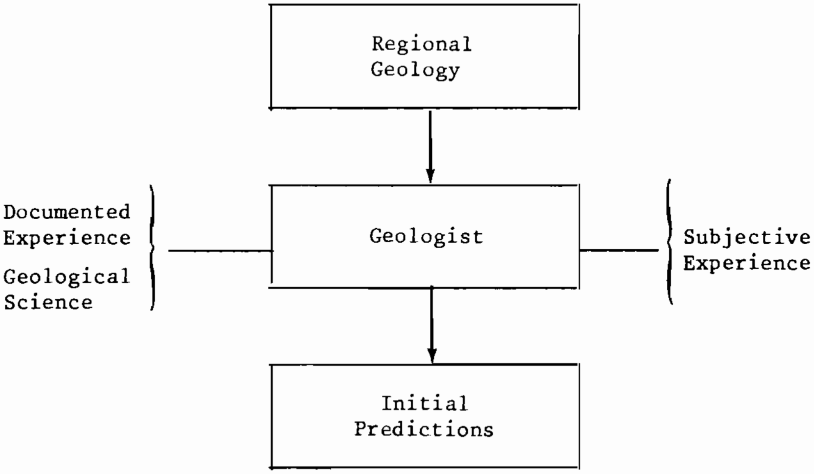

Figure 2.

The approach proposed is that each geologist be given information in the form of geological properties and estimates of $\underline{\Theta}$ and $\underline{\Omega}$ for grossly similar regions in which more extensive exploration has been conducted, and local characteristics of the region in question. Then through a process of careful questioning and gaming directly assess his feelings about possible values of $\underline{\Theta}_o$ and $\underline{\Omega}_o$, the local parameters, in terms of probability measures. This process might be extended by preconditioning data from other regions in terms of local characteristics (that is, regression or factor analyses applied to the new region). In this way, each expert bases his judgment primarily upon the same hard data set, and incorporates his past individual experience and concepts of geological processes purely subjectively.

As Morris points out, it is not a simple task to ascertain the independence of expert opinion. If the opinion is independent, the likelihood function of eq. (3) reduces to the simple multiplicative form of the marginal likelihoods; but if it does not, interdependencies must be modelled, and these may have complex and nonobvious forms. In particular, if experts base their judgments partially upon the same data, then their opinions are not independent. Proceeding as outlined above, however, mitigates this dependency by forming opinions that are conditioned on the data set, and, thus, may be conditionally independent, which would allow a simple multiplicative form. Mitigating the problem of dependence caused by similar geological theory is not so easily achieved, and indeed will require further attention to the design of assessment schemes.

The second step of the process is coalescing opinion. How can likelihoods of geologists' opinion be generated? Currently this problem is difficult to treat except in simplistic ways, but the theoretical base of this approach is only now expanding (for example, Morris, 1974). As a first approximation one can assume that the likelihood of a prediction is related only to the absolute value of the discrepancy from the true parametric value, that is, that experts' opinions are unbiased and that error is symmetric about true values. If one assumes a simple analytical function, for example, a normal distribution, to represent this error, then the variance of that distribution is a sufficient description of expert credibility. It would fall to the analyst or policy maker to subjectively decide upon values of this variance (that is, "credibility") for each expert he consults--but, this is always the task of the analyst whether he achieves it quantitatively or qualitatively. Symbolically, this analysis is of the form

$$f^{o}[\underline{\Theta}_o,\underline{\Omega}_o|\{f_i(\underline{\Theta},\underline{\Omega})] \propto f^{a}[\underline{\Theta}_o,\underline{\Omega}_o]$$

$$\times \prod_{i=1}^{z} \int_{\underline{\Theta}} \int_{\underline{\Omega}} f_i(\underline{\Theta},\underline{\Omega}) f_n(\underline{\Theta},\underline{\Omega}|\underline{\Theta}_o,\underline{\Omega}_o, \underline{\underline{\Sigma}}) d\underline{\Theta}_o d\underline{\Omega}_o \quad , \qquad (4)$$

where $f^o(\cdot)$ is the probability distribution used as a prior in subsequent resource estimates; $f^a(\cdot)$ is the analysts' prediction of the parameters (which might be uniform); $f_i(\cdot)$ is the i^{th} geologist's prediction; and $f_n(\cdot|\underline{\Theta}_o,\underline{\Omega}_o,\underline{\underline{\Sigma}})$ is the normal distribution (in this case the likelihood) with mean $\underline{\Theta}_o,\underline{\Omega}_o$ (that is, the assumed true values) and variance matrix $\underline{\underline{\Sigma}}$. As a first approximation, it seems reasonable to assume that errors in the estimate of $\underline{\Theta}$, the parameters of the size distribution, and $\underline{\Omega}$, the parameters of spatial dispersion, are independent. So,

$$\underline{\underline{\Sigma}}_i = \begin{bmatrix} \sigma^2_{i\Theta} & 0 \\ 0 & \sigma^2_{i\Omega} \end{bmatrix}, \tag{5}$$

in which $\sigma_{i\Theta}$ is the credibility assigned to geologist i's estimate of $\underline{\Theta}$, and $\sigma_{i\Omega}$ is the credibility assigned to his estimate of $\underline{\Omega}$.

The approach just described, clearly, is very rough. Considerable effort, and in particular attempts to apply such methodologies, would need to be invested before a workable and practical procedure could be developed. Nevertheless, an approach somewhat of the type outlined is needed to analytically include geological opinion within the context of regional resource estimation. Ignoring this prior information leads to estimates which are not comprehensive, overly diffuse, and possible erroneous.

4.2 Likelihood Function

In the Bayesian scheme, eq. (2), characteristics of the sampling plan are entirely contained within the likelihood function. This is the probability of obtaining the sample actually observed--that is, the deposits actually discovered--conditioned on values of the parameters $\underline{\Theta}$ and $\underline{\Omega}$. This probability may or may not depend on the order of discovery.

For simple random sampling each observation is assumed independent, and their ordering unimportant. If deposits of size x_i are discovered in this way, their likelihood is

$$\begin{aligned} L(\underline{a}|\underline{\theta}) &= p(a_n|a_1,\ldots,a_{n-1},\underline{\theta})\ p(a_{n-1}|a_1,\ldots,a_{n-2},\underline{\theta}) \\ &\quad \ldots p(a_2|a_1,\underline{\theta})\ p(a_1|\underline{\theta}) \quad , \qquad (6) \\ &= \prod_{i=1}^{n} f(a|\underline{\theta}) \quad , \end{aligned}$$

where $f(a|\underline{\Theta})$ is the distribution of deposit sizes from which discoveries are made.

As Kaufman (1974) points out, however, discoveries of mineral deposits do not follow a simple-random process. First, the total population of in situ deposits is finite; and second, larger deposits have a greater probability of being found than smaller ones. Once a deposit is found it is "removed" from those which might still be found, and thus sampling is "without replacement." This means that the order of discovery is important.

Kaufman assumes that deposits appear in the sample with probability proportional to the ratio of their size to the cumulative size of still undiscovered deposits. This is the probability relative to other deposits appearing, or the probability conditioned on a discovery. He also postulates that in situ deposits be considered a simple-random sample from some infinite super-population, $f_s(x|\underline{\theta})$, then infers values of the parameters of that distribution. Considering eq. (1) once again, this approach allows inferences on the distribution of the random variables x_i in the resource estimate, and also inferences about the sum of undiscovered sizes. It does not allow direct inferences of the in situ number, N.

While this procedure offers an approach to estimating total resources, it does not make use of all available information, and does not yield spatial characteristics which might be used in optimizing future exploration strategies. However, it may be expanded to include the likelihood of numbers of deposits being discovered and the nonuniform geographic distribution of exploration, and thus to overcome these objections.

4.2.1 Spatial Dispersion Function

The spatial dispersion of mineral deposits is most often treated as a point process in two dimensions.[2] Parameters of the spatial dispersion model are then estimated by dividing the geographic region into quadrats and fitting curves to the distribution of numbers of deposits per quadrat.

Empirical data displays more clustering than the Poisson model would predict, thus other models have been considered and at present there seems to be widespread satisfaction with the negative binomial model (DeGeoffroy and Wu, 1970; Griffiths, 1966; Uhler and Bradley, 1970--other models are discussed in Rogers, 1974). Among the few criticisms of the negative binomial is that it tends to underestimate the frequency of quadrats with high numbers of deposits (Kaufman and Bradley, 1973; see Figure 3).

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[2] Kaufman and Bradley's (1973) random-walk simulation is one of the few exceptions.

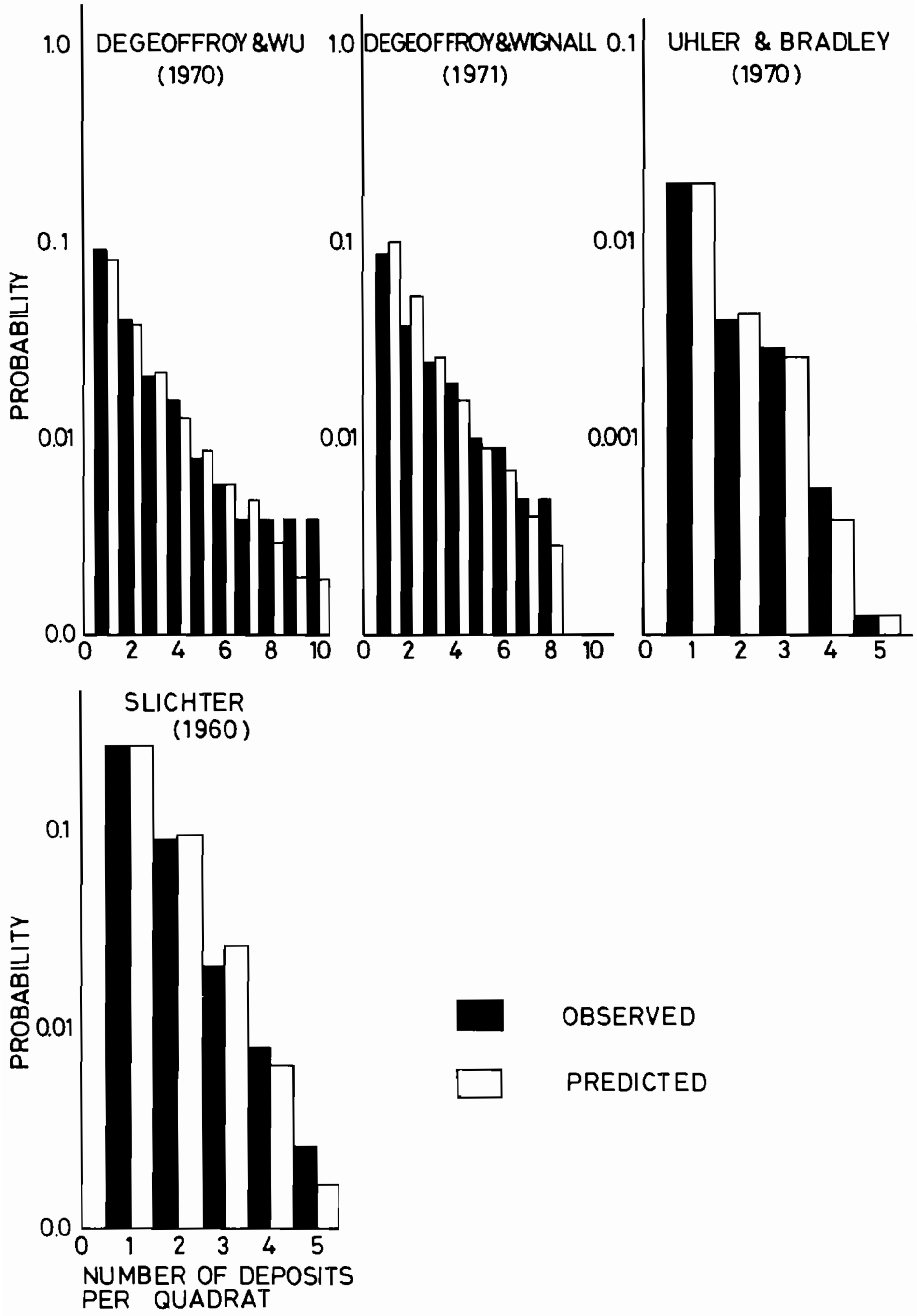

Figure 3. Fit of the negative binominal to empirical data.

Previous work typically assumes the number of known deposits per quadrat to be mutually independent samples from the spatial dispersion process; thus,

$$L(n_1,\dots,n_q|\underline{\Omega}_o) = \prod_{i=1}^{q} p_{nb}(n_i|\underline{\Omega}_o) \quad , \tag{7}$$

where q is the number of quadrats, n_i the number of known deposits in quadrat i, and $\underline{\Omega}$ the parameters of the spatial dispersion process (whose values are to be inferred). This procedure leads to results which are difficult to interpret for the following reasons:

1) Known numbers of deposits are not samples from the spatial process $p(N|\underline{\Omega})$ but are lower bounds on the actual number in a quadrat.

2) If the analysis is restricted to intensively explored quadrats, which would yield truer samples of $p(n|\underline{\Omega})$, the sample of quadrats is biased toward greater density (that is, the most intensively explored quadrats are also the ones with the most extensive mineralization or deposition).

3) If very sparsely explored quadrats are included, the sample is biased toward low numbers per quadrat; the probability of discovering in situ deposits in these quadrats is small.

This approach clearly leads to incorrect estimates.

4.2.2 Search Effort

The number of deposits found in exploration obviously depends on the amount and spatial allocation of search effort. If this effort is nonuniformly distributed geographically, then the probability of discovery is nonuniform also. Although this principle is intuitively clear, it may explain certain anomalies in resource modelling, and may lead to mitigation of the three objections just mentioned.

Assume temporarily that deposits were actually dispersed according to a negative binomial process. Then let one deposit be found in some quadrat, c, as shown in Figure 4. As deposit locations are positively correlated, this increases the favorability of quadrat c for containing additional deposits. That is, the probability of c containing at least one more deposit is increased from 0.19 to 0.52 (using DeGeoffroy and Wu's parameters). Therefore, an optimal exploration strategy would be to allocate more effort to exploring quadrat c than other quadrats. Since this process feeds back upon itself as more discoveries are made, high n quadrats appear in observations with probability disproportionately higher than their frequency

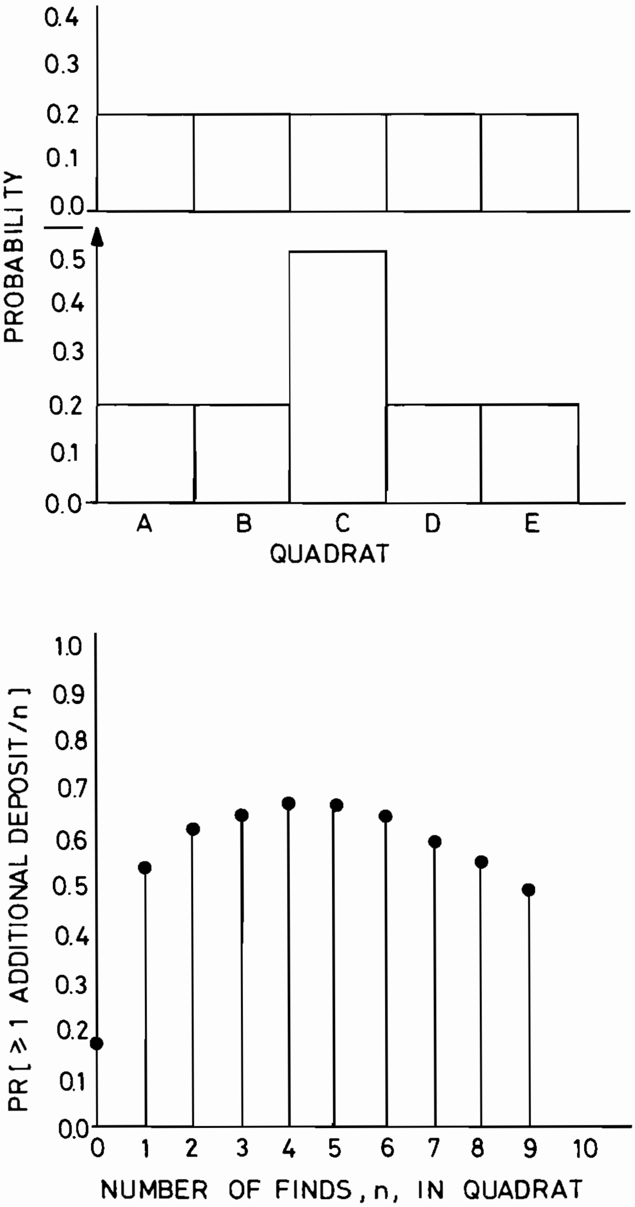

Figure 4. Probabilities of ≥ 1 additional deposit conditioned on discoveries--negative binomial distribution, data after DeGeoffroy and Wu, 1970.

in situ. Thus the objection of Kaufman and Bradley may only reflect nonuniform exploration.

Returning to eq. (7), one sees that the likelihood is not merely the spatial dispersion model, but must be modified by the probability of finding in situ deposits. We will call this latter relation the detection function. The detection function has the property that when there is no exploration effort ($\psi = 0$) the probability of a discovery is zero ($p(n = 0) = 1.0$), and as $\psi \to \infty$, $p(n = N) \to 1.0$). Here n and N are the number of discovered deposits and the total number of in situ deposits, respectively. So, as is intuitively clear, the probability of discovering deposits within a quadrat depends on the number of deposits present and the effort exerted to find them.

4.2.3 Form of the Detection Function

While the detection function begins at zero and reaches an asymptote of 1.0, its exact form depends on the strategy of allocating search effort and the distribution of deposit sizes.

Consider a quadrat of area A which contains a single deposit of area a. If ψ units of search effort are randomly allocated to points within the quadrat, the probability of finding the deposit is (see Figure 5).

$$\begin{aligned} \Pr(\text{find}\,|\,\psi) &= 1 - (1 - a/A)^{\psi} \\ &\simeq 1 - e^{-\psi(a/A)} \qquad a/A < 0.1 \quad . \end{aligned} \tag{8}$$

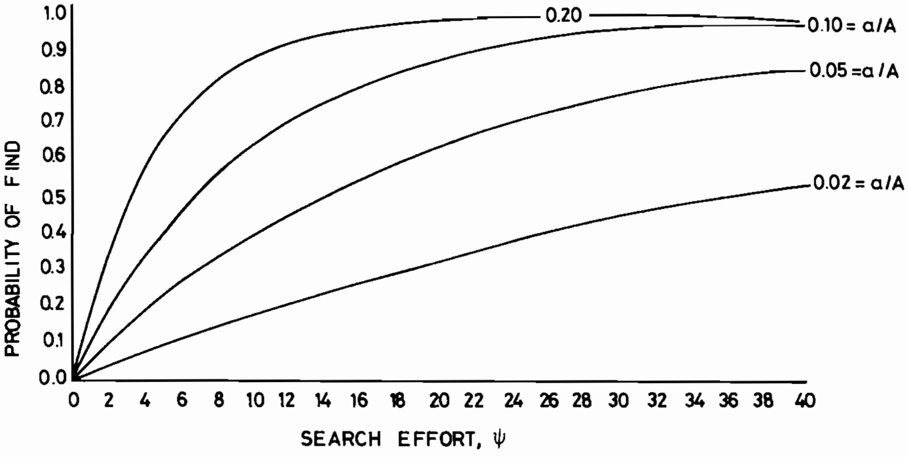

Figure 5. Random search.

If a systematic allocation is used (that is, a grid), then p(find) depends both on the target and grid geometries, as illustrated in Figures 6a to 6d. Similar curves can be generated for other systematic allocations (for example, geophysical methods) or for "optimal search" when prior locations probabilities can be specified (Morse, 1974).

Without detailed information on the way exploration has been conducted, there is no way to precisely reconstruct the detection function. Therefore, in making resource estimates we must make assumptions on its shape. On the one hand, exploration may be viewed as the uncoordinated effort of many separate decision makers. If this is so, then a random model seems appropriate. On the other hand, exploration may be carried out by one decision maker as in the case of a government ministry or large corporation. Were this so, then a purely systematic model might be appropriate. Both are crude approximations, but perhaps satisfactory first attempts.

Both random and grid search can be approximated by an exponential detection function of the form[3]

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[3] Ryan's (1973a, 1973b) deterministic model of discovery within a play are of this form, though he does not directly treat it as a detection function. In his model cumulative-newfield-wildcats is used as a measure of ψ, and he introduces a constant multiplied by ψ to account for "geological knowledge." To find the regional resources he equates rate of new discoveries to the product of resource and detection function:

$$R = U_\infty \left[1 - e^{-\beta k w}\right] ,$$

where

R = rate of discovery,

U_∞ = total resource,

β, k = constants,

w = cumulative new wildcats.

This deterministic model closely fits empirical rates of discovery within individual plays, and thus adds credibility to the random exploration model. However, his equation has three adjustable parameters and thus is flexible.

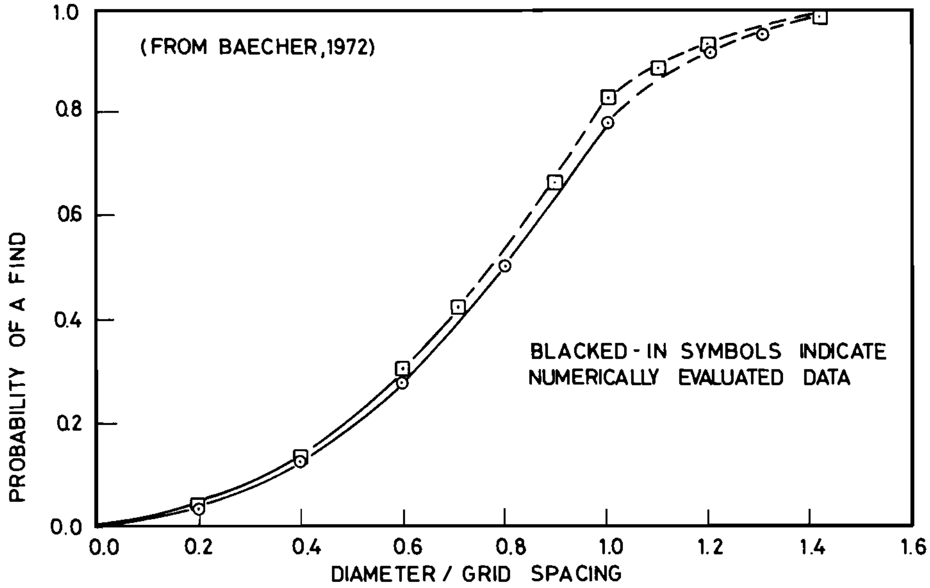

Figure 6a. Probability of finding circular and square bodies with square point grid (effort proportional to (grid spacing)$^{-2}$).

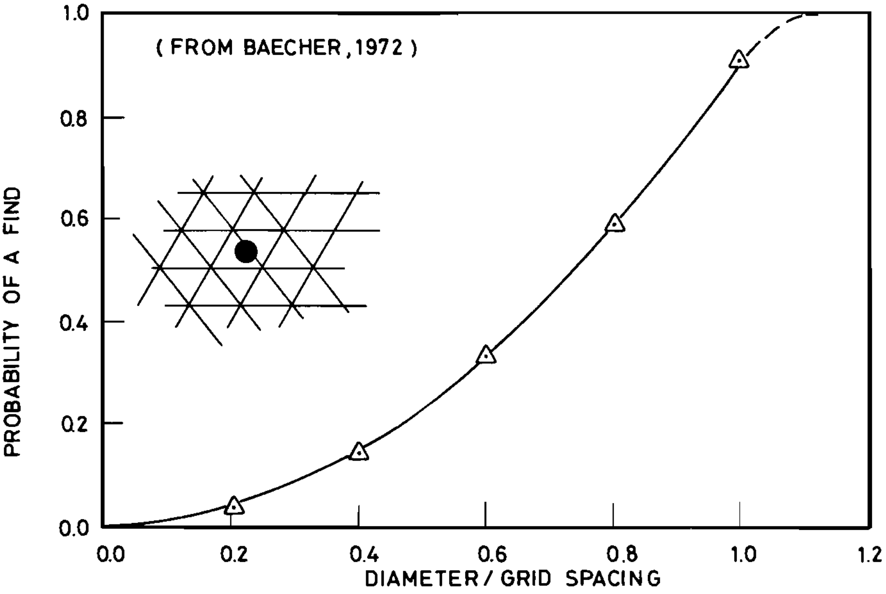

Figure 6b. Probability of finding body with triangular point grid.

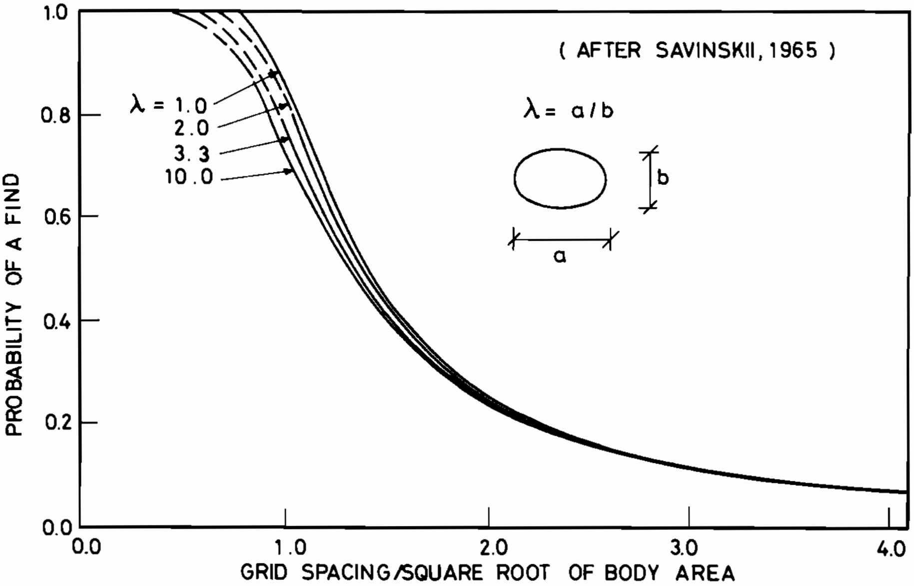

Figure 6c. Probability of finding elliptical bodies with square point grids.

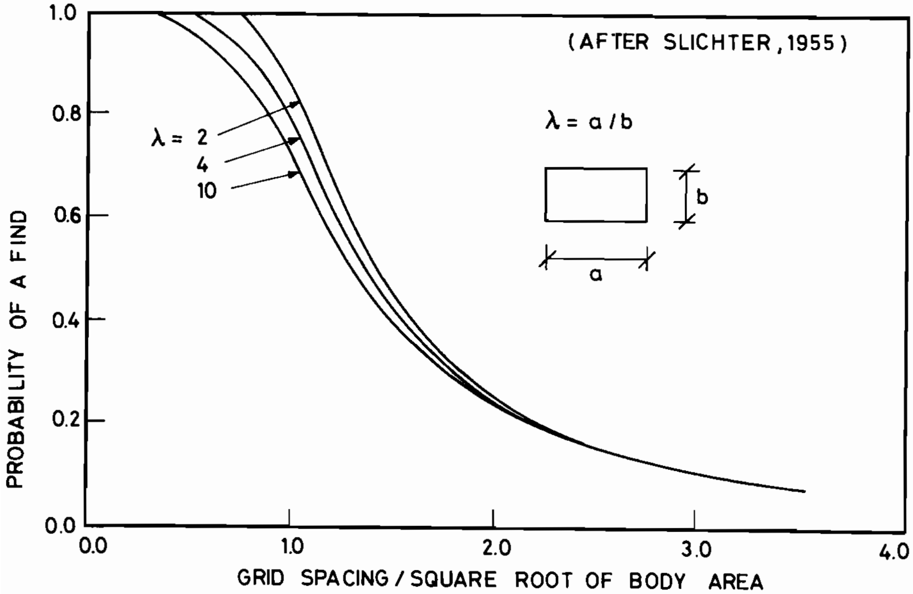

Figure 6d. Probability of finding rectangular body with square point grid.

$$p(\text{find}|\psi,a) = 1 - e^{-k\psi a/A} \quad , \tag{9}$$

in which k is a constant. This can be modified for uncertainty in deposit size in the normal way,

$$p(\text{find}|\psi,\underline{\Theta}) = \int_a p(\text{find}|\psi,a)\ f(a|\underline{\Theta})\ da \quad . \tag{10}$$

To form the likelihood function for inferring values of the spatial parameters, $\underline{\Omega}$, the number of discoveries must be related to the number of in situ deposits by an equation of the form

$$p(n|\psi,\Omega) = \sum_N p(n|N,\psi)\ p(N|\psi) \quad . \tag{11}$$

Here, $p(n|N,\psi)$ is a modification of the detection function to account for multiple deposits, and $p(N|\underline{\Omega})$ is the spatial dispersion process. Unfortunately, $p(n|N,\psi)$ is not a simple relationship,

Let n deposits be found in a particular quadrat in the order

$$a_1,\ a_2,\ldots,a_n \quad ,$$

with

$$\psi_1,\ \psi_2,\ldots,\psi_n$$

increments of exploration effort, respectively. Given that the first j-1 of these have been found, the probability of finding the j^{th} with one additional quantum of effort is

$$p(\text{find}|a_1,\ldots,a_{j-1},\psi=1) = p_j = \frac{\sum_{i=j}^{n} a_i - \sum_{i=n}^{N} a_i}{A - \sum_{i=1}^{j-1} a_i} \tag{12}$$

and the probability of having discovered the j^{th} deposit with the increment of effort, ψ_j, is

$$p(a_j|a_1,\ldots,a_{j-1},\underline{\theta},N) = \text{Pr (find on }_j\text{th quantum)}$$
$$\times\ \text{Pr}(a_j\text{ find}) \times f(a_j|\underline{\theta}) \quad ,$$

$$= \exp\{-k\psi_j p_j\} p_j \frac{a_j}{\sum\limits_{i=j}^{n} a_i + \sum\limits_{i=n}^{N} a_i} \quad f(a_j|\underline{\theta}) \quad P_n^N \quad . \tag{13}$$

As N is a random variable with parameters $\underline{\Omega}$, this becomes

$$p(a_j|a_1,\ldots,a_{j-1},\underline{\theta},\underline{\Omega}) =$$

$$\sum_N \exp\{-k\psi_j p_j\} p_j \frac{a_j}{\sum\limits_{i=j}^{n} a_i + \sum\limits_{i=n}^{N} a_i} f(a_j|\underline{\theta}) \; p(N|\underline{\Omega}) \; P_n^N \quad , \tag{14}$$

in which the term $S = \sum\limits_{i=n}^{N} a_i$, the sum of undiscovered deposits, is an uncertain quantity depending both on $\underline{\theta}$ and $\underline{\Omega}$. The likelihood of discoveries then is

$$L(a_1,\ldots,a_n|\underline{\theta},\underline{\Omega}) =$$

$$\sum_{j=1}^{n} \int_S \sum_N \exp\{-k\psi_j p_j\} p_j \frac{a_j}{\sum\limits_{i=j}^{N} a_i + S} f(a_j|\underline{\theta})$$

$$\times \quad p(n|\underline{\Omega}) \; f(S|\underline{\theta},\underline{\Omega}) \; P_n^N \, dS \quad . \tag{15}$$

Clearly, this equation is difficult to deal with, although as Kaufman has done, this might be approached by Monte Carlo simulation. It does account for exploration effort, however, and conceptually at least allows inferences to be drawn about the spatial dispersion of deposits.

The point of this short discussion is that inferences about the number of deposits in a quadrat or region (and thus about their spatial dispersion and the total amount of resources) must account for how and how hard they were looked for.

Further, inferences about spatial dispersion are not independent of inferences about size distribution; the simple-random sampling model is not satisfactory for this purpose.

5. CONCLUSIONS

This paper has discussed the place of sampling approaches to resource estimation in a broad context, and it has attempted to indicate that sampling approaches could lead to a more comprehensive analysis than is currently employed. Specifically, discussion has concentrated on three points about exploration and inferences drawn from it:

1) Geological exploration is fundamentally and necessarily a subjective undertaking; prior judgment of geologists based on findings in other regions and on concepts of geological processes must be included.

2) The analytical methods for including geological opinion from multiple experts must be theoretically rigorous and reflect current knowledge of probability assessment, judgmental biases, and subjective information processing.

3) The procedure used for modifying prior opinion by the local results of exploration should include consideration of exploration effort and its allocation through some detection function.

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SOME MODELS FOR LONG-TERM FORECASTING OF RAW MATERIAL PROVISIONS FOR OIL AND GAS PRODUCTION

M. Sh. Modelevsky and I. Ya. Fainstein

The development of oil and gas production in practically any country of the world is controlled by two basic groups of factors: the first group is connected with the growth of petroleum demand, the second group with the natural possibilities of meeting this demand. Explored (proved recoverable) reserves provide the highest reliable raw material basis for oil and gas production. Gas production continually represents an explored part of the total quantity of ultimate original potential resources (UPR).[1] In this manner, petroleum resources, reserves and production make up a complicated, stochastic, interconnected, geological-economic (natural-artificial) system. The input to this system includes the global geological, geochemical and geophysical processes of formation and accumulation of petroleum-in-place resources; the output to this system includes the processes of extracting commercial quantities of these minerals from the earth to meet the demands of man. It is through oil and gas consumption that this system is included in the total fuel-energy complex.

Figure 1 elaborates the conversion of petroleum UPR into proved reserves. It outlines the phasic development of exploratory works for oil and gas adopted in the USSR, and it also gives the structure of a "resources-reserves-production" (RRP) system and how it relates to the fuel-energy complex.

At any given moment in time the geological possibilities of producing oil or gas in a district (basin) are controlled by the value of the relationship between current (remaining) proved recoverable reserves as of the beginning of the year and the reserves to production ratio (RPR) reached that year (provision for production with proved reserves). The value of current proved reserves is dependent upon the degree of exploration for ultimate potential resources and the degree of extraction (cumulative production) for explored reserves (see Modelevskii, 1973; Ostryi and Poteriaeva, 1967; Hubbert, 1967).

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[1] In this paper only the recoverable part of these resources is considered.

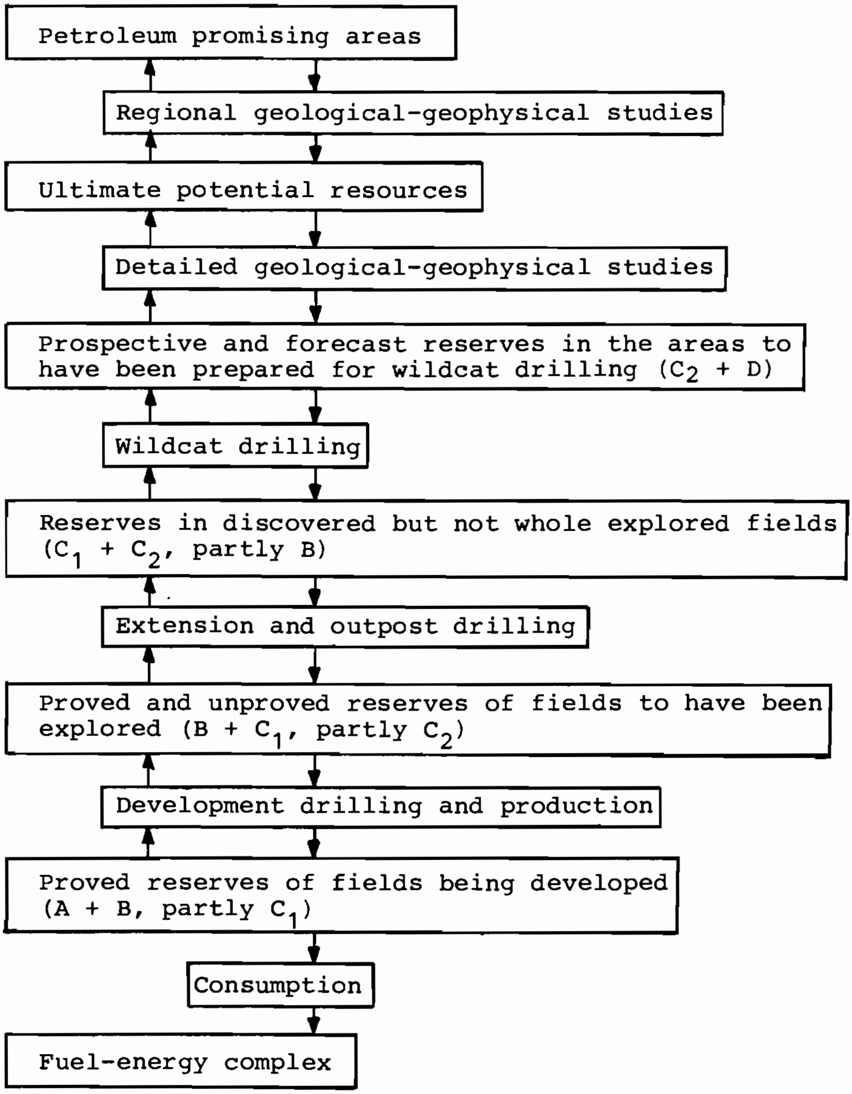

Figure 1. Outline of a functioning of RRP system and its links to the fuel-energy complex.

The coefficient of the degree of exploration for ultimate potential petroleum resources, K_1, is determined by the relationship between original explored reserves, R_o (current proved reserves R_c plus cumulative production), for the year being forecast and the ultimate potential resources, UPR:

$$K_1 = \frac{R_o}{UPR} \tag{1}$$

$$R_c = K_2 \cdot R_o \tag{2}$$

where K_2 is a coefficient of the nonutilization of the original explored reserves, the nonutilization being a function of the cumulative production value for the year being forecast (the less this coefficient value, so much, consequently, the more the original explored reserves are drawn up and utilized, and the less the degree of their temporary "immobilization").

It is possible to express the value of current proved reserves as of the date being forecast with the help of these two coefficients as a particular part of the ultimate potential resources:

$$R_c = UPR \cdot K_1 \cdot K_2 \quad . \tag{3}$$

Then the annual oil and gas production P as of the date being forecast with due regard for expected RPR (K_3), also as of this date, is expressed as:

$$P = \frac{UPR \cdot K_1 \cdot K_2}{K_3} \quad . \tag{4}$$

The rate of changing the degree of exploration for ultimate potential resources (the growth rate of K_1) depends on several conditions, geological, technical and economic. Various conditions in different areas should also have different influences: in some areas the depth of occurrence for oil and gas or the complexity of a pool structure may be the controlling factors. In other areas--remoteness from the market centres, the availability of consumers, cost indices, etc. may be the controlling factors.

However, time is thought to be the common positive index for all of these factors: the demand for oil and gas is constantly growing; drilling and transport possibilities increase; and the constant growth of costs for oil and gas makes it possible to develop oil fields that are economically profitable even under conditions which recently appeared to impede production development.

Figure 2 shows what happens when we change the degree of exploration of ultimate potential oil resources in a number of countries and districts as the period of intensive exploration, which usually comes after the first commercial fields have been discovered, increases. Changing the degree of exploration of the UPR of every country or district in due time is graphically characterized by sets of curves. Processing these data with the aid of the computer "Nairy-2" has revealed that five approximating curves can be singled out.

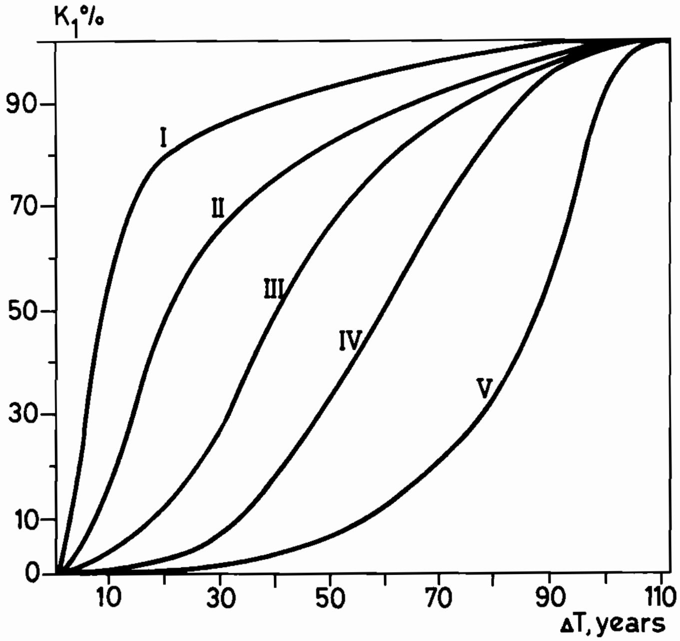

Figure 2. Changing the coefficient of the degree of exploration of the ultimate potential oil resources (K_1) as duration of exploration period (T) increases.

The curves differ from one another by the degree of elevation steepness, that is, by the time required to reach the same coefficient values of the degree of exploration of the UPR. In some cases the degree of exploration of these resources built up slowly during a long period of time, and then increased swiftly for a rather short period (curves IV and V). In other cases, on the contrary, the growth rate of the degree of exploration for resources was very high from the very beginning of oil field exploration, but then fell (curve I). In a third instance, changing the degree of exploration with time is of intervening character (curves II and III).

Curves IV and V characterize the dynamics of the coefficient of the degree of exploration of the UPR in the old oil-producing areas in which exploration and development of the oil fields started before 1920; these include, for example, Texas (on land), Oklahoma, California, Indonesia and so on. The degree of exploration of the UPR in these areas increased slowly over 50 to 60 years after the first oil fields were brought into production, and for the whole of this period it scarcely reached 10% to 12%. Only since the 1930's-1940's and especially since World War II have we noticed the beginning of sharp growth of the rates for the industrial exploitation of potential oil resources. These rates have increased 18 to 20 times compared to the preceding period. By 1973 in most areas they reached 50% to 70% and, in some areas (Oklahoma, Kansas), 98% to 99%.

Curve I characterizes dynamics of the coefficient of the degree of exploration of UPR in the youngest oil-producing areas of the world, in which the first large oil fields were brought into production after 1945, for example, Libya, Algeria, Nigeria, Cook-Inlet, the North Sea, Abu-Dhabi, Dubayy and so on.

The fact is that in these areas during the 10 to 15 years of exploration and oil production development the same degree of exploration was reached as that achieved in 60 to 100 years in the old areas. However, later on, as the stock of the most easily explored anticlinal traps was exhausted, the previously increasing rate of UPR exploration had to fall more and more. To reveal the remaining 10% to 15% of the oil resources in the present "young" areas a period of 40 to 60 years seems to be necessary unless scientific-technical progress can significantly increase the prospecting and exploration effectiveness for non-structural traps.

Curves II and III characterize dynamics of the degree of exploration of UPR in the areas which were brought into production mainly in the period between 1920 and 1945, for example, Mississippi and Alabama, Saudi Arabia, Bahrain, Iraq and so on. The exploration rates for oil resources in these "medium in age" areas are intermediate, between the rates which characterize this process in "old" and "young" areas.

We do not need to go into an analysis of the reasons which have led to indicated differences in the exploration rates for ultimate potential oil resources in various regions of the world (the main differences, in our opinion, were changes in the demand for oil, the technical possibilities for drilling, the growth of intranational and international oil transport, the value and peculiarities of resource distribution). However, we must point out that relationships that have been obtained (of a graphical or analytical kind) are to be considered as a model when changing the degree of exploration for these resources as the development of oil production proceeds. This model may be used to forecast a probable K_1 value for some data in the future.

One should plot a curve $K_1 = f(T)$, impose it on a diagram, choose the most suitable type of approximating curve and calculate probable K_1 values as of the required dates being forecast for in the areas with a developed oil-producing industry. For the areas where there are oil resources that have been explored already but whose commercial production has not been started yet, one should orient oneself towards a probable oil field development starting date, and calculate the possible rate of changing the degree of exploration for resources with curve I or close to it. For areas where only evaluations of oil resources are available, but no fields have been discovered, and where beginning dates for intensive prospecting operations appear to be unclear, the forecast for changing the degree of exploration for resources has become uncertain.

Three principal groups of areas are to be singled out regarding the dynamics of relations between current proved and original explored oil reserves (see Figure 3). The nature of the changing K_2 value as the degree of exploration for UPR in these areas proceeds to increase is also described by curves of the second and third orders. For "old" oil-producing areas the approximating curve is extremely steep having an intensive change of values on both axes of coordinates. At the beginning the rate of decreasing K_2 values outruns the growth of K_1 values, but then the rates of changing both indices are practically equal and, after the degree of exploration for resources has reached 60% to 70%, the curve is smoothed considerably. This takes account of the relationships between reserves growth and oil production in the above areas. The increase of explored reserves already there for a long period of time is commensurate with the oil production increase or even lower; in connection with this, the value of the cumulative production, increasing every year, at first was commensurate with the value of current oil reserves but later began to exceed it.

The dynamics of relationships between current proved and original explored oil reserves in most of the "young" oil-producing areas are characterized quite differently. Here, growth of new oil reserves at first considerably pass production increases as the degree of exploration for its UPR proceeds to increase. In connection with it, the coefficient K_2 value decreases slowly during a rather long period of time. It is not until the degree of exploration for resources has reached 50% to 70% that a drastic decrease of this index starts. This indicates that during this period an increase of new reserves becomes stable or decreases, but oil production continues to build intensively. With a K_1 value equal to 85%, the curve has to begin to smooth again taking account of a significant slowing down in the growth rates as well as in oil production. K_2 values for these areas have to approach K_2 values for "old" areas having the same degree of exploration for their resources.

The group of areas, mainly "medium" but also including some "old", is characterized by intermediate curves of K_2 dynamics. The approximating curve for this group of areas combines altogether with the curve for "old" areas with the values of the coefficient of the degree of exploration for the UPR equal to 80%.

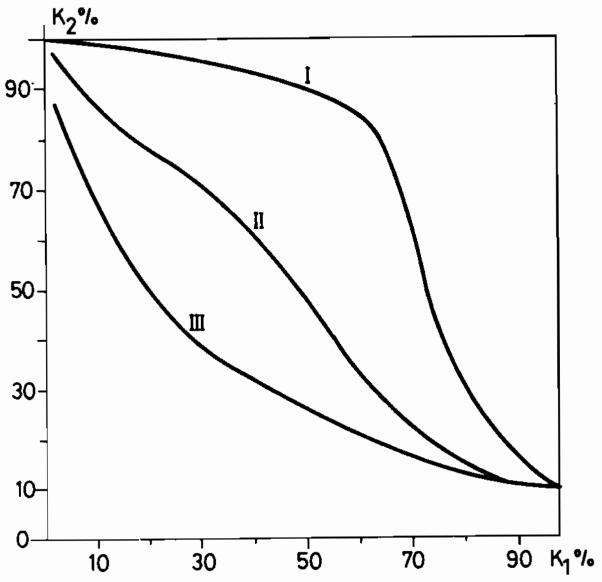

Figure 3. Changing the coefficient of nonutilization of the initial explored oil reserves (K_2) as the coefficient of the degree of exploration for its potential reserves (K_1) increases.

The curves which characterize a connection between the degree of exploration for the UPR and the correlation of current proved and original explored reserves are to have been attained, and are to be used for forecasting the probable levels of current reserves, of one or another year, as a function of the degree of exploration for the UPR for the same years defined previously by Figure 2. According to available actual data for every area one may use the approximating curve or the curves plotted with due regard for the particular data.

No less typical is the difference in the nature of the changing reserves-production ratio (RPR) seen as the degree of exploration of the ultimate potential resources changes (see Figure 4). This can be seen for a number of countries of the Middle East for the significantly variable nature of K_3 curves describing the dynamics of this index for "young", "medium" and "old" areas. Though in all the cases the K_3 value decreases intensively as K_1 proceeds to grow. In the first group of areas provision for production of explored reserves is kept at a rather high level (more than 50 times) up to a 70% degree of exploration for potential resources whereupon it regularly decreases, having reached a multiple of approximately 10 to 12 times by the end of the area exploration.

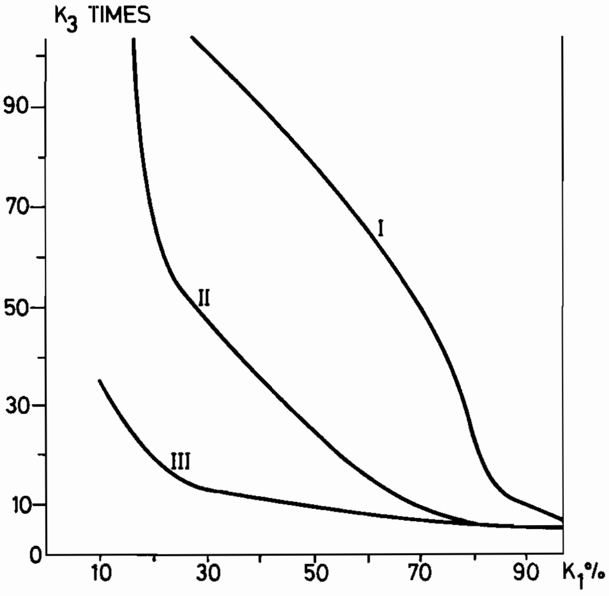

Figure 4. Changing the oil RRP (K_3) as the coefficient of the degree of exploration for oil ultimate potential reserves (K_1) grows.

In the second group of areas the rate of the decreasing K_3 value is higher: with the degree of exploration for UPR on the order of 70%, the curve reaches the level of 7 to 8 times. For the areas of the third group a still swifter K_3 value decrease is typical, as a whole, reaching a multiple of 7 to 8 times--even with the degree of exploration equal to 30% to 40%.

For most of the rest of the market economy and developing countries these differences seem to be less marked. Typically, we notice a total, rather intensive, decrease of RPR already at the first stages of exploration of areas and then a prolonged maintenance of this index at a relatively constant and considerably low level.

By these means it is believed that for the conditions of the market economy and developing countries the RPR for oil, which provides a sufficiently stable production growth, accounts for 15 to 25 times, but comparatively prolonged stabilization of production has produced 10 to 12 times.

Using relationships described above, one is able to calculate from equation (4) the maximum possible (from geological and partly economic positions) level of oil production for any period forecast. Having correlated obtained results with the contemplated valuations of the growth of oil demand, the technical and economic possibilities for the development of oil production in a given area, scientific-technical progress in drilling and production, changing world costs for oil, possibilities of transport, the oil market and so on, one is able to make this a complex forecast, that is, better grounded.

Values of coefficients entering equation (4) can be taken from the corresponding curves in Figures 2 to 4. Having calculated averaged values for these coefficients for three main groups of areas considered, it is possible to plot a summary theoretical model of changing the annual withdrawal of ultimate potential oil resources (ratio between annual production and total value of recoverable potential resources) as the degree of exploration increases (Figure 5). This model is rather close to the actual data concerning changing the coefficient of the yearly utilization of potential oil resources (K_4) for the areas considered. It is seen from Figure 5 that up to the degree of exploration for resources on the order of 40% the dynamics of the K_4 curve are approximately equal for all the groups of areas. However, in "old" and "medium" areas the growth rate of this index begins to decrease earlier and it reaches its maximum with a lower degree of exploration for resources than in "young" areas. The absolute value of this maximum is also lower. In "old" and "medium" areas the maximum of the annual oil production accounts for approximately 2% to 2.3% of the UPR and it is reached with a degree of exploration for resources of about 65% (and in some of the old areas, possessing, moreover, relatively small resources, only 1.4% to 1.5% with K_1 values on the order of 45%). In the areas not labeled as "young", the maximum oil production has been reached. However, judging by the nature of the curve I in Figure 5 the annual oil production will account for 3% to 3.3% of the UPR with the degree of exploration for the latter equal to 70% to 75%.

By these means, for the period of the maximum level of oil production, equation (1) acquires the form:

$$P_{max} = (0.02 - 0.03)\ \mathrm{UPR} \quad . \tag{5}$$

It is advisable to use equation (5) to determine the upper limit of the probable level of oil production in a country or an area in those cases where one is short of data to perform better grounded forecasts for particular periods or dates, as well as to carry out comparative valuations of "production possibilities" of individual countries and areas (for example, while accomplishing comparative evaluations of a probable role of particular countries and areas in the total production of a region).

Analogous studies have been carried out as applied to the natural gas resources. The key design of all the cases remains the same as for oil.

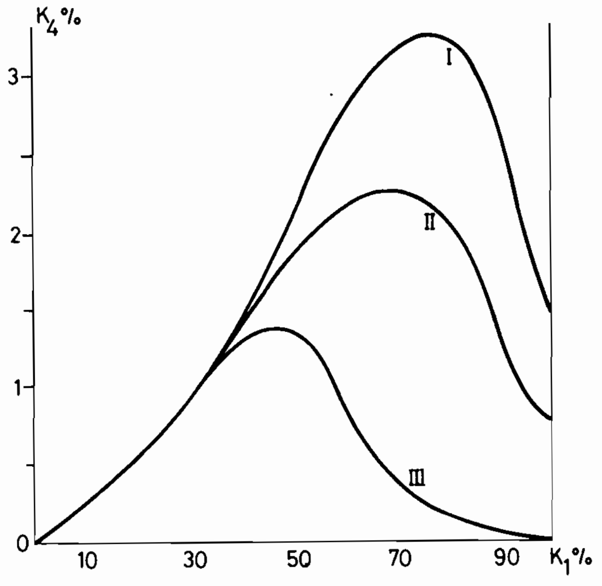

Figure 5. Changing the coefficient of the annual use of the oil UPR (K_4) as a coefficient of the degree of exploration for UPR (K_1) increases.

The method of the enlarged forecast of the resources-reserves-production system (RRP system) outlined above gives a general idea of an order of possible values of basic indices for raw material provisions for petroleum production. Together with the results of such large-scale forecasts for oil or gas consumption this overall valuation of raw material possibilities, as a whole, can be considered as a limiting level for the development of a national RRP system. In these cases, when forecasts have to be more specific, that is they refer not to a country but to a smaller object, it is necessary to keep in mind peculiarities of the structure and distribution of pools in individual areas and possible ways and times to carry out exploratory operations. Such a forecast requires distinct formalization of the geological notions and processes connected with the functioning of the natural-artificial system under consideration.

A considerable number of promising areas can be found within the limits of the area with proved or expected gas and oil bearing capacity. It is possible to determine their probable total amount on the basis of comparative geological analysis with the areas to have been studied effectively. Quantity and depth of wells and their distribution is to be considered constant for a given area. The exploration results in two events: 1) the field has not been discovered; 2) the field has been revealed. The latter result may have a multitude of variations depending on reserves of the field discovered, which variations are not equivalent from the point of view of exploration tasks. From the total number of areas to be drilled only some of them will contain oil or gas fields. To this, it is admitted that the selection of an area for wildcat drilling is accidental and, for a limited time period, the location of areas being searched for oil fields has no importance. Consequently, all the areas inside a promising area being explored are equivalent; that is, probability of success under a single test is considered to be constant, numerically equal to a "coefficient of commercial discoveries".

In this case discovery of a commercial field is to be looked upon as a coincidence of two accidental events: 1) discovery of an oil or gas field in general, 2) discovery of an oil or gas field with a commercial quantity of reserves (on the condition that the first event has already taken place). The probability of revealing such a field is determined by the product of probabilities of both events, but the probability of obtaining the prescribed reserves increase throughout the area, as a whole, is to be calculated from the equation of total probability (1).

$$P(Q \geq Z) = \sum_{M=1}^{N} C_N^M P^M (1 - P)^{N-M} \cdot \sum_{i=0}^{M-1} \frac{(Xm)e^{i-Xm}}{i!} \qquad (6)$$

where $P(Q \geq Z)$ is the probability of the fact that an increase of proved reserves throughout area Q will not be less than the prescribed increase Z; and

$$C_N^M = \frac{N!}{M!\ (N - M)!}$$

is the number of combinations of M elements from N ones where

N is the number of promising areas in an area being subjected to exploratory drilling;

M is the number of commercial oil or gas fields which are to be discovered in the area;

P is the coefficient of commercial discoveries; and

$$X_M = \frac{Z - M \cdot q\ \min}{\delta}$$

where

q min is the minimum value of the commercial reserves of one field, which seem to be economically payable to develop in a given area;

δ is the average excess of proved reserves of one field in a given area over value q min;

e is the basis of the natural logarithm.

In equation (6) the first sum represents the probability of discovery in a given area of M commercial fields under exploration in N promising areas. The second sum is the probability of obtaining in a given area a definite increase of reserves at the expense of discovery of M commercial fields (with reserves not less than q min) under exploration of N areas.

Calculations with the help of this stochastic model have been carried out by means of a specially worked out program the "BESM-4" computer. A geologically well studied area is taken as an example of a conventional gas-bearing area with the following initial indices: $p = 0.2$; q min = 10 billion m^3; δ = 12 billion m^3. Values N and M were chosen in different combinations (see Table 1).

Experimental stochastic characteristics of the RRP system of this conventional gas-bearing area across a horizontal line characterize the probability of an increase of proved gas reserves with the same (equal) number of areas being drilled; that is, with an equal volume (or intensity) of exploratory operations.

Across the vertical line they represent the probability of obtaining the expected increase of reserves under different volumes of these works (see Hubbert, 1967).

Obtained data make it possible to draw quite definite conclusions about necessary relationships between the increase of proved reserves being forecast and exploratory operations required for these volumes. So, from the data indicated in Table 1 it follows that an increase of proved reserves of natural gas accounting for 500 billion m^3 is ensured with rather high reliability (probability not less than 0.9) on the condition that not less than 150 promising areas have been drilled. If only 100 areas are drilled, the probability of obtaining such an increase of reserves will decrease by up to one-third.

The suggested method controls the probability of transference of potential resources into proved reserves depending on the number of promising areas introduced into exploratory drilling. Table 1 can be transformed quite easily into a probable matrix of volumes of exploratory operations and expenditures for their accomplishment. Thus, the method is to be used also to forecast capital investments necessary to develop a certain volume of proved oil or gas reserves with an expected level of probability (reliability).

Comparison of such estimated probable expenditures for exploratory operations with limited permissible (for economic reasons) values for these expenditures ascertained by optimization calculations in the fuel-energy complex, as a whole, will make it possible to choose objects of exploration more efficiently and economically within the limits of promising territories.

Table 1. Probability characteristics of the RRP system of a conventional gas-bearing area.

Number of promising areas in exploratory drilling	Expected increase of proved gas reserves, billion m^3												
	100	150	200	250	300	400	500	600	700	800	1,000	2,000	3,000
	Probability of obtaining the expected increase												
25	0.51	0.20	0.06	0.01	0	0	0	0	0	0	0	0	0
50	0.96	0.82	0.66	0.33	0.09	0.01	0	0	0	0	0	0	0
75	1	0.98	0.92	0.82	0.60	0.21	0.05	0	0	0	0	0	0
100	1	1	0.99	0.98	0.89	0.68	0.32	0.07	0	0	0	0	0
150	1	1	1	1	1	0.98	0.90	0.57	0.33	0.16	0	0	0
200	1	1	1	1	1	1	1	0.98	0.88	0.76	0.14	0	0
250	1	1	1	1	1	1	1	1	0.98	0.95	0.70	0	0
300	1	1	1	1	1	1	1	1	1	1	0.97	0	0
400	1	1	1	1	1	1	1	1	1	1	1	0	0
500	1	1	1	1	1	1	1	1	1	1	1	0.85	0.01

In this case, the suggested stochastic, chiefly geological model can be transformed into a model for the optimum functioning of the RRP system on the basis of which particular decisions are to be accepted regarding prospective development of the raw material basis for petroleum production. It is advisable to apply this model while performing prospective planning for a period of 10 to 15 years. It is also good practice to utilize it for "reserve control" of a large-scale forecast.

Strictly speaking, to obtain probable characteristics of the RRP system regarding every area, it is necessary before hand to find regularities in the distribution of different fields in this area according to the volume of reserves. It is a rather labour-consuming operation to select and process proper data which in some cases are difficult to obtain, and sometimes it is even impossible. However, for practical purposes one may assume a hypothesis about the overall normal character of the distribution of oil or gas fields in accordance with their importance; that is, with an increasing N number of promising areas in exploratory drilling, the distribution of the sum of reserves increases at the expense of the discovery of M fields in conformity with the central maximum theorem which approaches normal. This significantly simplifies all the calculations (the function of normal law has been tabulated; standard programs on normal law are available in the software of computers of all types and classes; the volume of necessary initial information is cut down; it becomes possible to consider areas with non-uniform geological conditions of oil and gas bearing capacity).

An experimental test of the degree of conformity of actual field distributions for reserves according to the normal law in a number of gas-bearing areas of the USSR has revealed that the maximum deviations of probable valuations do not exceed 6% with a noticeable decrease in the growth of areas drilled (see Hubbert, 1967).

It is extremely promising that there seems to be a method permitting the complete abandonment of any assumptions (a priori or a posteriori) about the kind of theoretical distributions of fields according to their importance. The question, instead, is about the probability determination of the expected increase of proved oil or gas reserves with a prescribed volume of exploratory operations (or capital investments) designed by a stochastic simulator of a functioning RRP system by applying "statistic tests" (Monte Carlo method).

The authors of this paper hope to obtain the first results of their research shortly for this new direction in probability studies of the raw material basis of petroleum production.

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DISCUSSION

Kaufman: I would like to ask King Hubbert if he can comment on the probability of error and the magnitude of errors in his well-known model.

Hubbert: My studies (see later) have had two principal objectives: to estimate certain critical data in the evolution of the US petroleum industry; and to estimate the amounts of oil and gas that will ultimately be recovered. With regard to the dates, in my 1962 report* the following dates were estimated:

- peak of proved reserves of US crude oil, 1962. (It occurred in 1962.)
- peak in crude oil production rate, 1967-1969. (The best mathematical curve for the data as of 1972 reached its peak in 1968; the actual peak production occurred in 1970).
- the peak date for proved reserves of natural gas was estimated to occur in 1969. (It actually occurred in 1967.)
- the peak in the production rate of natural gas was estimated to occur about 1976-1977. (It actually occurred in 1973.)

In 1962, the ultimate amount of crude oil to be produced in the conterminous states of the USA and adjacent continental shelves was estimated to be 170-175 billion barrels. In 1962, the estimate for the ultimate amount of natural gas to be produced in the lower 48 states was 960 to 1050 trillion cubic feet. By 1972, the corresponding estimate was 1000 to 1100 trillion cubic feet.

These figures will give at least a sense of the magnitude of the errors or of the precision of such estimates with regard to the critical dates. I know of no other estimate that comes

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*See "Energy Resources", National Academy of Sciences-National Research Council Publication 1000-D.

anywhere near this accuracy. Some have overestimated the date of peak production by as much as 30 years.

Khazzoom: Were your forecasts made without reference to prices? Pushed to its logical conclusion, are you really saying that no matter what happens to the price level, the peaking you forecast will continue to hold, and that we will be going downhill, regardless of the price level?

Hubbert: My analysis of US oil and gas discoveries has been based entirely on technological data, not monetary data. I have used such data as annual production; proved reserves; footage of exploration drilling. The use of such data has given results of remarkable accuracy.

Bauerschmidt: In your model of 1962 you did not include some areas for oil production: Alaska, off-shore, secondary, and tertiary methods. So, with your model, did you give a forecast for maximum US oil production or only for the 48 States excluding offshore production?

Hubbert: My detailed analysis of the US petroleum industry has been limited to the lower 48 States and adjacent continental shelves because these are the areas for which statistics are available. Alaska is a new territory, without a statistical record, and hence must be considered by other methods.

Odell: Mr. Baecher, what do you mean by a "region"?

Baecher: I mean something that can be assumed to have geologically homogeneous properties so that when you set up a probability model you can assume consistent probability density functions for certain aspects of the deposits you are after: size, spatial dispersion, etc.

Searl: Are the search models in two dimensions or three dimensions, thereby including depth?

Baecher: This, at present, is more an ideal than a model, so it is only two dimensional.

Hubbert: If exploration judgment is principally subjective, what is the point of doing geophysical surveys?

Baecher: What is the point of taking borings, too? When we have a conception of geology, we interpret our data in terms of the theories we have. Robinson, a few years ago, presented a very interesting short paper on how geological maps change with changes in geological theory. He clearly indicated with a set of maps--I believe they were from Canada--how drastically they can change as our judgmental conceptions of how geological processes work change. And so, no matter how we do exploration, we form hypotheses, judgmentally, and then we take a look at the data in the light of these.

Clarke: I would like to refer to the conception of geology we used, for instance, in allocating exploration for North Sea oil. The model we made was not about geological entities in space, it was about historical processes. We tried to see which parts of the North Sea might be interesting. From a suspicion we had, we tried to see from very little data where we might have accumulations in potential reservoir rock based entirely on process models in geology over a very long period of geological time. This is what determined current efforts of exploration. It had nothing to do with a collection of entities in space that have no temporal label attached to them.

Baecher: We carry all exploration programs on the basis of some preconception of where the things we are looking for might exist. If, before we start looking, we assume they could be anywhere, their probabilities are uniform. Now, if they are not, if on the basis of geological theory there are prior feelings about where they might lie not being uniform, we do not use a model that assumes uniformity of their distribution. And there are such other models. But clearly I am not trying to say that these models answer all problems in exploration. There is a major theory of search that applies to situations in which location probabilities are a priori nonuniform, and I do not see how the situation you described would not fit within that kind of framework, although you generate those a priori probabilities where they might lie on the basis of geological theory.

Odell: Clarke's feeling for the temporal process has been at work in determining the general location for the current hydrocarbons. In fact, this is the very base on which this model is presented. The fact that there have been temporal processes at work implies spatial distribution. You, as an oil geologist, and your colleagues cannot go out to exactly where there is some process of this kind. Some idea, some model working within the framework of the knowledge of the temporal process is the kind of approach that may lead to a reduction in the degree of exploration. At least, one would hope that would be the end result of the further out-working of this kind of model development. I do not see any conflict between the two approaches--they seem to be perfectly complementary.

Bowie: If the geological distribution is not uniform, and I think there is a fair consensus of views here that it is not, then what is the use of the model?

In your model, do you consider the grade of any particular element--whatever it may be--as being continuous from the parts-per-million level to the thousands-of-parts-per-million level or even into the per cent level, because this is quite important?

Baecher: As I just mentioned, this is not really a model; this is the result of some thinking that we have been doing. That latter point has not been considered at all. At this time, the approach is merely geometric. It considers only the distribution of volumes within a space that you cannot see.

Regarding the first question, on the basis of a lot of exploration--as the charts have shown--it seems that for some areas and some mineral deposits, this kind of spatial point distribution in the play seems to model the location of these deposits fairly well (four cases in the Great Lakes area of the USA, one from Alberta; two of the cases displayed relate to the sum of different mineral materials, and another to hydrocarbons).

Roadifer: I would like to ask a question about Baecher's Figure 3, particularly for Uhler and Bradley which is for hydrocarbons. I do not know the size of the quadrats, nor do I know the size of the accumulations. There is a very important relationship here. Is it possible that the accumulations are larger than the quadrats, which in fact drastically affects that density?

Baecher: They certainly are.

Grossling: I have a similar experience in a major oil company of what you say. Most of the geologists were quite conservative. The geologists were very much opposed to anything that rationalized their "art" so to speak. I would like to say that I think your paper is a step in the direction of trying to understand. The geologist is not only an artist; he is also a scientist. And if he is going to investigate something, he has to try to find the laws involved. And one way to find the laws is to make assumptions, even a simple model, follow the assumptions, and then compare them with experiences. They may fall apart. Then you change the assumptions and tackle the problem again. I do not think that you should get discouraged; you should be encouraged.

PROCEDURES FOR ASSESSING US PETROLEUM RESOURCES AND UTILIZATION OF RESULTS

P. R. Rose

SUMMARY

Current methods for assessing oil and gas resources fall into four main classes:

1) Behavioristic--the statistical use of past behavior as an indication of future performance, commonly by employing exploration, production, and reserves growth-curves or through use of discovery-rates;

2) Volumetric--the determination of sedimentary volumes of basins or basin areas multiplied by some area-form or volume-form of petroleum-yield figures;

3) Geologic--the consistent application of experienced, professional exploration judgment to geological, geochemical, and geophysical data, so as to appraise those geological factors that control the occurrence and volume of oil and gas;

4) Statistical--the employment of statistical measures bearing either upon size-distribution of petroleum deposits or upon the expression of probabilities of their existence and/or discovery.

These methods may be used in various combinations. Each method has inherent advantages and shortcomings and may be more or less satisfactory depending upon scale and development-stage of the area to be appraised, as well as upon the purpose for which the resource estimates are utilized--whether for environmental safeguards, long-range alternate energy-source development, or short-range economic planning.

The Resource Appraisal Group (RAG) of the US Geological Survey was created in 1974 as a permanent organization having three responsibilities: a) research in resource appraisal methodology, b) application of appropriate methods to a continuing assessment of petroleum resources of the United States and the world, and c) publication of results for government and public use. Its first major assignment, completed in May 1975, was to produce a documented assessment of the remaining onshore and offshore oil and gas resources of the United States.

RAG's first US petroleum resource appraisal is based primarily upon the geologic method, but the study also employed volumetric procedures, both in frontier basins and as comparative guidelines in some developed basins. In addition, the study utilizes statistical methods, by expressing resource-predictions through probability curves rather than single numbers and by Monte Carlo and modified Delphi techniques for combining data. The study, prepared for the US Federal Energy Administration (FEA), was part of a larger report prepared by the FEA on US oil and gas reserves, production capacity, and resources.

Future resource studies by RAG will doubtless generate somewhat different results owing to additional data, refined procedures, and new methodology. Nevertheless, a solid organizational and procedural framework has been laid, featuring 1) the short-term, highly focused efforts of "area experts" throughout the US Geological Survey in the consistent assembly of reliable and pertinent geologic facts; and 2) the analysis of those data by experienced explorationists. This first RAG study utilized more than 70 US Geological Survey geologists and geophysicists, each expert in specific onshore and offshore regions, in the collection of critical data, which were then analyzed by a RAG team of seasoned petroleum geologists having an aggregate professional exploration experience in excess of 100 man-years.

Results of the RAG report suggest that the United States will continue to be dependent on foreign sources as long as oil remains a significant component of US energy consumption, and that our remaining producible oil resources and reserves are sufficient to supply the domestic component--about 60%-- of our total oil consumption for about 44 years. Alternate energy sources to replace petroleum must therefore be developed during that 44 year period. Although initial response to the report has been overwhelmingly positive, it is too early to evaluate the impact of the report on national energy planning.

There are substantial problems and increasing complexities in the rapidly developing field of resource appraisal. An additional problem exists in communication of understandable results to concerned non-scientific groups in such a way that valid and documented petroleum resource estimates will be used effectively in all phases of national and world energy planning.

INTRODUCTION

Assessment of undiscovered oil and gas resources is an increasing activity among private companies and government agencies. Exploration corporations and banking firms conduct resource assessment projects in order to establish priorities for exploration among many petroleum provinces, and to estimate the magnitude of investment that can be justified in any particular province. They usually focus upon volumes of expected oil and gas that are currently recognized as being "technologically recoverable". Government agencies assess remaining oil and gas resources so as to provide a sound basis for national energy planning, to weigh possible environmental damage against potential petroleum supply, to forecast possible future revenues from leasing and production, and to formulate predictions of future oil and gas production as a function of changing prices and costs.

At the present time, four basic methods for assessing oil and gas resources are in use as noted above in the summary. Most of these methods are now used in various combinations. Each method has inherent advantages and shortcomings, and may be more or less satisfactory. The degree of satisfaction will depend upon scale and development-stage of the area to be appraised, as well as upon the purpose for which the resource estimates are to be utilized--whether for environmental safeguards, long-range alternate energy-source development, or short-range economic planning.

This paper reviews the history and procedures of a comprehensive resource assessment carried out by the Resource Appraisal Group of the US Geological Survey. It discusses the results, in comparison with other estimates by both private industry and government, and dwells briefly upon certain national implications. Finally, it concludes with a discussion of how such a resource assessment can be utilized. The following discussion draws heavily upon the work of Miller et al. (1975), published as US Geological Survey Circular 725 entitled "Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States".

HISTORY

After a period of about 15 years during which programs in petroleum geology received little emphasis within the US Geological Survey, and the staff of petroleum specialists was depleted, the Branch of Oil and Gas Resources was established in August 1972. Activities in the field of oil and gas resource assessment by members and affiliates of the new Branch began immediately, and a resource appraisal by W.W. Mallory and others, issued as a US Department of Interior press release in March 1974, revised previous estimates of oil and gas resources downward and expressed them as ranges to convey the uncertainties involved. Just prior to the press release of March 1974, the Resource Appraisal Group (RAG) was organized, under the direction of Harry L. Thomsen, as one of the major programs within the Oil and Gas Branch. The group was assigned three responsibilities: a) research to develop appropriate methodology for resource assessment, b) application of these methods to a continuing assessment of US and international petroleum resources, and c) publication of results for government and public use. The Resource Appraisal Group, consisting of approximately 12 experienced petroleum geologists and a support staff of about six, was asked in September 1974 by the Federal Energy Administration (FEA) to conduct an appraisal of remaining recoverable oil and gas resources of the United States, both onshore and offshore, to be completed in May 1975.

PROCEDURES

The commissioned RAG report, which was part of a larger report prepared by FEA on US oil and gas reserves, production capacity, and resources, had the following requirements:

1) Methodology must be fully explained and documented;
2) The assessment must have a geologic, rather than a behavioristic, basis;
3) Resources must be appraised by regions rather than for the United States as a whole;
4) It must include crude oil, natural gas, and natural gas liquids.

As the study proceeded, it was decided to exclude heavy oils and tight gas sands in areas that are not now developed or are abandoned, and oil shale, tar sands, and coal gas. Offshore areas beyond 200 meters water-depth were not considered. No attempt was made to take into account increases in the price of oil since mid-1973. More than 100 geologic provinces, combined into 15 onshore and offshore regions, were considered in the report and final publication.

This first resource appraisal effort by RAG was based primarily upon the geologic method, but the study also employed volumetric procedures, both in frontier provinces and as comparative guidelines in some developed basins. In addition, RAG used statistical methods, by expressing resource predictions through probability curves, and by Monte Carlo and modified Delphi techniques for combining data.

The Resource Appraisal Group utilized about 70 US Geological Survey geologists and geophysicists, each expert in specific onshore or offshore provinces, to collect critical data bearing on the oil and gas resource potential of all petroleum provinces of the United States. These geologists were provided a standardized data format-sheet, developed by Betty M. Miller, on which were listed the data for critical oil and gas parameters (see Table 1).

A representative from RAG worked closely with each province expert to complete the data sheets and to become as familiar as possible with each province, using maps, cross sections, and other data provided by the province expert. After comprehensive review of all such information, and application of several different resource appraisal methods to each province,

Table 1. Critical oil and gas parameters used in RAG data format-sheets.

Location

Area

Data Availability

Sedimentary-Rock Volume

Stage of Exploration

Age of Rocks

Age of Deformation

Stratigraphy

Shape of Rock Bodies

Possible Reservoirs

Possible Top-Seals

Possible Traps

Possible Source-Rock

Potential for Favorable Geologic Features--Reefs, Deltas, Salt Domes, Pinchouts

Basin Configuration

Structural Features--Anticlines, Fault-Types

Thermal History

Types of Producing Trends

Cumulative Production

Measured Reserves

Oil and Gas Shows

Nonproducible Hydrocarbons--Tar Sands, Oil Shale, Tight Gas Sands

Producing Reservoirs--Oil, Gas

Oil, Gas Field Size Distribution

Character of Produced Hydrocarbons

Subsurface Pressures

Brine-Types

Temperatures

Recovery Factors

Production Curves--Annual and Cumulative

History of Development

Well Density

Numbers of Wells Drilled--Annual and Cumulative

Previous Resources Estimates

Province Expert's Resource Estimate

Analog Basins

---

the RAG representative then made a preliminary subjective resource assessment at different probability levels, consisting of:

a) A minimum estimate corresponding to a 95% probability that there is <u>at least</u> amount X;

b) A maximum estimate with a 5% probability that there is <u>at least</u> amount Z;

c) A modal estimate that represents the highest probability of occurrence, amount Y;

d) A statistical mean derived by: $\frac{X + Y + Z}{3}$.

Next, RAG representatives reviewed the geology and petroleum occurrence of each province with the Resource Appraisal Group Committee, composed of four to eight experienced petroleum geologists, each having an average professional experience of about 15 years. Each person on the committee was provided completed data format-sheets. A collective review and discussion of each province was conducted, followed by individual resource appraisals by each member of the committee using the subjective probability procedures described above. All individual estimates were then reviewed, differences were discussed (but not necessarily resolved), additional information was introduced and considered, and a group consensus was finally reached, using the subjective probability technique previously described. In areas where there was no previous petroleum production, marginal probabilities were calculated, expressing the probability of any commercial oil and gas occurrence. In totally unexplored provinces the use of such marginal probability led to a 95% probability estimate of a minimum of at least zero, for until oil and gas are actually found in such provinces there can be no high certainty that they are present in producible quantities.

The last stage in appraising each province was to refer RAG's estimates back to each appropriate province expert for review. In cases where substantial differences of opinion existed, the entire process was repeated, usually with new information considered. The final estimates for each province were then statistically combined into regional numbers using Monte Carlo simulation.

Estimates of oil and gas resources were published for each region and were combined further into broader categories for reporting. Statistical procedures for combining data were developed by Gordon M. Kaufman, Alfred P. Sloan School of Management, Massachusetts Institute of Technology.

For two frontier areas (the Atlantic OCS and the Bering Sea), it was decided to report resource estimates at the 75%-25% probability levels rather than at the 95%-5% levels. The main reason for this was that, because of the use of marginal probability in nonproductive frontier areas, the 95% probability estimate came out to be zero in those areas. It was felt by those responsible for use of these estimates that a zero estimate would so confuse people not familiar with the appraisal methodology that the 75%-25% levels were adopted. For the Atlantic Outer Continental Shelf, for example, US Geological Survey Circular 725 reported 75%-25% estimates at 2-4 billion barrels of oil, whereas the original 95%-5% estimates were 0-6 billion barrels. In such areas lacking discovered recoverable hydrocarbons, probability estimates in extreme ranges are weak and estimates at intermediate levels may be more useful for planning purposes.

Speculative references (US Geological Survey Circular 725, p. 1) to the possible effect of continued elevated prices or of increased price/cost ratios were made by economists outside RAG, although the economic analysis to substantiate the speculation is not yet available.

In summary, extensive geological data were collected and posted systematically for each potential petroleum province in the United States. These data were reviewed by a team of highly experienced petroleum geologists, who generated province resource estimates using subjective probability methods. The province estimates were then statistically combined for reporting in 15 major US petroleum regions. A formal report with text and figures was delivered to the FEA in early June; this report was published as US Geological Survey Circular 725, "Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States". It is available at no cost on request from the US Geological Survey, National Center, Reston, Virginia 22092.

All the geological and statistical data are on file in Denver, Colorado, at the Resource Appraisal Group offices, where they are open for public inspection. The full methodology is reviewed in US Geological Survey Circular 725, which also includes the probability curves for all regions. Accordingly, a documented basis for productive professional discussion of methods and results now exists. We hope that other petroleum geologists will absorb and criticize US Geological Survey Circular 725 and, thus, help us refine our resource estimates through the input of new ideas and new data.

The Resource Appraisal Group plans to continue to generate periodic assessments of US oil and gas resources. Future studies by RAG will doubtless generate somewhat different results, owing to new or additional data, refined procedures, and new methodology. Even so, it is believed that the overall US oil and gas resource estimates will probably not change substantially, even though resource estimates for individual basins, provinces or regions may change markedly. Such changes probably will tend to cancel each other out in terms of total national oil and gas resources.

RESULTS

In the interest of brevity this paper emphasizes the results pertaining to crude oil, rather than considering oil, natural gas, and natural gas liquids equally. For a full discussion of all these resources the reader is referred to US Geological Survey Circular 725. In any case, the results (and implications) for natural gas are generally compatible with the crude oil results.

In order to consider the RAG estimates in perspective, it is appropriate first to review the status of US production and reserves (see Table 2). As of December 31, 1974, the United States had already produced about 106 billion barrels of oil. Measured reserves total about 34 billion barrels. In addition, about five billion barrels are expected to be produced through application of secondary recovery procedures (indicated reserves). Finally, additional drilling and development of existing, newer fields over the next few years is expected to add about 23 billion barrels to reserves. This category, called "inferred reserves", is not considered among "reserves" by some other estimators. Thus, the United States has about 62 billion barrels of crude oil reserves, compared with 106 billion barrels of crude oil that have already been produced.

Results of the Resource Appraisal Group's efforts indicate that somewhere between 50 and 127 billion barrels of crude oil, discoverable and producible under conditions prevailing over the last decade or so, remain to be discovered in the United States. The statistical mean for these estimated oil resources is about 82 billion barrels.

Between 29 and 64 billion barrels of these oil resources are in onshore US basins of the lower 48 states (statistical mean ±44 billion). Onshore Alaska is believed to contain between 6 and 19 billion barrels, with a statistical mean of 12 billion. Offshore, a range of 10 to 49 billion barrels is anticipated, with a mean of 26 billion barrels (see Table 2). Generalized resource estimates for natural gas and natural gas liquids are indicated in Table 3.

Figure 1 indicates, by region, the ranges of undiscovered recoverable oil and gas resources forecast for the United States. Figure 2 compares recoverable liquid hydrocarbon resource estimates generated over the past few years by many different groups using several different definitions and different methodologies. It indicates that the 1975 RAG results are in broad agreement with a number of geologic-type estimates by the National Academy of Sciences (National Research Council, 1975), Mobil Oil Company (cited by Gillette, 1974), Weeks (1960), and behavioristic-type forecasts by Hubbert (1974). These particular forecasts suggest that between about 70 and 100 billion barrels of producible oil and natural gas liquids remain to be discovered in the United States.

The 1975 RAG results may be compared with a group of higher estimates in the 200-450 billion barrel range (Theobald, et al., 1972; U.S. Department of Interior/USGS, 1974; Hendricks, 1965). These estimators did not have access to extensive data or adequate numbers of experienced personnel, and so relied upon volumetric/behavioristic methodology, and assumed discovery rates which may not be consistent with US exploration experience.

Table 2. Production, reserves, and undiscovered recoverable oil resources for the United States, December 31, 1974 (billion barrels) (from Miller et al., 1975).

	Regions	Cum.Product.	Dem. Reserves		Tot.Cum.Prod. & Demon.Resrvs.	Inferred Reserves[1]	Undiscovered Recoverable Resources	
			Meas.	Indict.			Stat.Mean	Est. Range[2] (95%-5%)
ONSHORE	1. Alaska	0.154	9.944	0.013	10.111	6.1[3]	12	6 - 19
	2. Pac.Coast.States	15.254	2.699	1.091	19.044	0.3	7	4 - 11
	3. Western Rocky Mts	1.115	0.417	0.089	1.621	0.7	4	2 - 8
	4. Northern Rocky Mts	6.021	1.461	0.256	7.738	1.2	7	5 - 11
	5. W.Texas & Eastern New Mexico	21.385	7.060	1.991	30.436	1.6	8	4 - 14
	6. Western Gulf Basin	31.345	7.082	0.587	39.014	8.6[4]	8	5 - 12
	7. Mid-Continent	17.203	1.805	0.211	19.219	1.3	6	3 - 12
	8. Michigan Basin	0.645	0.082	0.008	0.735	0.2	1	0.3 - 2
	9. Eastern Interior	4.346	0.283	0.009	4.638	0.3	1	0.6 - 2
	10. Appalachians	2.539	0.155	0.067	2.761	Negl[5]	1	0.4 - 2
	11. Eastern Gulf & Atlantic Cst.Pln	0.039	0.042	0.006	0.087	0.1	1	0.2 - 2
	Tl Lwr 48 Onshore	99.892	21.086	4.315	125.293	14.3	44	29 - 64
	Tl Onshore US	100.046	31.030	4.328	135.404	20.4	56	37 - 81
OFFSHORE (0-200 meters)	1A. Alaska	0.456	0.150	Negl.[5]	0.606	0.1[3]	15	3 - 31
	2A. Pac.Coast.States	1.499	0.858	0.258	2.615	0.2	3	2 - 5
	6A. Gulf of Mexico	4.135	2.212	0.050	6.397	2.4	5	3 - 8
	11A. Atl.Coast.States	0.000	0.000	0.000	0.000	0.0	3	2 - 4[6]
	Tl Lower 48 Offs.	5.634	3.070	0.308	9.012	2.6	11	5 - 18
	Tl Offshore US	6.090	3.220	0.308	9.618	2.7	26	10 - 49
	Tl Lower 48	105.526	24.156	4.623	134.305	16.9	55	36 - 81
	Tl Alaska	0.610	10.094	0.013	10.717	6.2	27	12 - 49
	TOTAL US	106.136	34.250	4.636	145.022	23.1	82	50 -127

[1] Inferred reserves were derived for all regions based on historical data.

[2] The low value of the range is the quantity associated with a 9% probability (19 in 20 change) that there is at least this amt. The high value is the quantity with a 5% probability (1 in 20 chance) that there is at least this amount. Totals for the low and high values are not obtained by arithmetic summation; they are derived by stat. methods.

[3] Inferred reserves based on national onshore average.

[4] Inferred reserves based on data in AAPG Memoir 15 (Cram, 1971).

[5] Negligible--less than 0.001 billion barrels.

[6] Estimates reported at the 75% & 25% probability levels because, in this area, these levels are judged to be more applicable for some planning purposes. It can also be noted that in frontier areas, lacking discovered indigenous or sufficiently great as to weaken probability estimates at extreme ranges. For purposes of comparison with other recorded ranges, the 95%-5% probability range in offshore Atlantic is 0-6 billion barrels of oil.

Table 3. Production, reserves, and undiscovered recoverable resources of natural gas and natural gas liquids for the US, December 31, 1974 (onshore and offshore to water depth of 200 meters) (from Miller et al., 1975).

Area	Cumulative Production	Reserves			Undisc. Recoverable Resources
		Demonstrated			
		Measured[2]	Indicated[3]	Inferred[4]	Range[5],[6] (95% -5%)
	Natural Gas[1] (Trillions of cubic feet)				
Lower 48 Onshore	446.366	169.454	Not Applicable	119.4	246 - 453
Alaska Onshore	0.482	31.722		14.7	16 - 57
Total Onshore	446.848	201.176		134.1	264 - 506
Lower 48 Offshore	33.553	35.811		67.4	26 - 111
Alaska Offshore	0.423	0.145		0.1	8 - 80
Total Offshore	33.976	35.956		67.5	42 - 181
Total Onshore & Offshore	480.824	237.132		201.6	322 - 655
	Natural Gas Liquids (Billions of Barrels)				
Total Onshore & Offshore	15.730	6.350	Not Applicable	6	11 - 22[7]

[1] Cum. production and estimates of reserves & resources reflect an assumed recovery of about 32% of the oil and 80% of the gas-in-place. Some portion of the remaining oil-in-place is recoverable through application of improved recovery techniques. Estimates are based on figures released by the API and the AGA in April 1975.

[2] Identified resources that can be economically extracted with existing technology. Estimates are the "proved reserves" of the API and AGA.

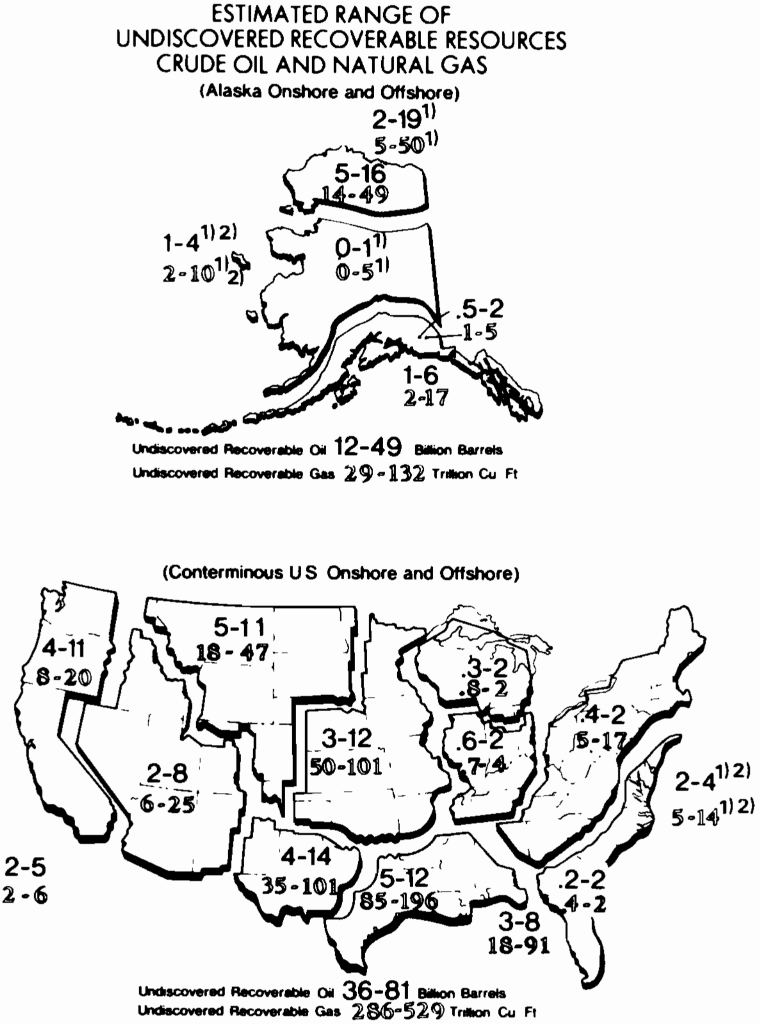
[3] Identified resources, economically recoverable if known fluid injection technology is applied. Estimates are from API.

[4] Resources est. to be recoverable in the future as a result of extensions, revisions of estimates & new pays in known fields beyond those shown in indicated reserves.

[5] The low value of the range is the quantity assoc. with a 95% prob. (19 in 20 change) that there is at least this amt. The high value is the quantity with a 5% prob. (1 to 20 change) that there is at least this amt. Totals for the low & high values are not obtained by arithmetic summation; they are derived by stat. methods.

[6] The reader is cautioned against averaging ranges.

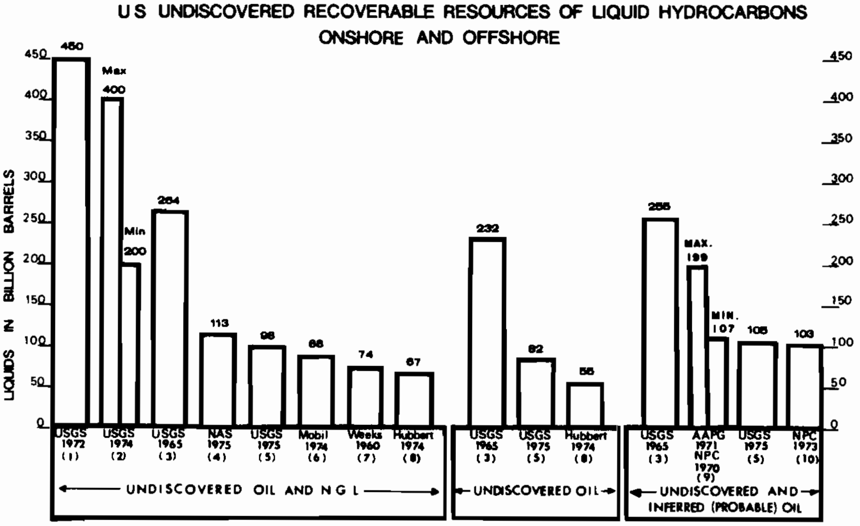
[7] The calc. estimates of undis. recoverable resources are derived from natural gas estimates by applying historical NGL Natural Gas ratios. These figs. suggest that if added to crude oil estimates, natural gas liquids would increase the estimates of petroleum liquids by approx. 20%.



[1] Marginal probability applied.

[2] Estimates reported at the 75% and 25% probability levels because, in this area, these levels are judged to be more applicable for some planning purposes. It can also be noted that in frontier areas, lacking discovered indigenous or adjacent recoverable hydrocarbons, uncertainty is sufficiently great as to weaken probability estimates at extreme ranges. For purposes of comparison with other recorded ranges, the 95%-5% probability range in offshore Atlantic is 0-6 billion barrels of oil.

Figure 1. Undiscovered recoverable resources of crude oil and natural gas for the United States. Reported as a range of values at 95%-5% probability in billions of barrels for oil and trillions of cubic feet for gas (from Miller et al., 1975).



(1) Theobald and others, US Geol. Survey Circ. 650, 1972. Includes water depth to 2,500 m (8,200 ft).

(2) US Department of Interior News Release, March 26, 1974. Includes water depth to 200 m (660 ft).

(3) Hendricks, US Geol. Survey Circ. 522, 1965. Adjusted through 1974. Includes water depth to 200 m (660 ft).

(4) Nat'l. Academy of Sciences, "Mineral Resources and the Environment", 1975. (See National Research Council). Water depth not indicated.

(5) US Geol. Survey "Mean", Oil and Gas Branch Resource Appraisal Group, 1975. Includes water depth to 200 m (660 ft).

(6) Mobil Oil Corp., Expected Value: Science, 12 July 1974. (See Gillette). Includes water depth to 1,830 m (6,000 ft).

(7) Weeks, L.G., Geotimes, July-Aug., 1960. Adjusted through 1974. Water depth not indicated.

(8) Hubbert, Senate Committee Report, 1974. Includes water depth to 200 m (660 ft).

(9) Am. Assoc. Petroleum Geologists Mem. 15, (Cram, 1971). Also National Petroleum Council, "Future petroleum provinces of the United States," 1970. Some areas are excluded from this estimate. Includes water depth to 2,500 m (8,200 ft). Maximum represents "Preferred estimate" based on 60% recovery; minimum represents 30% recovery.

(10) National Petroleum Council, "US Energy outlook--oil and gas availability", 1973. Includes water depth to 2,500 m (8,200 ft).

Figure 2. Comparative estimates of oil resources in the United States (modified from Miller et al., 1975).

Intermediate-level resource forecasts issued by the National Petroleum Council and the American Association of Petroleum Geologists (Cram, 1971) showed a "preferred" value of 199 billion barrels for remaining oil resources. This preferred value, however, was based upon a 60% recovery factor, which is not realistic by current production and supplemental recovery experiences. Using a recovery factor of 31.1%, which approximated the 1971 primary recovery efficiency in the United States, however, a remaining resource estimate of 107 billion barrels was obtained as shown in Figure 2.

Figure 3 shows appraisals of total recovery and recoverable oil resources[1] of the United States (excluding Alaska) through time; it indicates that there have been a number of fairly consistent estimates for the "lower 48" and adjacent OCS areas, clustered around 200 billion barrels, as put forth by Hubbert (1956, 1962, 1967, 1974) using the behavioristic approach, and several industry-oriented geological/statistical appraisals by Stanolind (Schultz, 1952), Humble (Pratt, 1956), and Mobil (cited by Gillette, 1974). Figure 3 also indicates a series of higher US Geological Survey resource estimates, beginning with a 300 billion barrel estimate by the Interior Department in 1956, continuing with a series of volumetric/behavioristic estimates in the 400 to 600 billion barrel range, and declining again during the establishment of the Oil and Gas Branch and thereafter, when a large number of petroleum geologists were hired and substantial new geological and geophysical data became available. The Resource Appraisal Group utilized geological/volumetric/statistical methods. Figure 3 illustrates the effect of using extensive geological information and varied experienced exploration judgment in generating petroleum resource assessments.

The 1972 National Petroleum Council estimates are seen to lie in an intermediate range between the 200 billion barrel cluster and the higher grouping. The steady climb of US cumulative production-plus-measured reserves from 1950 to 1975 has been included in Figure 3 in the interests of perspective.

In summary, the results of the Resource Appraisal Group's 1975 resource assessment (US Geological Survey Circular 725) indicate that there are no longer significant differences among most resource authorities as to the amount of remaining recoverable oil resources in the United States and that about 82 billion barrels of crude oil probably remain to be found onshore and offshore in the United States.

IMPLICATIONS

According to US Geological Survey Circular 725 the United States has already produced or discovered about twice as much oil as now remains to be discovered (168 billion barrels versus 82 billion). With this in mind, a few facts should be mentioned:

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[1] Total recovered and recoverable oil resources = cumulative production plus reserves plus undiscovered recoverable resources.

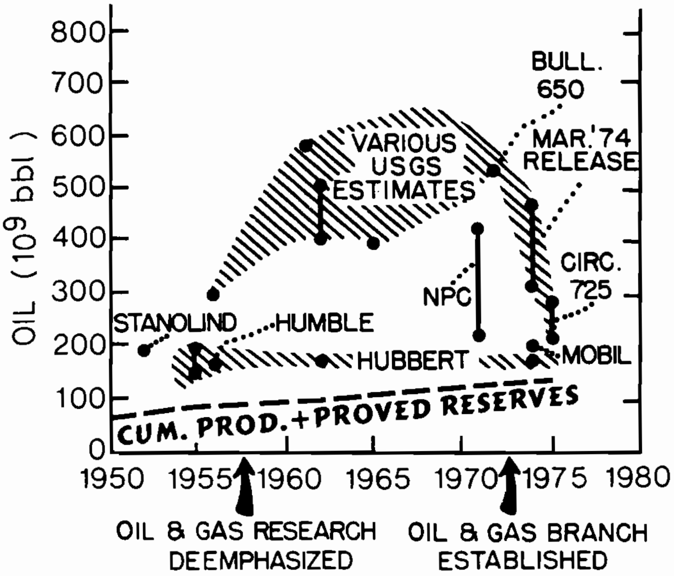

Figure 3. Estimates of total recovered and recoverable US oil resources (excluding Alaska) during period 1952-1975. Total recoverable oil resources = production + proved reserves + indicated / inferred reserves + undiscovered recoverable resources.

1) Crude oil is the dominant energy source used in the United States.

2) Production of crude oil in the United States has been declining steadily since 1971, and measured reserves have also been declining since about 1960.[2] .

3) Annual US consumption of crude oil products, excluding natural gas liquids, is about 5.3 billion barrels (US Department of Interior/Bureau of Mines, 1975), of which 3.2 billion barrels (60%) is produced domestically; the remainder, 2.1 billion barrels (40%) must come from foreign sources.

4) The greatest potential for discovery of giant oil fields, appears to lie in US frontier areas--offshore and the Alaska onshore--because most of the world's oil lies in relatively few large fields, and such fields are usually discovered early in the exploration cycle of any given province.

5) It is generally accepted that the United States must eventually switch to alternate energy sources such as oil shale, coal, nuclear and/or solar, with oil and natural gas "buying time" during which the conversion is accomplished.

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[2] Except for the 1968 reserve-addition represented by the Prudhoe Bay field.

How much time do we have to convert to alternate energy sources, based on undiscovered producible domestic oil resources? Obviously, changing economics will exert a major influence here, but to help visualize our reserve/resource position in perspective we can make some rough calculations. At current rates of domestic production, the existing 62 billion barrels of reserves constitute perhaps a 19-year supply. If there are indeed about 82 billion barrels of producible resources remaining, and a large proportion can be discovered and developed within this 19 year period (with the remainder being developed steadily thereafter), then these 82 billion barrels represent only an additional 25-year supply. But utilizing the 95% and 5% probability estimates by RAG (50 and 127 billion barrels respectively), these resources may represent supplies for as few as 16 years or as many as 40 years. In any case, this conjectural <u>total</u> supply, probably about 44 years, but perhaps only 35, or as much as 59 years, relates only to the <u>domestic</u> component of our present petroleum budget--we still would have to continue to import at least one-third of the oil we consume, by present standards. Meanwhile US oil demand is growing.

It may also be helpful to view these crude oil resources in terms of annual discovery-rates. Historically, discovery of crude oil in the conterminous United States and adjacent offshore has fluctuated widely, increasing from 1900 to 1951 and decreasing thereafter. About 4.4 billion barrels were discovered in 1951, our best year, and annual discoveries since then have moved generally downward, ranging between 3.5 and 2.0 billion barrels (Hubbert, 1974, p. 95). If the US exploration effort could be maximized so as to reachieve even our most successful annual level (4.4 billion barrels), it would still require 19 years--exactly the length of time it would require for depletion of our present reserve--to discover the hypothetical 82 billion barrels. At current annual discovery levels of 2.0 billion barrels, 41 years would be required to discover the 82 billion barrels. These calculations suggest that the United States will be fortunate even to maintain its present domestic production level, let alone increase it substantially.

Rapid discovery of giant fields, however, may conceivably improve the US domestic production situation, and it would appear that the current effort to accelerate exploration in frontier areas, which hold the greatest potential for giant field-occurrence, is compatible with the national need for speedy and substantial production increases.

It is interesting that the RAG estimates (mean 44 billion barrels) for remaining <u>onshore</u> reserves of the lower 48 States, are larger than for the remaining frontier areas (mean 38 billion barrels). Because these onshore resources lie in partially explored areas, it seems probable that most of this oil will be in many relatively small fields, rather than a few giant ones. This in turn suggests additions to reserves in small, steady increments, rather than the needed rapid large additions.

Accelerated exploration, development and the installation of supplemental recovery procedures in these existing petroleum provinces does hold the potential for speediest additions to domestic production, although the expected volumes would not be so large as those provided by giant fields developed offshore. Such projects would involve a much larger proportion of the independent sector of the petroleum industry than would offshore activities. Economic stability and incentives would encourage this sector of the industry toward maximizing its efforts.

Some legitimate room for hope exists, of course, through improved supplemental recovery techniques, or from oil shale development, which might well prolong or even increase domestic oil production, and which must serve as feedstocks for petrochemicals and lubricants if the United States eventually has insufficient crude oil to use as fuel. Furthermore, stringent conservation measures might well reduce consumption substantially. Nevertheless, it seems clear that the United States probably has less than 50 years during which to convert to alternate energy resources, and that it will be difficult to substantially increase our domestic production during that time.

During this conversion period, the time required for discovery and development of the undiscovered recoverable resources causes great difficulty in rapidly utilizing these resources. For example, it takes about five to eight years to fully develop a major oil field to maximum production. Thus even if the United States is to maximize its domestic petroleum exploration efforts and adopt stringent conservation measures to prolong the life of our anticipated oil resources, it is still likely that it must be partially dependent on foreign oil sources.

UTILIZATION OF RESULTS

The first published product of the Resource Appraisal Group, US Geological Survey Circular 725, received widespread publicity in the news media when it was released in June 1975. The report has been well received in industry, government and academic sectors alike, apparently for four reasons:

a) The procedures are thoroughly documented.

b) An adequate number of experienced petroleum explorationists and knowledgeable areal geologists were available to interpret abundant geologic data.

c) The results are compatible with many independent resource estimates conducted by other knowledgeable and competent groups.

d) The resource estimates are presented in probabilistic mode.

The results were utilized by the Federal Energy Administration in preparing its 1975 report to the Congress on US oil and gas reserves, production capacity, and recoverable resources and by the Energy Research and Development Administration (ERDA) in its national planning. The Federal Power Commission (FPC) has endorsed the estimates. The implications of US Geological Survey Circular 725, however, were touched upon only in official press releases and have not been widely discussed to date, either in scientific or popular publications.

Resource economists expressed great interest in the results, because presentation in probabilistic mode is readily adaptable to a variety of uses and manipulations. Such analysis of economic factors affecting resource estimates is indeed highly desirable, but will be very difficult because of the complex physical and economic nature of the petroleum exploration and production business. Probabilistic presentation of resource numbers is also useful for different kinds of planning: short-range economic ventures may require a reasonable expected minimum for investment purposes, whereas environmental planners may prefer to allow for a reasonable maximum of resource development.

The concensus of recent resource appraisal estimates, including the 1975 RAG results suggest that we may have less than 50 years in which to shift to other sources of energy to replace our dwindling oil supplies, and that we probably will not be able to escape substantial dependency on foreign sources during the transition period.

The technical subject--Petroleum Resource Appraisal--is now in a state of "scientific explosion", with many new techniques being developed, evaluated, and applied by many different groups. Major difficulties in this field center on: 1) consistent definitions, 2) reliable data, 3) the effects of economics on the resource-base, 4) the need for a continuing geologic foundation and input into statistical and economic procedures, and 5) the maintenance of scientific objectivity.

However, far larger problems lie in the utilization of results. When petroleum resource studies are carried out by private companies, the results are commonly received by geoscientists and engineers in higher management circles, who have the technical background to understand both the limitations and the need for assessing the remaining petroleum potential of different areas. But the effective communication of results to the decision makers in government is a much more difficult process, complicated inevitably by diverse backgrounds and the democratic process. This is the area where the greatest challenge lies in petroleum resource appraisal.

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A PROBABILISTIC MODEL OF OIL AND GAS DISCOVERY

E. Barouch and G. M. Kaufman

We describe here properties of a model of oil and gas discovery designed to provide probabilistic answers to:

1) How many undiscovered pools remain in a given geological zone, and what is their size distribution?

2) What additions to economically recoverable oil (gas) will accrue from an increment of exploratory effort?

Our model is objective in the sense that it is a representation of the probability law of a data generating process. In general, the parameters of the process are not known with certainty and must be inferred from data, from expert opinion, or from a mixture of both. Personal probability judgments of experts, properly expressed, can be used in conjunction with the model to provide an answer to the first question above for unexplored areas, as well as for areas where drilling data is available.

An extensive discussion of the assumptions on which our model is built is given in Kaufman et al., forthcoming and its mathematical properties are studied in Barouch and Kaufman (1974). For completeness we briefly review the substance of these two studies before presenting some more recent results.

Our model incorporates certain geological facts and is based on assumptions that describe the manner in which exploration technology and observed statistical regularities of the size of pools interact to generate discoveries. The proposed model of the discovery process has four major components:

a) A submodel of pool sizes discovered in a homogenous geologic population of pools in order of discovery.

b) A submodel of wildcat drilling successes and failures.

c) A submodel of the economics of a single exploratory venture.

d) A submodel of the "capital market" for exploratory ventures.

When assembled, these submodels constitute a probabilistic model of the returns in barrels of oil and/or Mcf of gas generated as a function of price and physical nature of the reservoirs available for exploitation.

BASIC ASSUMPTIONS

Our basic assumptions about the physics of the evolution of a *play* reflect both petroleum folklore and the content of a variety of statistical studies of the discovery process. A *prospect* is a geological configuration conceived to have trapped hydrocarbons and which is a target for drilling. McCrossan has defined a *play* as a group of prospects and pools (located in the same petroleum province) that are geologically similar. Thus a play is a geologically homogeneous subpopulation within the population of pools and prospects in a petroleum province, and because of the homogeneity of members of this subpopulation, it is a natural candidate for statistical analysis. In particular, pools and prospects within each play have statistically homogeneous *economic* attributes. Using the play as a basic unit of analysis we can meaningfully separate physical and engineering properties of the discovery process from economic effects.

Two basic assumptions we make about the discovery process within a play are

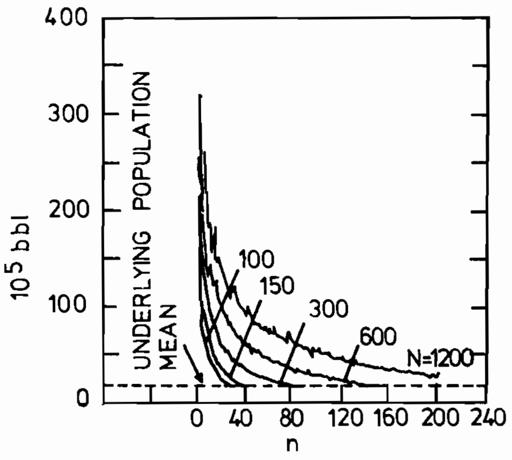
I) (Lognormal size distribution) Let A_i be the size of the i^{th} pool among N pools deposed by nature in the geological zone within which the play takes place. The A_is are values of mutually independent identically distributed lognormal random variables.

II) (Sampling without replacement and proportional to random size) Given $A_1,\dots,A_N$ the probability of observing $A_1,\dots,A_N$ in that order is

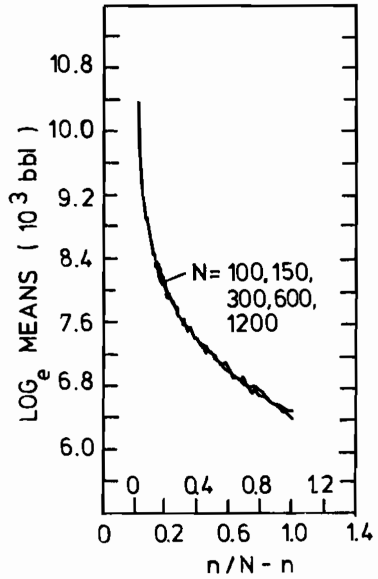
$$\prod_{j=1}^{n} A_j/(A_j + \cdots + A_N) \quad .$$

IMPLICATIONS OF ASSUMPTIONS I AND II

One of the striking features of a Monte Carlo simulation of Assumptions I and II in combination is the behavior of the mean size of pools discovered in order of discovery. Figure 1 displays the graph of this function (which we might call an "exploration decline curve" by analogy with "production decline curve"). It declines extremely rapidly at first, passes through a turning region, and then declines slowly.



Simulated means of size of n^{th} pool discovered for finite population sizes N = 100, 150, 300, 600, and 1,200.



Log of simulated means of size of n^{th} pool discovered for finite population sizes N = 100, 150, 300, 600, and 1,200, displayed as a function of n/N - n, the proportion of undiscovered pools discovered.

Figure 1.

Figure 2 is the graph of means of (rescaled) sizes of pools in Alberta plays--in order of discovery. Except for the effect of an outlier at the thirty-third discovery, these means roughly exhibit the same behavior as the graph generated by simulation: the larger pools are, on the average, found first and the mean size of discovery declines as more and more discoveries are made. Values of the function displayed in Figure 2 were computed by first dividing pool sizes within each play by an estimate of the mean size of pools within that play, then averaging the rescaled first discoveries across all plays, second discoveries, etc.

Additional evidence supporting the plausibility of Assumptions I and II is cited in Kaufman et al. (forthcoming). However, it is possible to do more rigorous statistical testing of their validity. Assumption I has been examined and tested in various ways by many authors; Assumption II has not. Certain mathematical properties of the model must be understood before we can describe some of the tests of II what we have in mind. In particular, we need a computable expression for the sampling density (density of observed values of pool sizes) so that estimators of the model's parameters can be calculated and used in a program of testing.

MATHEMATICAL PROPERTIES

Let Y_j denote the observed value of the jth observation, define $\underline{Y} = (Y_1, \ldots, Y_n)$ as the vector of observations in a sample of size $n \leq N$, and assume that f is a member of a class of densities (all of whose members are concentrated on $[0,\infty]$) indexed by a parameter $\underline{\Theta} \in \Theta$ so that $\tilde{A}_i$ has density $f(\cdot|\underline{\Theta})$. Then given $\underline{\Theta}$, N, and infinitesimal intervals $dY_1, \ldots, dY_n$, the probability of observing $\tilde{Y}_1 \in dY_1, \ldots, \tilde{Y}_n \in dY_n$ in that order (or equivalently, of observing $\underline{\tilde{Y}} \in d\underline{Y}$) is

$$P\left\{\underline{\tilde{Y}} \in d\underline{Y} | \underline{\Theta}, N\right\} = \frac{\Gamma(N + 1)}{\Gamma(N - n + 1} \left[\prod_{j=1}^{n} Y_j f(Y_j | \underline{\Theta}) dY_j\right]$$

$$\int_0^\infty f^{*N-n}(S|\underline{\Theta}) \prod_{j=1}^{n} (Y_j + \cdots + Y_n + S)^{-1} ds \quad . \tag{1}$$

Here, f^{*N-n} is the density of the sum of $N - n$ A_i's.

When the density of the $\tilde{A}_i$s is f and f possesses moments of all order, an asymptotic expansion of the density of $\underline{\tilde{Y}}$, valid for large $p \equiv N - n$ and fixed $b_j = Y_j + \cdots + Y_n$, $j = 1, 2, \ldots, n$ is

$$I_{N,n}(\underline{Y}) \prod_{j=1}^{n} Y_j f(Y_j)$$

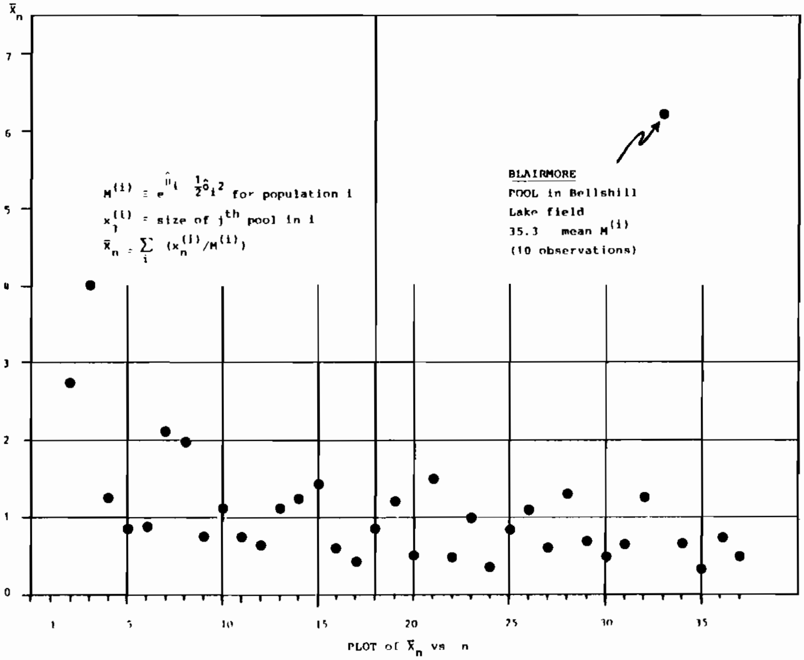


Figure 2. Scaled averages of size of discovery n = 1, 2, ..., 37.

where, defining M_i as the ith moment of f and V as its variance,

$$I_{N,n}(\underline{Y}) = \frac{\Gamma(p + n + 1)}{\Gamma(p + 1)} \prod_{j=1}^{n} [pM_1 + b_j]^{-1}$$

$$\times \{1 - \tfrac{1}{2}pVg_2(pM_1,\underline{Y}) + \tfrac{1}{8}p^2V^2g_4(pM_1,\underline{Y}) \qquad (2)$$

$$+ p(\tfrac{1}{6}M_3 - \tfrac{1}{2}M_1M_2 + \tfrac{1}{3}M_1{}^3)g_3(pM_1,\underline{Y}) + 0(p^{-3})\} \quad .$$

The functions $g_m(pM_1,\underline{Y})$ are rational functions of $\underline{Y}$ and pM_1 and $g_m = 0((pM_1)^{-m})$.

If f is lognormal and has parameters μ and σ^2 such that $E(\log_e\tilde{A}_i) = \mu$ and $Var(\log \tilde{A}_i) = \sigma^2$, then the above expansion is valid in a region for which $n \cdot \exp\{\sigma^2\}/N - n$ is smaller than order one; that is, it is 0(1).

With f lognormal it has been programmed into the National Bureau of Economic Research's TROLL system and can be used to compute approximate maximum likelihood estimates (MLE) of μ and σ^2 for given values of the number N of pools in a play. When σ^2 is "small" and $N - n$ is "large" the expansion works well, but it breaks down when $n/N - n$, the proportion of undiscovered pools discovered, times $\exp\{\sigma^2\}$ is of order one. Asymptotic expansions of the moments of observations can be computed by further analysis of the above expansion for the density, but they will be valid only for small values of n.

Consequently, we have designed asymptotic expansions of the density of $\underline{\tilde{Y}}$ and of the first two moments of the conditional density of $\tilde{Y}_n$ given $Y_1,\ldots,Y_{n-1}$ that are uniformly valid for large p over a large portion of the possible values of μ, σ^2, and n. These expansions mirror what we see in the simulated graph of the first moments $E(\tilde{Y}_1),\ldots,E(\tilde{Y}_n)$ of the $\tilde{Y}_j$s:

1) $E(\tilde{Y}_n)$ regarded as a function of n has a mathematical turning point at roughly $n \sim \sqrt{N}$; that is, the mathematical form of $E(Y_n)$ changes character in moving from the left to the right of the turning point.

2) To the left of the turning point $E(\tilde{Y}_n)$ looks as if it decays much faster than to the right.

3) It is a function of n/p.

A uniform expansion of the density with the above properties requires study of a rather complicated scale balancing of parameters; we have done so for

$$M_1 = \exp\{\mu + \tfrac{1}{2}\sigma^2\} = 0(p^{1/4}) \quad ;$$

$$K = \frac{1}{n}\sum_{j=1}^{n} b_j = 0(p^{5/4}) \quad ;$$

$$V = M_1^{\,2}(\exp\{\sigma^2\} - 1 = 0(p) \quad ;$$

$$n = 0(\sqrt{p})$$

$$e^{\sigma^2} = 0(\sqrt{p})$$

The simulation took place for $100 \le N \le 1{,}200$. This is a sufficiently large range to make us confident that the above scale balance can be extended to other values of N, provided N is sufficiently large compared with 1. It is rather delicate, breaking down when σ^2 is large compared with log n.

Using the above scales and results from Barouch and Kaufman (1974), the density of $\underline{\tilde{Y}}$ can be written as

$$n\left(\frac{ip}{\lambda}\right)^n \binom{p+n}{p} \prod_{j=1}^{n} Y_j f(Y_j)/[b_j + pM_1] \tag{3}$$

$$\times \int_0^\infty e^{Q[\delta \log z - iz - \frac{1}{2}z^2]} dz$$

where $Q = \frac{p}{\lambda} = 0(p^{1/2})$, $\delta = \lambda\Theta = 0(1)$, $\Theta = \frac{n-1}{p}$, and

$$\lambda = p^2 V/(K + pM_1)^2 = 0(p^{1/2}) \text{ with } K = \frac{1}{n}\sum_{j=1}^{n} b_j \leq 0(p^{5/4}).$$

K goes to the limit b_1 if all the b_js are the same; that is, we recover sampling with replacement. It also maintains the symmetry of the b_js. We study eq. (3) in the above limits for Q large and fixed δ of order one. This coincides with our intuition drawn from the results of the simulation, since we have two coinciding saddle points for $\delta = 1/4$, manifesting a turning point. When the two saddle points are close enough ($\delta \cong 1/4$) the asymptotic expansion of the integral in eq. (3) must take this closeness into account. More explicitly the contribution from each of the two nearly coinciding saddle points must be taken together. As a consequence, the usual method of steepest descents is not applicable and we must employ the more sophisticated scheme for asymptotic computation designed by Chester et al. (1956) for problems of this sort.

Their method for constructing uniform expansions for the case of two nearly coincident saddle points begins by introduction of a new complex variable μ implicitly defined in terms of z as

$$h(z,\delta) \equiv \delta \log z - iz - \frac{1}{2}z^2 = \frac{1}{3}u^3 - \xi(\delta)u + A(\delta) \quad ,$$

the parameters $\xi(\delta)$ and $A(\delta)$ being determined by the condition that the (u,z) transformation is uniformly regular, here near $\delta = 1/4$ and $z = -i/2$. They show that with $\xi(\delta)$ and $A(\delta)$ so computed, there is one branch of the transformation that is uniformly regular and use this fact to compute uniformly asymptotic expansions of $\int p \exp\{-h(z,\delta)\}dz$ of the form

$$\exp\{-pA(\delta)\}\left\{\frac{Ai(p^{2/3}\xi)}{p^{1/3}} \sum_{j=0}^{\infty} \frac{a_j(\delta)}{p^j} + \frac{Aj(p^{2/3}\xi)}{p^{2/3}} \sum_{j=0}^{\infty} \frac{b_j(\delta)}{p^j}\right\} \tag{4}$$

where

$$\mathrm{Ai}(\xi) = \frac{1}{2\pi i}\int_{\infty e^{-\pi i/3}}^{\infty e^{\pi i/3}} \exp\{\frac{1}{3}u^3 - \xi u\}du$$

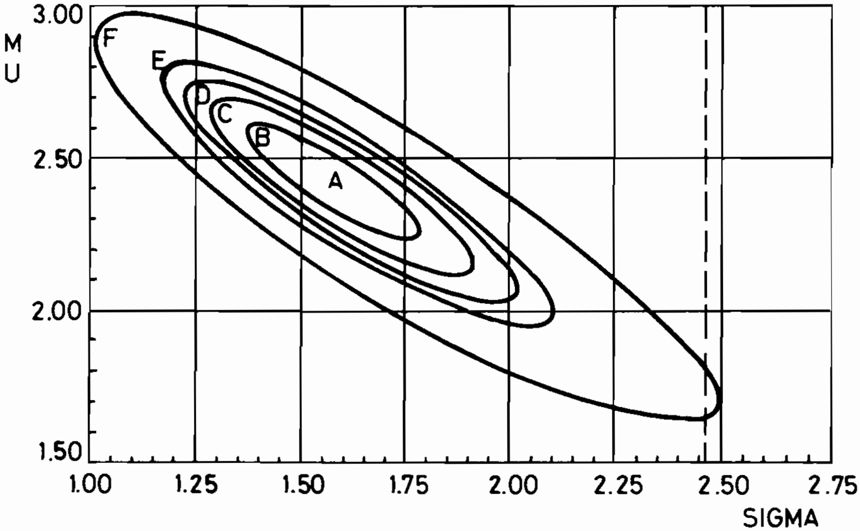
and $\mathrm{A\acute{i}}(\xi) = d\mathrm{Ai}(\xi)/d\xi$; that is, $\mathrm{Ai}(\xi)$ is the Airy function and $\mathrm{A\acute{i}}(\xi)$ its derivative. Terms $a_j(S)$ in the series of eq. (4) can be computed recursively from knowledge of $a_0(S)$ and $a_1(S)$; terms $b_j(S)$ can be computed in a similar fashion (see Chester et al. (1956) formulae (4.3) and 4.4)).

We have developed a simple method for computing a_0, a_1, b_0, and b_1 in our particular case and are currently building software for numerical computation using this expansion.

ESTIMATING OF MODEL PARAMETERS: THE NORTH SEA

In our opinion it is better to use several methods for estimating the parameters μ, σ^2, and N, cross-checking the results yielded by each against the others. We plan to use the uniform asymptotic expansion (3) to compute MLE of parameters and also to compute nonlinear least squares estimators. At the moment only the expansion (2) of the density is programmed for computation.

As an example we have processed a sample of 24 fields from the North Sea, the "size" of each being expressed in 10^7 barrels of recoverable oil. Figure 3 is a graph of iso-contours of the log of the expansion (2) of the sampling



A = -128.12
B = -128.20
C = -128.30

Figure 3.

density regarded as a function of μ and σ^2 for N = 303 and fixed, that is, iso-contours of the log-likelihood function. The maximum value of the log-likelihood is -128.12 at $\mu = 2.422$ and $\sigma^2 = 1.569$, corresponding to a mean field size for the population of all fields of

$$M_1 = e^{\mu + \frac{1}{2}\sigma^2} \times 10^7 = 246{,}693{,}000 \text{ recoverable barrels}$$

and an expectation of aggregate amount of recoverable oil in place of

$$N \cdot M_1 = 303 \cdot M_1 = 74.75 \times 10^9 \text{ recoverable barrels} \quad .$$

The maximum value of the likelihood function is relatively insensitive to the choice of N, varying only slightly for $200 \leq N$. Maximum likelihood values of μ and σ^2 are more sensitive as can be seen from Table 1 below. In this table n is the sample size, N the number of fields in the play, and μ_0 and $\sigma_0{}^2$ are (approximate) MLE. As a function of N the value of the log-likelihood first increases slightly, reaching a local maximum at N = 303 then decreases until N = 2,000, at which point it again increases. At $N = \infty$, its value is -127.801. We emphasize that μ_0 and $\sigma_0{}^2$ are MLE for fixed N, and it is not true in general that that N yielding the largest log-likelihood value at the (conditional on N) maximum likelihood estimates μ_0 and $\sigma_0{}^2$ corresponds to a joint MLE of μ, σ^2, and N. However, in the absence of further information, N = 303 is a plausible point estimate of N.

Table 1. North Sea data.

n	N	μ_0	σ^3	Likelihood Value
24	200	2.47	1.45	-128.279
24	300	2.45	1.6	-128.124
24	303	2.422	1.569	-128.120
24	400	2.3	1.7	-128.179
24	500	2.32	1.6	-128.269
24	600	2.35	1.6	-128.369
24	750	2.5	1.3	-128.463
24	999	2.6	1.2	-128.314
24	2,000	2.6	1.2	-128.894
24	5,000	2.6	1.2	-127.551
24	10,000	2.6	1.21	-127.425
24	20,000	2.6	1.21	-127.362
24	10^5	2.59	1.22	-127.31
24	∞	2.51275	1.27988	-127.80

Were the 24 observations used here taken to be values of independent lognormal random variables; N plays no role whatsoever, and MLE of μ_0 and of σ_0^2 are 3.78 and 1.28 respectively, implying an M_1 at these values of 833,319,000 barrels of recoverable oil in place--a number about 3.4 times larger than that produced by use of eq. (3).

This preliminary study of North Sea data will be repeated and expanded using a uniform expansion of the density of the $\tilde{Y}_j$s.

Given an approximation to the conditional moments $E(\tilde{Y}_n^k|Y_1,\ldots,Y_{n-1})$ of $\tilde{Y}_n$ given $Y_1,\ldots,Y_{n-1}$ a nonlinear least squares method for estimating μ, σ^2, and N can be designed by re-expressing $\tilde{Y}_n$ given $Y_1,\ldots,Y_n$ in terms of a new random variable $\tilde{\varepsilon}_n$ defined by $\tilde{Y}_n = E(\tilde{Y}_n|Y_1,\ldots,Y_{n-1})\cdot\tilde{\varepsilon}_n$, for n = 1,2,... for then

$$\tilde{Y}_1 = E(\tilde{Y}_1)\tilde{\varepsilon}_1$$

$$\tilde{Y}_2 = E(\tilde{Y}_1\ Y_2)\tilde{\varepsilon}_2$$

$$\vdots$$

$$\tilde{Y}_n = E(\tilde{Y}_n|Y_1,\ldots,Y_n)\tilde{\varepsilon}_n$$

is regression-like. Bayesian methods can in principle also be used to derive posterior distributions for parameters and predictive distributions for $\tilde{Y}_n$, $\tilde{Y}_{n+1},\ldots,$ given $Y_1,\ldots, Y_{n-1}$. These are topics of current research.

TESTING OF ASSUMPTION II

We wish to test the hypothesis that observations are generated by sampling proportional to random size and without replacement (which we shall call H_0) against one or more specific alternative hypotheses (which we label $H_1,H_2,\ldots$). Such tests are tests of *model structure* rather than of model parameters, but require nonetheless that the model's parameters be estimated. We propose several, none of which we have yet thoroughly investigated.

One is a likelihood ratio test of H_0 against the hypothesis that pool sizes are generated lognormally and sampling is without replacement such that pools remaining to be discovered each have an equally likely chance of being discovered next. The sampling density of $\underline{Y}$ for H_0 and H_1 are

$$H_0:\quad I_{N,n}(\underline{Y}) \prod_{j=1}^{n} Y_j f(Y_j) \equiv \ell(\mu,\sigma^2|N,\underline{Y};H_0)$$

and

$$H_1: \prod_{j=1}^{n} f(Y_j) \equiv \ell(\mu,\sigma^2|N,\underline{Y};H_1)$$

where f is lognormal with parameters μ and σ^2.

Defining g as the geometric mean $[\prod_{j=1}^{n} Y_j]^{1/n}$ of $Y_1,\ldots,Y_n$ and $s^2 = \frac{1}{n}\sum_{j=1}^{n} [\log Y_j - \log g]^2$, at the ordinary MLE's log g and s^2 of μ and σ^2 respectively, the density

$$\prod_{j=1}^{n} f(Y_j) = [\sqrt{2\pi}sg]^{-n}e^{-n/2} \quad .$$

For the North Sea data cited earlier, $\log_e\{\prod_{j=1}^{n} f(Y_j)\} = -127.80$. The corresponding value when H_1 obtains and N = 303 is -128.12, so that the likelihood ratio is

$$\frac{\ell(\mu_0,\sigma_0^2|N,\underline{Y};H_0)}{\ell(\log g,s^2|N,\underline{Y};H_1)} = e^{-.320} = .726 \quad .$$

After 24 discoveries, H_1 seems slightly more favorable. If we use only the first 20 field sizes discovered, the ratio is 1.335; the change is primarily owing to the twenty-second discovery being roughly eight times the geometric mean of discovery sizes for n = 20. Without further investigation we conclude that these 24 observations are not decisive in favoring one of the two hypotheses.[1] If the distribution of the likelihood ratio can be computed, it is possible to be more precise.

A Bayesian version of a test of H_0 versus H_1 generating posterior odds in favor of or against H_1 can be done provided that a (proper) prior distribution for parameters is given. Zellner (1970) gives a thorough account.

Once we have discovered every pool in a play (an admittedly unlikely event), it is possible to test Assumption II against specific alternatives without any reference to the density f, regarding the sizes of discoveries as a finite

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[1] The leasing pattern for North Sea tracts undoubtedly influenced the ordering of discoveries, and should be taken into account.

population of known values from which we have sampled.[2] Given all pool sizes in the play, $A_1,\dots,A_N$, Assumption II says that the probability of observing them in a particular order, say, $A_1,A_2,\dots,A_N$ is $\prod_{j=1}^{N} A_j/(A_j + \cdots + A_N)$. The equivalent version of H_1 as given above is H_1: 1/N!. Thus the likelihood ratio becomes

$$N! \prod_{j=1}^{N} A_j/(A_j + \cdots + A_N) \quad . \tag{5}$$

Simple arithmetic shows that the value (5) is extremely sensitive to the order in which the A_is are observed if their range of values is large.

If we add a number α to each A_j, and write

$$\prod_{j=1}^{N} (A_j + \alpha)/(A_j + \cdots + A_N + [N - j + 1]\alpha) \tag{6}$$

in place of $\prod_{j=1}^{N} A_j/(A_j + \cdots + A_N)$, then when α is zero, eq. (6) conforms to H_0, and when $\alpha \to \infty$, eq. (6) conforms to H_1. Finding the value of α that maximizes eq. (6) is informative about which of the two hypotheses is more likely.

It is usually the case that all pools in a play have not been discovered. Defining S_{N-n} as the sum of sizes of undiscovered pools in a play with N pools, given H_0 the probability of observing sizes $A_1,\dots,A_n$ in that order is

$$\prod_{j=1}^{n} A_j/(S_{N-n} + A_j + \cdots + A_n) \quad . \tag{7}$$

Given an independently generated estimate of S_{N-n}, eq. (7) can be used for testing in the same fashion.

While incomplete in detail and in scope, this brief discussion of ways to test one of our basic assumptions gives the flavor of the kind of statistical analysis we feel is necessary to validate model structure.

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[2] We wish to thank Frank Anscombe and John Hartigan for suggesting how to test given this view of the problem.

OTHER SUBMODELS

In Kaufman (forthcoming) we outline the structure of submodels of wildcat successes and failures, of the economics of a single exploratory venture and of a "capital market" for exploratory ventures. Details will be forthcoming in the Sloan School working paper series.

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HYPOTHETICAL PROBABILISTIC PROTOTYPE OF AN UNDISCOVERED RESOURCES MODEL

Yu. A. Rozanov

Interest in problems of undiscovered resources was stimulated recently by the energy crisis; in particular, the use of some kind of probabilistic models for undiscovered resource estimating was discussed in the Proceedings of the last American Institute of Petroleum Geologists (AIPG) Research Symposium (1974). We suggest in this paper a possible hypothetical prototype for a probabilistic resource allocation model.

Suppose all principal (geological-geographical) resource allocation areas are defined. Two questions arise at the outset: How are the resource areas distributed over the earth? and How are resources distributed in each area of a given type?

We shall deal with world resources (that is, oil) considering sufficiently large areas S; it seems reasonable to assume that (random) resource fields in different areas may be treated as independent. But even large resource areas are sufficiently small compared with the earth's surface, and one may treat them as "random points." Moreover, one may realize that God during Creation threw these points <u>randomly</u> over the earth, so that Poisson distribution may be a satisfactory hypothetical model for resource areas allocation. (For conditions under which Poisson distribution arises, see for example Feller, 1950, 1957). Thus in a large region A (say, of a few million square km) one may expect to find different types of resource areas. Hypothetically we may have:

n_1 times the type S_1

n_2 times the type S_2

. . . .

n_k times the type S_k

(for rather <u>small</u> $n_1, n_2, \ldots, n_k$) with probability

$$\prod_{i=1}^{k} \frac{(|A|\lambda_i)^{n_i}}{(n_i)!} e^{-|A| \sum_{i=1}^{k} \lambda_i} \tag{1}$$

where $|A|$ characterizes the proper size of the region A considered, and parameters λ_i characterize the mean values of different areas of type S_i "per unit" of the region A.

It seems reasonable to assume that parameters λ_i do not depend on the region A, or depend on

$$\lambda_i(A) = \begin{cases} \lambda_i & \text{if } S_i \text{ is consistent with } A \\ 0 & \text{if } S_i \text{ is not consistent with } A \end{cases} .$$

In the case where $\lambda_i(A) = 0$, we certainly have $n_i = 0$, so we have to set

$$\frac{0^{n_i}}{n_i!} = \begin{cases} 1 , & n_i = 0 \\ 0 , & n_i \neq 0 \end{cases}$$

in equation (1).

Let us now consider the resource area S of a certain geological-geographical type. The notion of resource areas is suggested by the intuitive assumption that the resource field in such an area is homogeneous, that is, that a total resource volume under a surface point $x \in S$ may be described by the random variable

$$\xi(x) , \; x \in S \quad , \tag{2}$$

which forms a random homogeneous field (with a probability distribution depending on the resource area S considered).

The homogeneity of $\xi(x)$, $x \in S$, formally means that it is part of homogeneous random field

$$\xi(x) , \; x \in R^2$$

and in particular that

$$E\eta(x) = \mu = \text{const}$$

$$E[\eta(x)\eta(y)] = E[\eta(x - y)\eta(0)] = R(x - y) \quad . \tag{3}$$

It seems reasonable to assume that the following property of the relationship among variables $\xi(x)$, $x \varepsilon S$, holds true. Let us consider some region $A \subseteq S$ with boundary $\Gamma = \delta A$. Suppose we know exactly the resource depth along the boundary Γ so one may thus consider

$$\xi(x), \quad x \varepsilon \Gamma \quad ,$$

as given.

Then the (conditional) probability distribution of variables

$$\xi(x), \quad x \varepsilon A$$

inside region A, for a given resources allocation outside A, is determined by the boundary resources $\xi(x)$, $x \varepsilon \Gamma$.

Let us consider only a discrete allocation parameter x, say $x = (x_1, x_2)$ where x_1, x_2 run integer numbers, and take a certain $x = (x_1, x_2)$ with the nearest points y, $|y - x| = 1$. Our assumption concerning the relationship among $\xi(x)$, $x \varepsilon S$, that was just described may be formulated in the following way. The conditional probability distribution of variable $\xi(x)$ in the case of fixed resources $\xi(y)$, $y \neq x$ is determined by the nearest resources $\xi(y)$, $|y - x| \leq 1$. This qualitative assumption immediately gives us the following quantitative result.

The correlation function R(x) for a general homogeneous field may be represented as

$$R(x) = \int_{-\Pi}^{\pi} \int_{-\Pi}^{\pi} e^{i(x_1\lambda_1 + x_2\lambda_2)} f(\lambda_1, \lambda_2) \, d\lambda_1 \, d\lambda_2 \quad . \qquad (4)$$

In our case this corresponds to the spectural density

$$f(\lambda_1, \lambda_2) = \frac{6^2}{1 - a_1 \operatorname{Cos} \lambda_1 - a_2 \operatorname{Cos} \lambda_2} \qquad (5)$$

with parameters $6^2 > 0$, $|a_1| + |a_2| < 1$ (see, for example, Rosanov, 1967).

If we assume in addition that our field is isotropic (that is, that correlation in both orthogonal directions is the same), then

$$a_1 = a_2 = a \quad , \quad |a| < {}^1\!/_2 \quad .$$

Note that if the resource volume $\xi(x)$ discovered at point x is considerably less/more than usual, then it seems natural to expect similar phenomena at the nearest points y, $|y - x| \leq 1$. Accordingly one may assume that variables $\xi(x)$, $x \varepsilon S$, are positively correlated, that is,

$$R(x) \geq 0 \quad . \tag{6}$$

This property of the correlation function holds true if the corresponding parameters a_1, a_2 in formula (5) are positive:

$$a_1, a_2 > 0 \quad . \tag{7}$$

Indeed, functions Cos λ_1, Cos λ_2 as well as their products $(\text{Cos } \lambda_1)^{n_1}$ and $(\text{Cos } \lambda_2)^{n_2}$ are positively defined functions, so the spectral density

$$f(\overline{\lambda}) = 6^2 \sum_{n=0}^{\infty} (\alpha_1 \text{ Cos } \lambda_1 + \alpha_2 \text{ Cos } \lambda_2)^n$$

is of a similar type, that is,

$$\sum_{k,j} C_k C_j \text{ if } (\overline{\lambda}_k - \overline{\lambda}_j) \geq 0$$

for any constants $C_1, \ldots, C_m$; and its Fourier coefficients $R(x)$, $x = (x_1, x_2)$, are non-negative.

Of the "standard" multidimensional probability distributions one may, to describe the resource field, use the so-called Γ-distribution which gives a good fit with positive, positively correlated random variables $\xi(x)$, $x \varepsilon S$ with the given correlation function $R(x)$ (see, for example, Rosanov, 1974). But for a sufficiently large resource area S it seems reasonable to assume that the total resource volume

$$\sum (S) = \sum_{x \varepsilon S} \xi(x) \tag{8}$$

is a random variable with Gaussian distribution, because variables $\xi(x)$ are weakly dependent (similarly to a Markov chain) and the central limit theorem may be applied.

We have

$$E \sum (S) = \mu \cdot |S|$$

where $|S|$ is a number of resource points $x \varepsilon S$ and μ is the mean value of resources at each point,

$$\sigma^2(S) = \mathrm{Var} \, \Sigma \, (S) = \sum_{x,y \varepsilon S} R(x - y)$$

$$= \int_{-\Pi}^{\pi} \int_{-\Pi}^{\pi} |\phi(\lambda_1, \lambda_2)|^2 \, f(\lambda_1, \lambda_2) \, d\lambda_1 \, d\lambda_2$$

where

$$\phi(\lambda_1, \lambda_2) = \sum_{x \varepsilon S} e^{i(x_1\lambda_1 + x_2\lambda_2)} \quad .$$

Thus, one may believe that the total resources in the area S will be within the limits

$$\mu \cdot |S| + r_1 \, \sigma(S) \leq \Sigma \leq \mu \cdot |S| + r_2 \, \sigma(S) \qquad (9)$$

for any $r_1 \leq r_2$ with the corresponding probability

$$\Phi(r_2) - \Phi(r_1) = \frac{1}{\sqrt{2\pi}} \int_{r_1}^{r_2} e^{-u^2/2} du \quad . \qquad (10)$$

Considering a large region A with various resource areas $S_1, \ldots, S_n$ one may treat the resources

$$\Sigma \, (S_k) \quad ; \qquad k = 1, \ldots, n \quad ,$$

as independent Gaussian variables. When all areas $S_1, \ldots, S_n$ are known, the total resource volume

$$\Sigma \, (A) = \sum_{k=1}^{n} \Sigma(S_k) \qquad (11)$$

is also a Gaussian variable with the mean value

$$E \, \Sigma \, (A) = \sum_{k=1}^{n} E \, \Sigma \, (S_k)$$

and variance

$$\sigma^2(A) = \mathrm{Var} \sum (A) = \sum_{k=1}^{n} \sigma^2(S_k) \quad .$$

In the event of an absolutely undiscovered region A, according to eq. (1) the random variable $\sum$ (A) may be assumed to have a probability distribution which is a mixture of the Gaussian distributions with mean values

$$n_1 E \sum (S_1) + \cdots + n_k E \sum (S_k)$$

and variances

$$n_1 \sigma^2(S_1) + \cdots + n_k \sigma^2(S_k)$$

with the corresponding weights

$$\prod_{i=1}^{k} \frac{(|A|\lambda_i)^{n_i}}{(n_i)!} e^{-|A| \sum_{i=1}^{k} \lambda_i}$$

It is supposed that a "size" $s = |S|$ is one of the parameters which characterize the proper resource area of type S. One may consider a more sophisticated model, assuming that the size $s = |S|$ of any type S is an uncertain variable with a probability distribution depending on this type S. But in this case the "mixed Gaussian distribution" of the total resources $\sum$ (A) (see eq. 11)) will be more complicated.

Note that all parameters of our probabilistic model may be estimated with proper statistical data in a standard way. Some specificity may be found for the parameters a_1, a_2 in eq. (5). The probabilistic meaning of these parameters is the following:

$$\Delta\xi(x) = \xi(x_1, x_2) - \alpha_1\Big[\xi(x_1 + 1, x_2) + \xi(x_1 - 1, x_2)\Big] - \alpha_2\Big[\xi(x_1, x_2 + 1) + \xi(x_1, x_2 - 1)\Big] \qquad (12)$$

a random variable which, for $\alpha_1 = a_1$, $\alpha_2 = a_2$ and any $x = (x_1, x_2)$, is in the wide sense independent of the field

$\xi(y)$, $y \neq x$; and particularly (a_1, a_2) is the minimum point of

$$F(\alpha_1,\alpha_2) = E|\Delta\xi(x)|^2 \quad .$$

According to this phenomenon we may suggest estimating unknown (a_1,a_2) by observations $\xi(x)$, x S, as the minimum point of the function

$$\Phi(\alpha_1,\alpha_2) = \sum_x |\Delta\xi(x)|^2$$

where $\Delta\xi(x)$ is defined in eq. (12).

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A PROBABILITY APPROACH TO ESTIMATE VOLUMES OF UNDISCOVERED OIL AND GAS

R. E. Roadifer

INTRODUCTION

Hydrocarbon resources or potential ultimate recovery may be classified as shown by Figure 1. The proved plus prospective ultimate recovery is the total discovered recoverable from known fields. The cumulative production is the best known because it has actually been measured. Proved reserves are calculated with some uncertainty, but are generally well grounded enough to serve as collateral to borrow money. Prospective reserves are not as well known as proved reserves, but they are discovered and calculated on engineering bases.

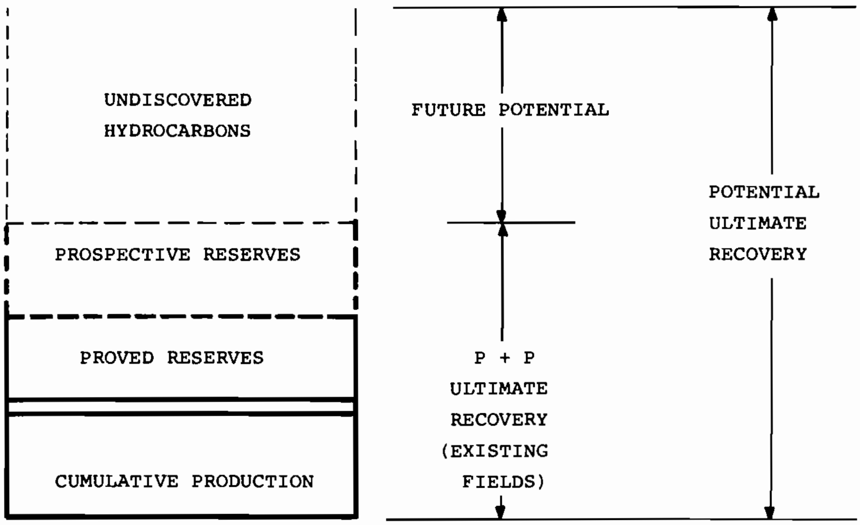

Figure 1. Classification of hydrocarbons used in this report.

The Future Potential or Undiscovered Hydrocarbons is the least known quantity within the classification and it is the part of the Potential Ultimate Recovery that we are principally concerned with here. There is a finite limit to the potential ultimate recovery, but it is unknown at this time. Realizing that the precise actual value of the quantity of hydrocarbons ultimately recoverable is not obtainable, we nevertheless wish to approach as close as possible to that unknowable value and to express it in terms of risk or probability.

This method of estimating volumes of undiscovered oil and gas recognizes that exact answers are not attainable. The estimates involve considerable subjectivity, but they are based on geological and geophysical data. The input and results are expressed as ranges of values, rather than only as single values.

The factors controlling volumes of oil and gas have been analyzed and defined by the parameters shown on Table 1. A) Untested area within trap is usually the most difficult of all of the parameters to determine, and it has the greatest effect upon the results. B) Untested area expected to be productive expressed as a percent accounts for the fact that not all traps hold hydrocarbons and that the traps holding hydrocarbons are not necessarily entirely full. This may be stated as success times areal fillup. C) Pay thickness is estimated as an overall average value for all of the fields expected. D) Gas-oil mix is part of the model which has often been poorly understood. It is simply the ratio established by dividing total gas expressed as mcf by the total oil expressed as barrels in a play or basin. This parameter is used in the chain multiplication of the model to allocate reservoir volume, which has been established by producing parameters A), B) and C), to oil and to gas. Parameters E), F) and G) are recovery factors for oil, gas and natural gas liquids which may be obtained in a number of ways directly or by analogy for the reservoir types expected.

Table 1. Parameters.

A)	Untested Acreage Within Trap (mm ac)
B)	Untested Acreage Expected to be Productive (%)
C)	Average Pay Thickness (ft)
D)	Gas-Oil Mix (mcf/bbl)
E)	Oil Recovery (bbl/ac ft)
F)	Gas Recovery (mcf/ac ft)
G)	NGL Recovery (bbl/mmcf)

It is necessary to define the basic exploration unit within which the parameters are estimated in addition to defining the parameters for which individual probability estimates are made. Figure 2 shows a hypothetical basin that demonstrates the exploration play basin analysis and evaluation concept. A play may be geologically limited or it may be limited areally by political boundaries, by physiographic boundaries such as shorelines, by operational boundaries defined for company operations, etc. The play is also limited stratigraphically, that is, vertically, in order to evaluate the different reservoir types on different bases. For example, it is necessary to consider a deeply buried carbonate reservoir expected to yield gas separately from a shallow sandstone with oil. Several plays within a basin may be combined probabilistically into one basin estimate, but each parameter for each play is evaluated individually and on its own merit. This basin has a surface area of about 72,500 sq km or 28,000 sq miles. The stratigraphic section on the right indicates that there may be up to 8,000 meters of sedimentary section. One play is indicated by the cross-hatched area and the arrow on the column.

PROBABILISTIC ESTIMATES

An estimate for one parameter for one play will demonstrate the basic input probability estimate. Table 2 is a questionnaire of the type that may be used to collect estimates in the form of probability distributions. Notice that there are five value entry blanks which are to be filled in with the highest to lowest average pay thickness that the estimator can conceive and support. The question switches from the highest to the lowest estimate across 50%, so the completed questionnaire has probability estimates at 1%, 25%, 50%, 75% and 99%.

Figure 3 shows an estimate of pay thickness plotted as a cumulative probability distribution on both linear and logarithmic probability graphs. The log-probability plot is shown to demonstrate that the crucial factors of oil accumulations, for example their ultimate sizes, tend to conform to log-normal distributions. The linear plot demonstrates how the estimated frequency distributions are effective in the probability model. The mean of this probability distribution function (PDF) is calculated to be 78.9 feet, but the whole distribution is of greater importance in this program. Notice that the steeper segments of the curve in the vicinity of the mode define the values that will be encountered more often than other values by random selection along the probability scale. For example, values will be selected more often from the steeper part of the curve near the inflection point or mode above the median than from the more gently sloping part of the curve in the low probability, high value range. The actual estimates are at the five points shown on the distribution (1%, 25%, 50%, 75% and 99%). The distribution shows a range from a 99% chance that the average pay thickness is 30 feet or more to a 50% chance that it is 75 feet or more and a 1% chance that it is 150 feet or more.

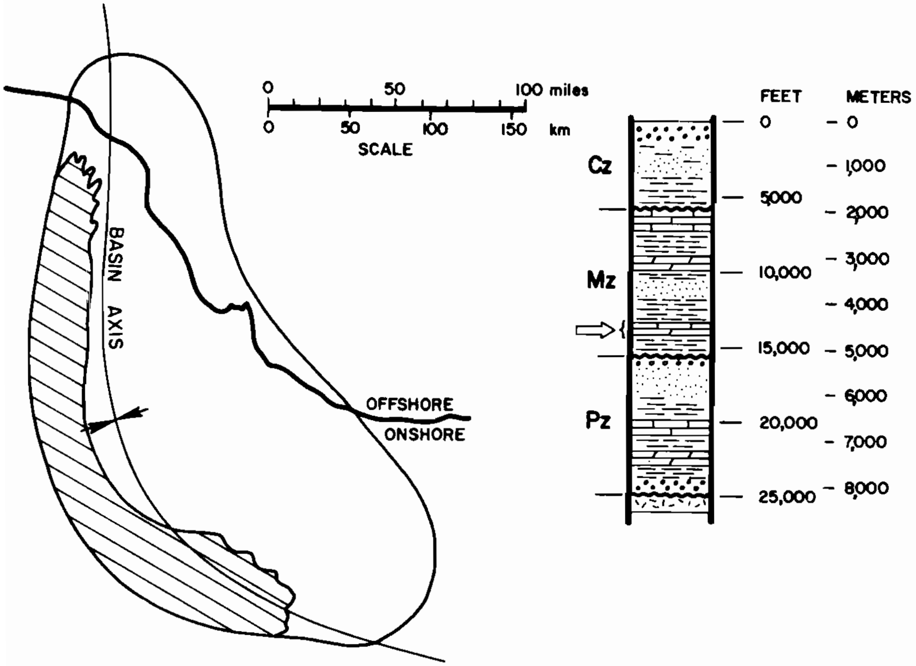

Figure 2. Basin X.

Table 2. Average feet of pay expected in the future (see definitions).

No more than 1% chance the average feet of pay will be as high as __________ feet.

No more than 25% chance the average feet of pay will be as high as __________ feet.

There is a 50/50 chance the average feet of pay will be __________ feet.

No more than 25% chance the average feet of pay will be as low as __________ feet.

No more than 1% chance the average feet of pay will be as low as _________ feet.

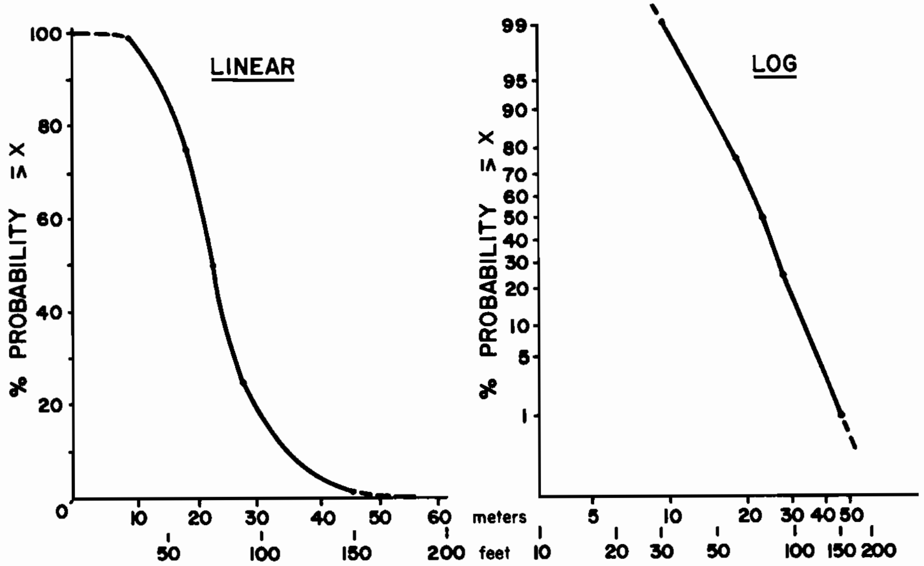

Figure 3. Estimated average pay thickness cumulative probability M. basin, continental tertiary onshore and offshore.

For a given play, probability estimates similar to the thickness estimate are made for each of the seven parameters. A complete matrix of 35 estimates for one play is shown by Table 3, including the thickness estimate which was shown in detail. Notice that the method allows for the possibility in some cases that there may be a risk that no hydrocarbons are present. In this case a zero is entered under 99% for untested acreage expected to be productive. The estimated chance that there is no hydrocarbon bearing trap truncates the distribution, but provides a 75% chance that .6% or more of the area in the trap may be productive. The estimate ranges up to 9% productive at the 1% chance. The 9% productive is derived from 30% of the traps estimated to be hydrocarbon bearing and those traps averaging 30% areally filled. This matrix of probability estimates plus the two single-value estimates for GOR and gas conversion comprise the input data for a computer program.

Table 3. Input parameters probabilistic estimate future potential m. basin, continental tertiary onshore-offshore.

Parameters	Probability				
	1%	25%	50%	75%	99%
A. Untested area within Trap (mm ac)	3.5	1	.6	.35	.1
B. Untested Area Expected to be Productive (%)	9	2.5	1.5	.6	0
C. Average Pay Thickness (ft)	150	90	75	60	30
D. Gas-Oil Mix (mcf/bbl)	15	6	4	2.7	1
E. Oil Recovery (bbl/ ac ft)	450	340	300	260	200
F. Gas Recovery (mcf/ ac ft)	1,700	1,100	950	800	500
G. NGL Recovery (bbl/ mmcf)	40	20	15	10	5

Note: GOR = 1 mcf/bbl.
Gas Conversion 6 mcf/bbl.

It is evident that assembly of such estimates requires a large effort and vast expertise. There is no way that we know of to avoid some subjectivity in the estimates, but this method does emphasize objectivity. Although the method utilizes a statistical approach, it also employs geological and geophysical data. One way to handle this large data gathering problem is to rely upon experts in the field who have the most current information on individual areas and plays. The estimates gathered from the experts are reviewed by a small monitor group of about three people. The monitor group questions the experts to reveal and examine the background data and thought processes that have gone into the estimates. The process of arriving at the final assessments is, we may say, a modified Delphi technique. The monitor group also "filters" the data to adjust, if necessary, for differences in judgment across boundaries of responsibility, etc.

COMPUTER PROGRAM

A flow chart of the computer program which uses Monte Carlo simulation to examine each of the input distributions an exhaustive number of times and product it with the other parameters is shown by Figure 4. As indicated in the lower left corner, the probability estimates used in the program are identified by oblong hexagons. Total reservoir volume is determined in the sequence indicated across the top of the flow chart. The operation indicated in the upper right corner is the step in the simulation where the total reservoir volume is separated into oil-bearing and gas-bearing fractions. The oil and gas components of the computation are then operated upon separately and at last combined together with the single-value estimates of GOR and gas conversion into oil equivalent. Results may be obtained as frequency distributions of oil only, gas only, or gas, oil and natural gas liquids combined into barrels of oil equivalent (BOE).

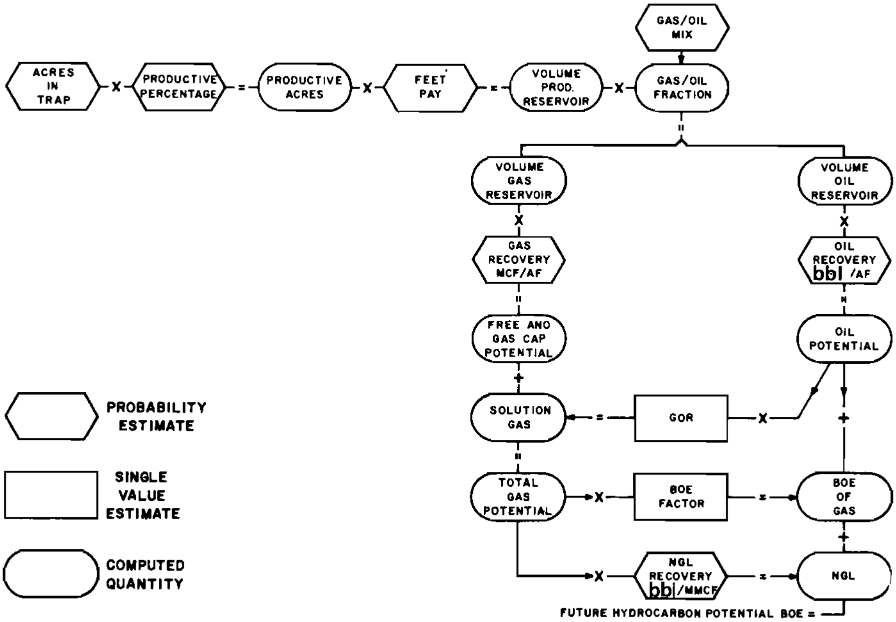

Figure 4. Flow chart estimate of future hydrocarbon potential.

PROBABILITY RESULTS

The frequency table calculated by the computer, from the complete input matrix, is shown in Table 4. The printout shows near the top that the computation is based on 1,000 observations, which means that there have been 1,000 passes for each of the calculation steps or, in other words, the input distributions

Table 4. Frequency table of future hydrocarbon potential (in mm BOE).

		Density		Cumulative	
Interval Range		Frequency	Percentage	Frequency	Percentage
0.0	0.0	11	1.10	11	1.10
0.0001 -	30.1245	145	14.50	156	15.60
30.1245 -	68.7456	134	13.40	290	29.00
68.7457 -	118.2598	148	14.80	438	43.80
118.2599 -	181.7396	93	9.30	531	53.10
181.7397 -	263.1240	101	10.10	632	63.20
263.1240 -	367.4629	72	7.20	704	70.40
367.4629 -	501.2307	57	5.70	761	76.10
501.2307 -	672.7278	53	5.30	814	81.40
672.7278 -	892.5962	52	5.20	866	86.60
892.5962 -	1174.4785	32	3.20	898	89.80
1174.4785 -	1535.8665	41	4.10	939	93.90
1535.8665 -	1999.1843	17	1.70	956	95.60
1999.1843 -	2593.1816	16	1.60	972	97.20
2593.1816 -	3354.7168	8	0.80	980	98.00
3354.7168 -	4331.0430	9	0.90	989	98.90
4331.0430 -	5582.7422	9	0.90	998	99.80
5582.7422 -	7187.4883	2	0.20	1000	100.00
7187.4883 -	9244.8555	0	0.0	1000	100.00
9244.8555 -	Over	0	0.0	1000	100.00

(.263) Mean = 445.891 Variance = 632110.563 Uncertainty = 14.658

Value at 20 percent = 42.8060
Value at 80 percent = 627.4292

Oil potential - 251.6925 mm bbl
Gas potential - 1155.7419 bcf
NGL potential - 19777.9531 m bbl

have each been sampled 1,000 times in a Monte Carlo simulation procedure. The mode or most-likely value of the distribution is in the interval range 69-118 MMBOE at about 56% probability. The median is, of course, at 50% by definition. The expected value is recorded at the bottom of the table together with the probability of its occurrence, its variance and a measure of uncertainty. In this case at 14.6, the uncertainty, determined by dividing the value at 20% probability by the value at 80% probability, is high. The probability of the expected value is low at about 26%. The high uncertainty or conversely the low probability gives an impression of the uncertainty of the input estimates used in the simulation. At the bottom of the output sheet, oil, gas and NGL potential have been separated out of the expected value which is given in terms of all three combined as BOE.

Figure 5 is a linear scale graph of the frequency table in Table 4. It shows graphically that there is no certainty in the estimate of the presence of hydrocarbons in this particular play. The mode or most-likely value is in the steepest part of the curve, at the inflection point, above the median. The expected value of 446 million BOE is labeled at about 26% probability, and the graph shows that in the very high-risk, low probability range there is a remote chance of values up to nearly 6 billion barrels equivalent of oil and gas combined.

The computer program stores the calculations from each play to combine the results finally for all of the plays in a basin, as shown by Figure 6. The probability scale here is the same as that shown on the last graph of a single play, but the X-axis values are much larger. Note that with all of the plays combined, this distribution indicates a certainty of some hydrocarbons in the basin. The shoulder at the top of the graph indicates that there is a virtual certainty of nearly half a billion BOE. The uncertainty for all of the play estimates combined is much less than for the single play shown. The expected value of about 3 1/3 billion BOE is at 35% probability, and there is a slight chance of nearly 20 billion BOE.

The frequency distribution results are obtainable by play and by basin as we have seen. They may also be combined into assigned regions, continents or world compilations all by probability simulation. Output frequency tables may be obtained in terms of oil only or gas only in addition to the combined or BOE presentation. The known volumes of hydrocarbon production and reserves in developed basins comprise the remainder of the ultimate potential, which is entered into the program for each basin or area where applicable.

CONCLUSION

It is important to evaluate the separate parameters of hydrocarbon accumulations rather than to estimate quantities of oil and gas directly. Better estimates result from analysis of a hydrocarbon generation-trap system than from direct estimating of hydrocarbon volumes because the component parameters can be measured or evaluated more directly. The

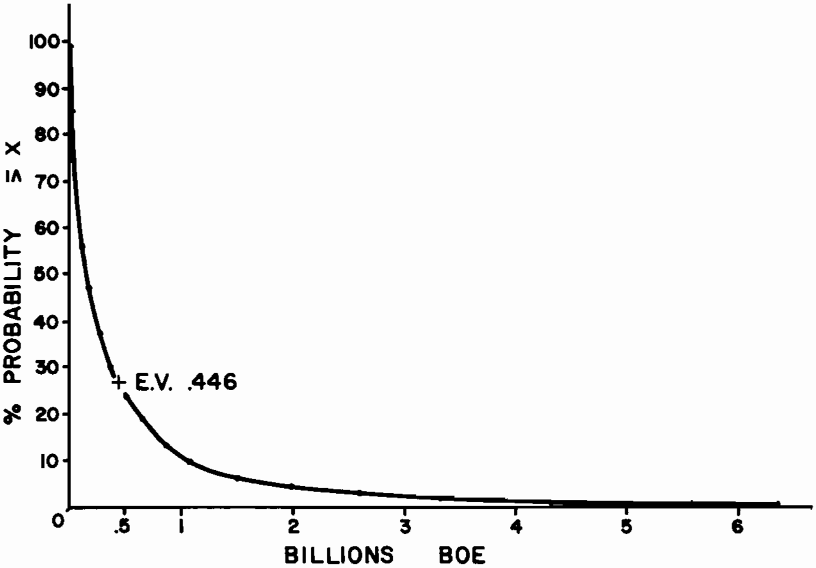

Figure 5. M. basin continental tertiary onshore and offshore future potential (uncertainty 14.6).

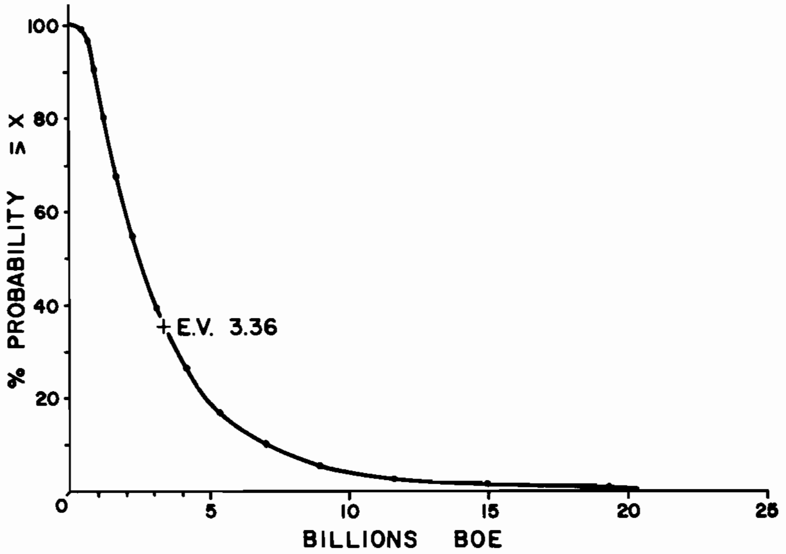

Figure 6. M. basin future potential (uncertainty 3.8).

individual probabilistic estimates of the parameters are documented as input and recorded in the output, so they may be reviewed and updated readily when new data are available. We feel that the greatest single potential weakness of this system is the play that has not been conceived.

The estimates resulting from this kind of rigorous analysis are valuable for private company selection of exploration ventures. Because the estimates are presented as probability distributions, they provide an evaluation of the chances that there may be large volumes of hydrocarbons as well as a near certainty of estimated small volumes. When single-value estimates are required, the expected value is the best estimate. Such estimates may also provide reasonable appraisals of regional, continental or worldwide resources.

ACKNOWLEDGMENTS

Mobil Oil Corporation's permission to publish this discussion is gratefully acknowledged. Many Mobil Oil employees, particularly explorationists and computer science personnel, contributed to the development of this system of estimating future hydrocarbon potential. Contributors are too numerous to list all of them by name. Most of the geological-technical development work was by O.B. Shelburne and G.A. Atkinson.

HYDROCARBON ASSESSMENT USING SUBJECTIVE PROBABILITY AND MONTE CARLO METHODS

K. J. Roy

INTRODUCTION

This paper deals with the problems encountered in deciding on the best methods to evaluate oil and gas potential and the solutions to which we came. The philosophy behind the methodology and the mechanics of the assessment scheme are discussed also.

Estimates of hydrocarbon resources are made primarily as a basis for planning. To be satisfactory, an estimate of hydrocarbon resources should answer the questions:

1) How much pooled hydrocarbon exists?
2) Where is it?
3) How much is oil and how much is gas?
4) What size accumulations are expected?
5) How certain are the estimates?

Often, despite lack of data and the consequent uncertainty, decisions must be made. Under these circumstances the questions above are best answered by providing a range of estimated values and their probability of occurrence. The smaller the data base the greater the uncertainty and the larger the range of possible values, but the decision maker has in hand a range of estimates and the probability at which they occur. In the case where data are abundant, the range of estimates may be small and the margin of error low. The risk of the venture must be weighed against the return in deciding a course of action.

The Department of Energy, Mines and Resources, Canada, has made three assessments of Canada's hydrocarbon resources since 1970. (The estimates of resources combine proven reserves with estimates of undiscovered recoverable potential. Undiscovered recoverable hydrocarbon potential is the quantity of undiscovered oil and gas that is postulated to be present in new pools and that is recoverable from a well bore by conventional technologies. In this paper, the term potential will refer to undiscovered recoverable hydrocarbon potential).

The first estimate, made in 1972, used the volumetric method[1] and produced single number estimates. The 1973 assessment was made using a "volumetric" method but included qualitative consideration of "exploration plays". To incorporate uncertainty, the estimates were given in the form of cumulative distribution functions but Monte Carlo methods were not used. The 1974 estimates were made using Monte Carlo methods and the "exploration play" method was used where possible. The results were reported as cumulative distribution functions which indicated the probability of occurrence at each of the estimated values. Incorporated in the answer was the possibility that pooled hydrocarbon does not occur in any given prospect.

METHOD

A major problem in assessing Canada's hydrocarbon potential is evaluation of the frontier areas where, in many cases, little drilling has been done and data are sparse. The methods described here focus on this type of situation. The subjective opinion of experts, after consideration of the facts, is the basis of the estimates. The assessment is done by a committee of geologists from the staffs of the Departments of Energy, Mines and Resources and Indian and Northern Affairs. Data are collected, analyzed and presented by geologists and geophysicists working in the areas to be assessed. After consideration of the available information, the committee decides on the approach to take and makes the assessment.

The assessment methods:

a) Break the estimating procedure into component parts in order that the assumptions and decisions made at each step can be critically examined by the committee and, if necessary, by others;

b) Incorporate into the estimate the probability (the "risk") that any factor related to the hydrocarbon occurrence has a value less than or equal to some minimum value; and

c) Express the estimate of potential as a range of values of potential and the probability of occurrence of any value in the range.

The estimate of potential can be considered as a solution to an equation relating a series of variables to hydrocarbon potential. In general, the specific values of most of the variables in the potential equation is unknown, and it is possible for any of the variables to have a wide range of

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[1] An assessment method in which potential is calculated as the product of a volume of rock and a yield of hydrocarbon per unit volume.

The marginal probability, the probability that pooled hydrocarbon occurs in any given prospect, is obtained by consideration of the "oil occurrence factors" in light of available data. In this example, it is estimated that there is a 0.8 chance that any given prospect in the play will have an area of closure greater than one square mile, that the reservoir facies exist throughout the area (probability of 1), and that there is a 0.8 chance of it having porosity greater than the minimum cutoff value. From regional considerations the seal is considered adequate (probability of 1), but the timing of the structures is late relative to suggested time of hydrocarbon migration (probability 0.5). Preliminary geochemical work indicates that the source may be inadequate (probability of 0.5). Preservation and recovery are adequate. The product of the marginal probabilities is 0.16. The factors considered in arriving at the total marginal probability are not the complete list, but only those that generally are considered the most important. The marginal probability can be interpreted as an estimated success ratio--16% of the prospects are expected to contain pooled hydrocarbons or a given prospect has a 16% chance of containing pooled hydrocarbons. The size of the pool is, however, unspecified. It is important to assess down to very small pool sizes so that the total spectrum is included. After this is done, the distributions can be truncated, without redoing the estimate, at any minimum size required.

The probability distribution describing the potential of the play can be expressed as follows:

$$P\ (\text{Play Potential}) = P\ (\text{Prospect Potential}) \cdot P$$

$$(\text{that there is pooled hydrocarbon in a prospect}) \cdot$$

$$P\ (\text{number of prospects}) \quad .$$

In the case where the number of prospects is expressed as a frequency distribution the equation is not solved directly. Rather, a random sample of the number of prospects curve determines the number of samples taken from the conditional pool size distribution for that particular iteration, and the "risk" factor determines the number of the samples that are nonzero. These nonzero samples are added to produce one estimate of play potential. A series of estimates is produced by successive iterations and are collected into a distribution of estimates of play potential. Figure 1 is a flow diagram of the steps in the method from definition of the potential equation to derivation of the play potential.

If the committee is not satisfied with the results after going through the assessment procedure, the committee then goes back to the distributions describing the variables and to the marginal probabilities and tries to change them. In some cases, new ideas or new data are available and rational changes can be made. Often they cannot and the committee must live with the estimates as given. The facility to critically examine the component parts is crucial in the very necessary reappraisal procedure.

values. Because there is a range of values associated with the variables, the solution to the equation will also have a range of values. This range is expressed in a frequency distribution of solutions that answers the question: what is the probability that the potential has a value greater than any given value? The distribution of answers is arrived at by stating the estimates of equation parameters in the form of subjective frequency distributions and combining them in the potential equation by Monte Carlo methods. (Cumulative distribution functions are drawn to describe the input variables because it is easier for the geologist to answer the question, What is the chance that the variable has a value greater than "x"? than it is to answer the question, What is the probability the variable value is "x"?)

The estimating of variable values is done in two steps. First the question is asked, given that the variable has a value greater than some selected minimum, What is the probability that its value will exceed $x_1, x_2, x_3, \ldots, x_{max}$? This defines a "greater than" cumulative density function (conditional probability) of estimated values conditional on the value being greater than a minimum cutoff. The next question is what is the probability (the marginal probability) that the value of the variable is greater than the minimum? This is given as a single number and results from consideration of available data and the committee's experience in petroleum geology in general. The two probability distributions can be combined, using Bayes' Theorem, to produce the joint probability distribution that indicates the committee's opinion of the chance of occurrence of any given value. Consideration of the estimates in terms of two separate probabilities (conditional and marginal) is done in order that assumptions and judgments can be more clearly identified. Also, it allows collection of the marginal probabilities into a single "risk" which can then be compared directly to estimators' opinion of the uncertainty of the venture.

The form of the "potential" equation is related to the nature of the data being considered. Although there are numerous variations, two basic equation types are the "volumetric" equation (Equation Type I, Table 1) and the "exploration play" equation (Equation Type II, Table 1).

The volumetric method makes use of analogues to the basin, area or rock unit under consideration. Volumetric assessment is usually done at the basin level and ultimate yield of recoverable hydrocarbon per unit volume of rock is determined for basins geologically similar to the basin under consideration (Klemme, 1971). The yield is multiplied, in a potential equation of Type I, by the volume of the basin to be evaluated. The approach is usually inadequate because most basins have no adequate analogues and, if they do, the proven ultimate potential figures are not available or are unreliable. The method is, however, a useful check on the "exploration play" method and, if very little data are available, the "volumetric" method may be all that is possible

Table 1. Examples of types of potential equations.

Equation I - "Volumetric"

$$\text{Potential} = \text{volume of the basin} \cdot \text{yield of hydrocarbon per unit volume} \;.$$

Equation II - "Exploration play"

$$\text{Potential} = \text{area of trap} \cdot \text{formation thickness} \cdot \text{porous fraction} \cdot \text{porosity} \cdot \text{trap fill} \cdot (1\text{-water saturation}) \cdot \text{oil fraction} \cdot \text{recovery factor} \cdot \text{dimension constants} \;.$$

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to use. It is necessary, however, to describe the yield and perhaps the volume by frequency distributions and to incorporate the possibility that the basin may be barren of pooled hydrocarbons.

In the "play" method, assessment is made of individual, demonstrated or conceptual, exploration plays in an area. The assessments are added, using Monte Carlo methods, to produce an estimate of the basin's recoverable hydrocarbon potential. The "play" method requires more data than the "volumetric" method but answers the questions, What are the sizes of the accumulations present? and, What is more specific as to where the hydrocarbon occurs? The answers to both questions are necessary for economic analysis of ventures in the region.

Exploration plays are composed of prospects, and play assessment is basically the addition of prospect assessments. It is desirable, but generally impossible, to identify all prospects and to evaluate them individually. What can be done is to produce frequency distributions that describe the range and frequency of occurrence of values that the parameters in the potential equation may have throughout all prospects in the play. These distributions, as drawn, are conditional on the variables having a greater than minimum value. Multiplication of parameter distributions produces the distribution of sizes of prospects in the play or the pool size distribution in the play conditional on pooled hydrocarbon occurring in the prospects.

The conditional distribution can be "risked" by multiplying the probability at each size value by the marginal probability (the chance of pooled hydrocarbon occurring) to produce the joint distribution which describes the probability that the pool size will be larger than a given value and incorporates the probability that, in a given prospect, there will be no pooled hydrocarbon. The joint distribution is combined again using Monte Carlo methods, with a distribution of estimates of number of prospects in the play to produce the distribution of estimates of play potential.

An example using Table 2 should clarify the procedure. The meaning of terms in Table 2 are generally obvious except for a few:

1) Reservoir thickness--thickness of rock with porosity greater than the minimum porosity cutoff.
2) Effective porosity--porosity greater than the porosity cutoff.
3) Trap fill--the fraction of the pore volume of the trap above the hydrocarbon-water contact.
4) Gas fraction--the fraction of the hydrocarbon in trap that is unassociated gas.

Assume a play in which the potential equation is:

Potential of a typical prospect = area of closure · reservoir thickness · effective porosity · trap fill · (1-water saturation) · gas fraction · recovery factor · expansion coefficient · dimension constants .

From consideration of the available data it is estimated that, given the prospects have geometric closure, the maximum area of closure of any structure in the area is estimated to be 50 square miles and the minimum, one square mile. From consideration of the structural style, seismic coverage, and other factors, the intermediate values are estimated. Using these numbers the conditional subjective probability distribution describing the area of closure of traps within the play is drawn. A similar procedure is used to obtain the distributions for the other parameters in the equation.

The basis of estimates of area, thickness and porosity are the geological and geophysical data in the region. Water saturation, recovery factor and expansion coefficients are arrived at by consideration of analogous reservoirs and general engineering principles. Trap fill is considered in terms of migration paths, quantity of source and drainage area. Gas fraction estimates result from consideration of geochemical data, burial history, and drilling results in the area. The distributions are multiplied, using Monte Carlo methods, to produce a distribution of estimated pool sizes conditional on the presence of pooled hydrocarbon (as in Figure 1).

Table 2. A data input form used in the assessment system.

NAME
BASIN/PLAY/PROSPECT LOCATION DATE BY

POTENTIAL EQUATION VARIABLES	CONDITIONAL PROBABILITY							OIL OCCURRENCE FACTORS		REMARKS
	100	95	75	50	25	5	0		MARGINAL PROBABILITY	
AREA OF CLOSURE VERTICAL CLOSURE VOLUME UNDER CLOSURE AREA OF PAY	1.0	10	18	23	26	33	50	PRESENCE OF GEOMETRIC CLOSURE	0.8	
RESERVOIR THICKNESS RESERVOIR FRACTION FORMATION THICKNESS	10			40			90	PRESENCE OF RESERVOIR FACIES	1.0	
"EFFECTIVE" POROSITY	0.08			0.12			0.16	PRESENCE OF POROSITY	0.8	
NET PAY								ADEQUATE SEAL	1.0	
TRAP FILL	0.05			0.4			0.7	ADEQUATE TIMING	0.5	
								ADEQUATE SOURCE QUALITY	0.5	
								ADEQUATE PRESERVATION	1.0	
RECOVERY FACTOR				0.35				ADEQUACY OF RECOVERY	1.0	
WATER SATURATION (FRACTION)				0.25						
SHRINKAGE (FRACTION)				0.7						
NUMBER PROSPECTS	3.0	8.0	15	20	25	40	60			
GAS FRACTION				0.5						
HYDROCARBON GAS FRACTION										
PROSPECT DEPTH										8,000 ft AVERAGE
PROVEN RESERVE										
								PRODUCT OF MARGINAL PROB.	0.16	

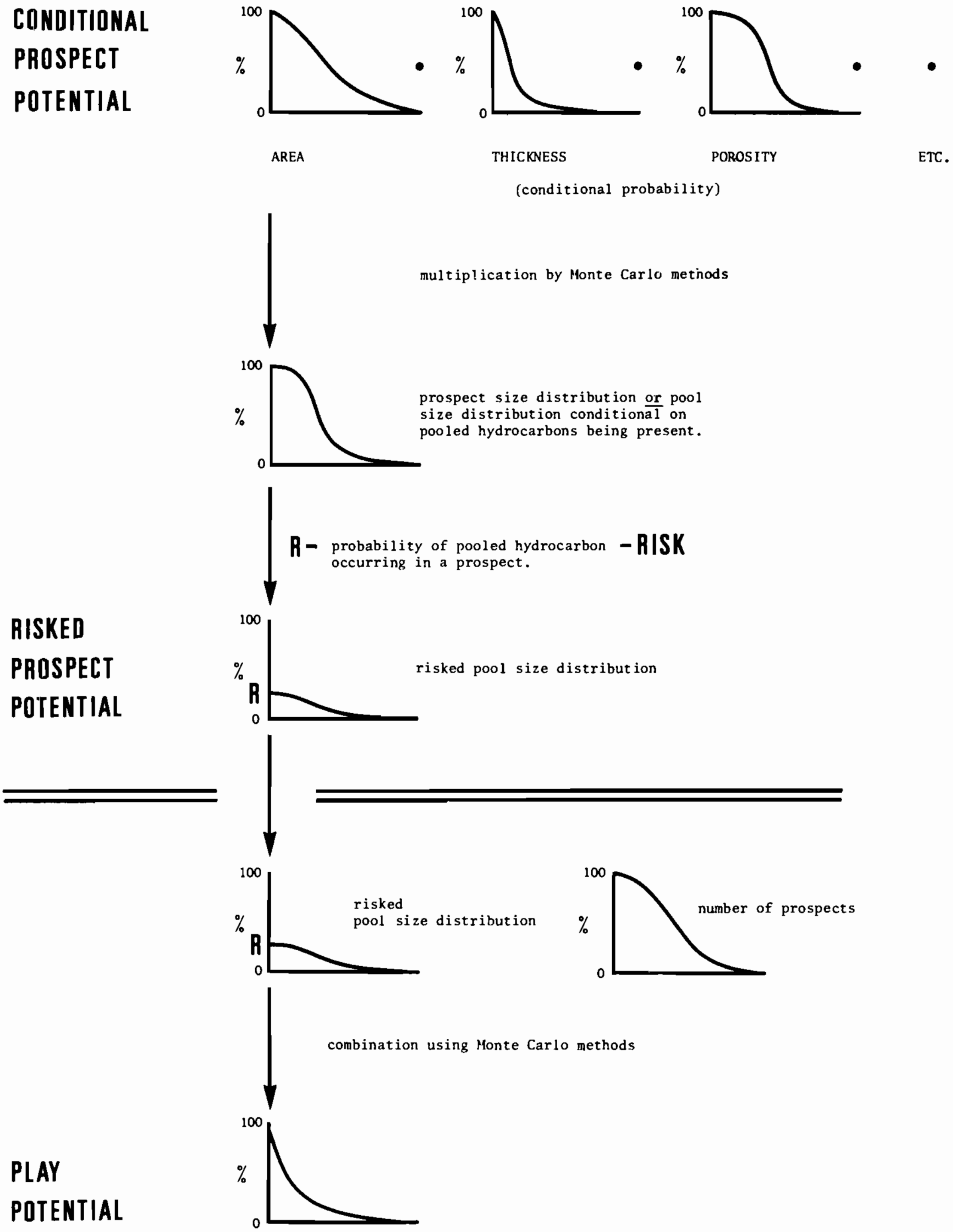

Figure 1. Flow diagram of procedure from definition of the potential equation to the production of estimates of play potential.

CONCLUSIONS

The "exploration play" method of assessment of hydrocarbon potential does the following:

a) It incorporates uncertainty into the estimates of potential.

b) It displays the possible range of estimates.

c) It indicates the expected pool-size distribution.

d) It indicates the general location of the hydrocarbon resource.

e) It breaks the assessment procedure into component parts that can be readily critically appraised.

Useful estimates of potential can be made under conditions of great uncertainty. The key work is useful. To be useful, the estimate must indicate the range of possible values and the uncertainty associated with each. This can be done using "potential" equations, subjective probability, and Monte Carlo methods. Resource estimates given without associated levels of certainty may be misleading. The certainty with which the estimate is held is as important as the estimate itself. Different decisions may require different levels of certainty. The coupling of uncertainty and estimate of resource makes the decision maker's life more complex but he must take responsibility for determining an acceptable chance of success in the context of the decision to be made.

DEFINITION OF TERMS

Bayes' Theorem--A formula that gives the probability of two events occurring as the product of the probability that event A occurs, times the probability that event B occurs given event A has occurred.

$$P(A,B) = P(A) \cdot P(A|B) \quad .$$

$P(A|B)$ is the conditional probability and $P(A)$ is the marginal probability.

Cumulative distribution function--As used here is a distribution that gives the probability that a random variable will have a value greater than a given value.

Density function--A distribution that gives the probability that a random variable will have a given value.

Exploration play--Hydrocarbon occurrences in which the pools are of similar age and are in reservoirs of the same lithology, have traps of the same or closely related type, contain hydrocarbons from the same source, and in general have had the same history. The play may be entirely conceptual, entirely proven by drilling, or partially explored.

Exploration play method--A method of assessment by which each play in a basin is assessed and the individual play assessments are added to produce a basin assessment.

Monte Carlo methods--Techniques by which solutions to mathematical equations are given in the form of frequency distribution of answers as a result of repeated substitution of randomly selected combinations of values of the parameters in the equation. In this paper the variables are described by cumulative distribution functions and the various combinations of values occur in proportion to the frequency of occurrence of the values of the variables.

Potential equation--An equation that expresses hydrocarbon potential in terms of series of variables whose value when determined lead, through the equation, to a prediction of the value of the hydrocarbon potential.

Prospect--A specific volume of rock that is expected to contain a hydrocarbon pool--an anomaly that would be drilled in hopes of discovering a covering hydrocarbon accumulation.

Resources--A term that includes all categories of reserves and undiscovered recoverable hydrocarbon potential.

Risk--The marginal probability, the probability that the parameters of hydrocarbon occurrence will have values greater than determined minimum.

Subjective probability--Probability arrived at by subjective judgments rather than by counting processes.

Undiscovered hydrocarbon potential--The quantity of undiscovered oil and gas postulated to be present in new pools and recoverable with present technology.

Volumetric method--An assessment method in which potential is calculated as the product of a volume of rock and a yield of hydrocarbon per unit volume.

Yield factor--A number expressing the ultimate yield of recoverable hydrocarbon per unit volume of rock. The number is arrived at by consideration of analogous fully explored areas.

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METHODOLOGY OF HYDROCARBON RESOURCE APPRAISAL IN RELATIONSHIP TO THE "PETROLEUM ZONE" CONCEPT AND PROBABILISTIC CALCULATION

G. Gess

INTRODUCTION

The evaluations of hydrocarbon resources deal with three kinds of reserves that are defined by their probability of existence. For each kind of reserve there are corresponding methods of evaluation:

1) The first type of method concerns the evaluation of proved reserves, that is to say, the amount of hydrocarbons known in fields under or on the point of exploitation. Calculation of these reserves, based on numerous and accurate data, requires sophisticated methods which take the technology of recovery methods into account.

2) The second type of method concerns the evaluation of possible reserves, that is, the quantity of hydrocarbons not yet discovered but which might exist since the geological environment is favourable. With this kind of method the geological aspects are fundamental because they rule the existence and the amount of these reserves. These methods are applied to areas more or less unknown and the appraisals of their potential are tainted with uncertainty. These methods, dealing mainly with geology, are completely different from the first type.

3) The third type of method concerns the evaluation of probable reserves that come in addition to proved reserves either in recognized but not yet exploited fields or in exploited fields that benefit from technological progress. Calculations here are determined according to which of the first two cases applies.

This paper is concerned with only the second type of method which deals with geological parameters. To outline the uncertainty of evaluations of these possible reserves I want to mention A. Bakirov and G. Ovanessov who found the world reserves of liquid hydrocarbon vary from 84 to 980 billion tonnes.

Now let us consider two methods to appraise hydrocarbon resources:

- the first is a method by analogy based on the Petroleum Zone concept;

- the second is a probabilistic method.

Both methods find their originality in their geological basis.

RESOURCE APPRAISAL AND PETROLEUM ZONE CONCEPT

This paper is part of a project originated by the Institut Français du Pétrole (France) and in which Elf-Erap and the Compagnie Française des Pétroles are associated. In oil exploration there are two main questions which arise when trying to select a prospective site:

a) is the considered area favourable to hydrocarbon accumulation? and

b) if yes, is the accumulation economic; that is, what is its potential?

To answer these questions by analogy we must:

1) have an idea of the existing actual cases of the petroliferous areas of the world; that is to say make up a file.

2) classify the actual cases into classes by using the similarity analysis; and

3) compare incompletely known or unknown areas to zones in the file and estimate their petroliferous potentials.

The File of Actual Cases

The first thing to do in making a file is to delineate, in a standard way, the different habitats for oil. The study of several petroliferous areas of the world indicates that hydrocarbon pools are generally rather well grouped in homogenous sets as, for example, the Persian Gulf.

In Saudi Arabia (see Figure 1) the production of petroleum comes from the upper Jurassic Carbonates of Arab Zones well grouped in the Hasa zone. Northward, two sets of pools produce essentially from the lower and middle Cretaceous zones in Kuwait and Safaniya. Within the folded Zagros mountains there is the large set of pools at Dezfūl producing mainly from the Asmari Limestone (Oligo-Miocene in age). Within each of these sets of pools the traps belong to the same type but important variations may occur from one set to another. The same homogeneity appears in the hydrocarbons. These facts lead us to define the Petroleum Zone concept as a continuous part of sedimentary space containing hydrocarbon pools which have in common:

- reservoirs belonging to the same productive series (same age and lithology);

- traps of a small number of types;
- hydrocarbons of a similar chemical nature.

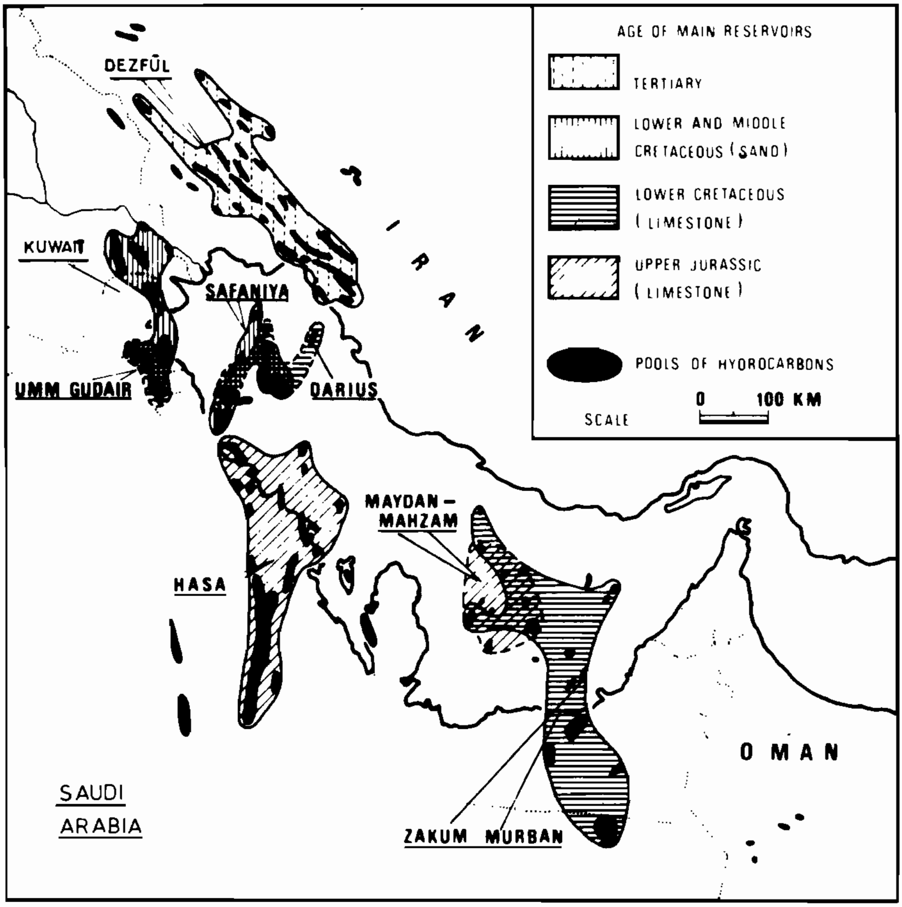


Figure 1. Main petroleum zones of Persian Gulf.

A petroleum zone (see Figure 2) is not only defined geographically but also stratigraphically in its vertical extension. It is rather similar to the "play" of the English speaking authors. Now that we have defined and delineated the Petroleum Zone, we can proceed to describe it (see Figures 3 and 4).

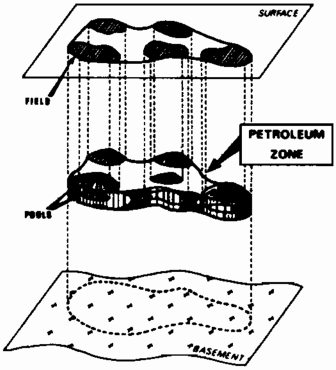


Figure 2. Petroleum zone concept.

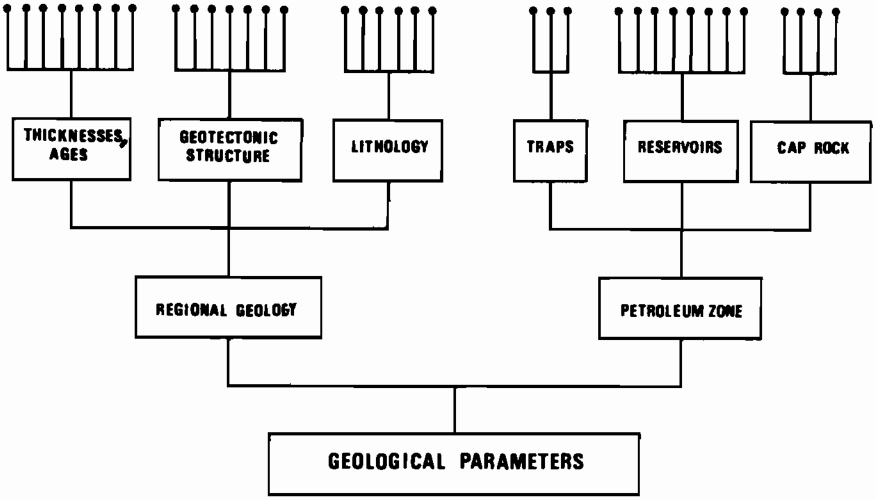


Figure 3.

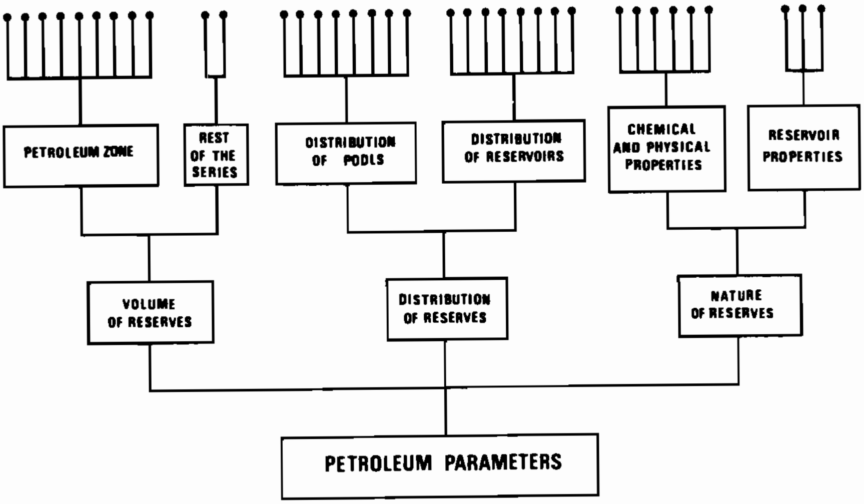


Figure 4.

We have established a list of 100 parameters which describe:

- The geological setting: ages, thickness, lithology, geotectonics, general characteristics of traps, reservoirs and cap-rocks.
- The hydrocarbons: in-place reserves, distribution of these reserves by pool, field, reservoir, characteristics of these--hydrocarbons, gravity, sulphur content, etc.

Non-numerical parameters such as lithology or type of traps must be transformed into numerical parameters through appropriate codes so that all file data can be computerized. At the moment the file contains more than 90 petroleum zones, but the results presented here concerns only 60 zones representing 6,800 pools distributed in 1,076 fields and yielding more than 300 × 10^9 cubic metres of equivalent in-place hydrocarbons.

The Classification of the Petroleum Zones

To obtain some models of hydrocarbon habitats we have analyzed similarities between petroleum zones (see Figure 5).

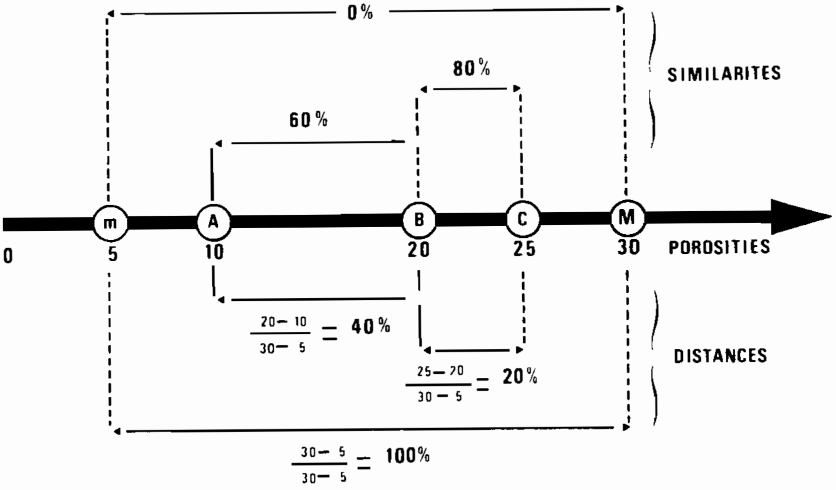


Figure 5. Calculation of similarity.

Calculation of Similarity

For example consider the average porosity parameter of petroleum zone reservoirs:

m = 5 is the lowest porosity of the file (5%);
M = 30 is the maximum porosity of the file (30%).

A,B,C are the porosity of three other zones of the file with porosities of 10%, 20%, 25% which are automatically between m and M. B and C are closer than A and B. These distances can be calculated as functions of the greater distance m × M and expressed in percent of m × M:

the distance AB = 40%, BC = 20% .

The same results are much better expressed by a similarity coefficient which is equal to 100% less the distance. So between the closer zones B and C the similarity is 80% and between A and B the similarity is only 60%. Of course between m,M the similarity is 0%. This calculation, generalized for several parameters, gives a similarity for each pair of petroleum zones.

More sophisticated similarity coefficients have been used, but the principle is roughly the same. The similarity between two zones is 100% when every parameter has the same value for each zone; it is nil when every parameter is maximum for one zone and minimum for the other. The results are given in Table 1 which is the matrix of similarity for every pair of petroleum zones of the file. Since the analysis of the results is not especially easy to handle, we have used cluster analysis and presented these results on a dendrogram.

Table 1. Matrix of geological similarities between petroleum zones.

Petroleum Zones	1	2	3	4	5	6
1	100.0	82.2	71.9	76.5	73.6	60.3
2	82.2	100.0	61.9	67.9	75.4	62.6
3	71.9	61.9	100.0	89.7	77.6	62.8
4	76.5	67.9	89.7	100.0	77.8	59.0
5	73.6	75.4	77.6	77.8	100.0	70.0
6	60.3	62.6	62.8	59.0	70.0	100.0
7	64.5	64.1	73.7	71.9	71.9	71.7

Figure 6 is a dendrogram of geologic similarity--the Petroleum Zones are identified by their number; on the left is the scale of similarity from 55% to 100%. A horizontal line shows either the average similarity between the two zones of a pair (for example 93% between zones 34 and 35) or the average similarity between the zones within a larger group. We can easily define on the dendrogram a number of classes grouping the petroleum zones having great geological similarities.

We know that the results of the calculation depend upon the choice of the similarity coefficient, the weight attributed to every parameter and the way they are weighted. That is the reason why we made the calculation in eight different conditions, and the classes labelled A to I were constituted by approximately the same Petroleum Zones whatever the method of calculation was.

These classes may be considered, in a first approach, as models of the habitats of hydrocarbon. They have the following characteristics:

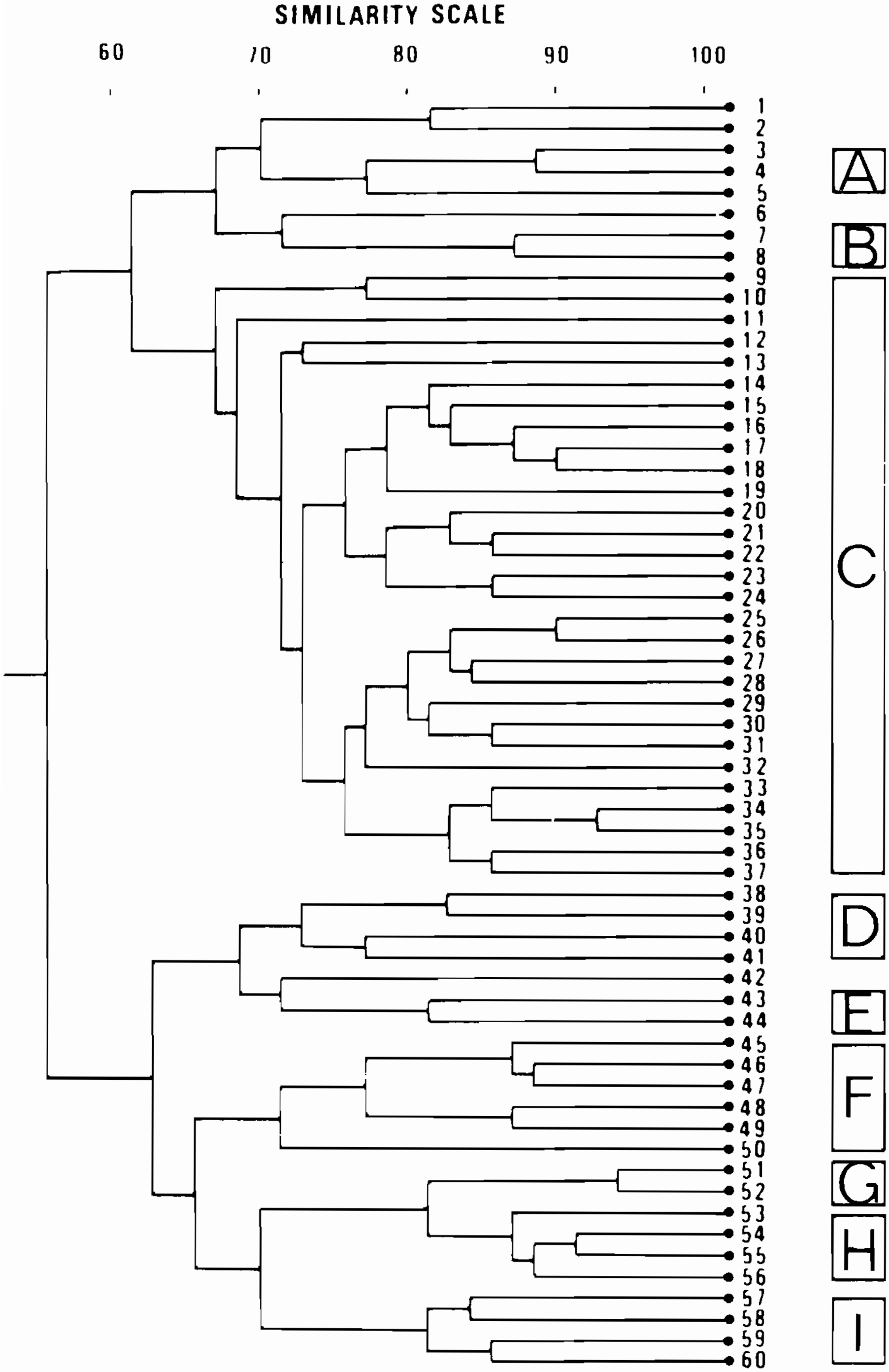


Figure 6. Dendrogram of geological similarities.

1) In each class there are stable geologic parameters; for example, the zones belonging to the class C are within a shaly-sandy series of tertiary late and post tectonic deeps with high rate of sedimentation. The reservoirs are sandy and occur in multiple lenses. Porosities are medium to high, etc.

2) In each class there are petroleum characteristics which are expressed in definite brackets. For instance the petroleum zones of class C have reserves per unit of area of poor to medium; the fields contain numerous pools of poor to medium area; the productivity by well is never high; the sulphur content of the oil is poor, etc.

3) Some statistical relationship (see Figure 7) between geologic characteristics and petroleum characteristics within a class can be found. For example, within class C there is a correlation between the in-place reserves by field and the number of structures per square kilometer.

We have, also, some multiple correlations which tie, for instance, the reserves to combinations of three to six geological parameters.

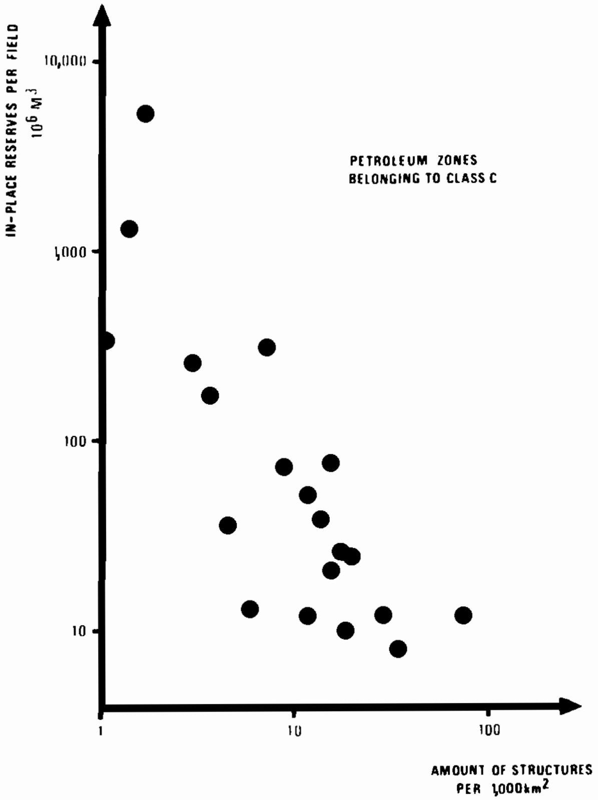


Figure 7. Reserves per field and quantity of structures.

Evaluation of the Potential of an Area

Let us consider an area to be evaluated. Geologists start the evaluation by delineating a number of potential petroleum zones, which can be described with the sole geological parameters which are known or reasonably supposed. Let us call X one of these potential petroleum zones (see Tables 2 and 3).

Table 2. Evaluation of the potential zone "X" similarity matrix.

	Identification of Petroleum Zones					
	4101	4201	4202	4203	4204	4205
4101	100.0	52.1	49.6	47.8	44.8	50.5
4201	52.1	100.0	72.8	65.3	71.6	65.6
4202	49.6	72.8	100.0	87.1	81.2	86.9
4203	47.8	65.3	87.1	100.0	81.3	86.9
4204	44.8	71.6	81.2	81.3	100.0	93.3
4205	50.5	65.6	86.9	86.9	93.3	100.0
X	52.9	73.1	82.0	82.1	86.0	87.8

Table 3. Evaluation of the potential zone "X" (dendrogram of similarities).

```
784  799  813  827  842  856  870  885  899  913  928  942  956  971
 *    *    *    *    *    *    *    *    *    *    *    *    *    *

                  ************************************   8113 Buchv
                  *
     *************************************************   8111 Marbo
     *
     *    ********************************************   9001 Gipsl
     *    *
     *    *           ********************************   8106 Lacru
     *    *           *
  ****************************************************   8104 Magda

  ****************************************************   8101 Talra

                      ********************************       X
                      *
                      *                    ***********   4205 Arad
                      *                    *
               ***************************************   4204 Banat
               *
               *      ********************************   4203 Save
               *      *
  ****************************************************   4202 Drave
```

The calculation of similarity between zone X and the other zones of the file gives a matrix and then it is possible to find out what Petroleum Zones of the file are more similar to X; here they are zones 4204 and 4205. In addition we can use the dendogram which indicates the class to which zone X belongs. Here it is the cluster including petroleum zone 4202 to 4205. The petroleum characteristics of that class might be used for predictions. And we can go on with the other potential Petroleum Zones within the area to be evaluated.

PROBABILISTIC EVALUATION TECHNIQUE

A. Seigneurin

Basically, any reserves calculation, whatever the scale of the study (pool, field, play, regional, etc.), is the result of a very simple computation:

$$T = \Sigma\ V\ \Phi\ S_h\ d\ K \qquad (1)$$

where

T = reserves of hydrocarbons,
V = volume of the trap,
Φ = porosity,
S_h = hydrocarbon saturation,
d = hydrocarbon density,
K = coefficient (recovery factor, volume factor)

But in most cases the application of this formula is much more difficult, because a precise measurement is generally impossible, and even more, some parameters are unknown. If we want to get rid of these difficulties, it is necessary to take these uncertainties into account, and to build probabilistic models.

We usually distinguish two kinds of uncertainties:

- one related to the fact that there is, or there are not, any hydrocarbons in the trap;
- the other related to the amount of hydrocarbons in the trap, provided the first condition is met.

The presence of hydrocarbons in one prospect requires the simultaneous presence of several conditions as shown in Table 1.

By knowing the probability of each elementary condition, it is easy to calculate a coefficient called success ratio, or discovery probability, or risk factor, which varies from 0 to 1 (1 corresponds to proved hydrocarbons).

Now, if we admit that hydrocarbons are present in the trap, we must evaluate their volume. For this purpose, we need an adaptation of formula (1) for the uncertainty of the data, and to find, at the same time, a formulation of the estimating error. But this adaptation is not unique, because the geologist

Table 1. Chance of success factors.

Factors:	Related to:
Generation	Presence of Source Rocks Favorable geochemical history ...
Migration	Permeable beds Favorable gradients...
Reservoir rocks	Adequate depositional environment and diagenesis. Favorable basin position...
Trapping	Structural configuration, facies... sealing...
Retention	Stractural configuration and sealing history
Information quality	

is asked to evaluate reserves under many different circumstances: in one field, one basin, one region, etc. So, we need different evaluation models, according to:

- the scale of the study,
- the geological type of the prospect,
- the nature and accuracy of information.

Thus, we have developed several models, out of which we shall present two:

- the first model deals with the evaluation of a field, with a certain number of wells drilled. It is based on the theory of "Universal Kriging", developed by Matheron (National School of Mines, Paris).

- the second model is adapted to scarce and inaccurate data, and uses a Monte Carlo simulation. This second model will be presented in one field evaluation and in one regional evaluation model.

FIELD EVALUATION USING THE KRIGING METHOD

Suppose we have drilled a few wells in the field to be estimated. For each well we have one measurement of the "net hydrocarbon thickness" Hi. The total amount of reserves, when

$\bar{H}$ stands for the mean value of H in the surface S, is given in the formulas:

$$T = \alpha \int_S H \, d S \quad ,$$

$$H = \Sigma \, h \, \Phi \, S_H \quad ,$$

$$S = \text{pool area}$$

where

h = reservoir unit thickness,
Φ = porosity,
S_H = hydrocarbon saturation.

We shall therefore obtain the reserves estimate by calculating $\bar{H}$ from the known values Hi. The error effecting this estimate will be a combination of:

- the errors on measurements of Hi,
- the "geostatistic error" on the estimating of $\bar{H}$,
- the geometric error on S estimating.

The Kriging method makes it possible to calculate both $\bar{H}$ and the geostatistic error, using the variogramm function. This function is the mathematical expression of the spatial variability of the parameter Hi. In order to make use of this method, CFP and SNPA (Aquitaine) have developed jointly one software package, KRIGEPACK.

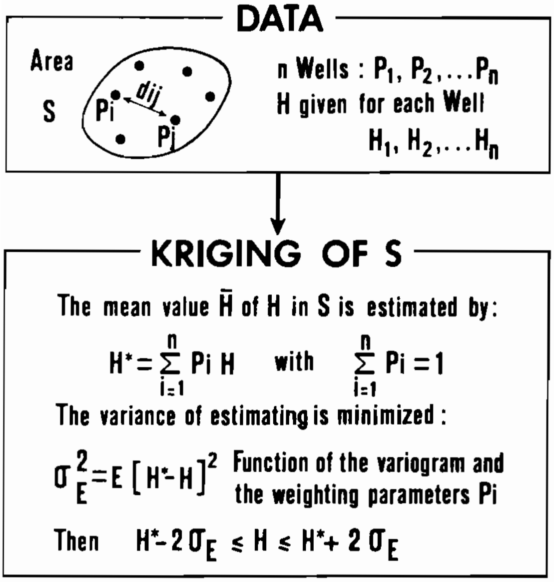
Figure 1 gives a summary of the method, as well as the results. We think that this method is particularly suitable for probable reserves estimating in the situation we face at the earlier stage of field development.

FIELD EVALUATION WITH LITTLE DATA

Let us now consider one field about which we have only:

- one seismic "picture" of the prospect,
- some "uncertain" data concerning the thickness, extension and petrophysic properties of the reservoir.

In this case, the estimate need not (and cannot) be as precise as in the first case. For instance, the shape of the trap (see Figure 2) can be assimilated in a simple geometrical figure (paraboloid, cylinder, etc.) whose surface and closure can be known (parameters H, E, F, S on Figure 2). This could lead to an easy calculation, if all these parameters, plus $\emptyset$, S_H, etc., are known for sure (see Figure 3).



After: A. HAAS and M. MOLLIER (SNPA)

Figure 1.

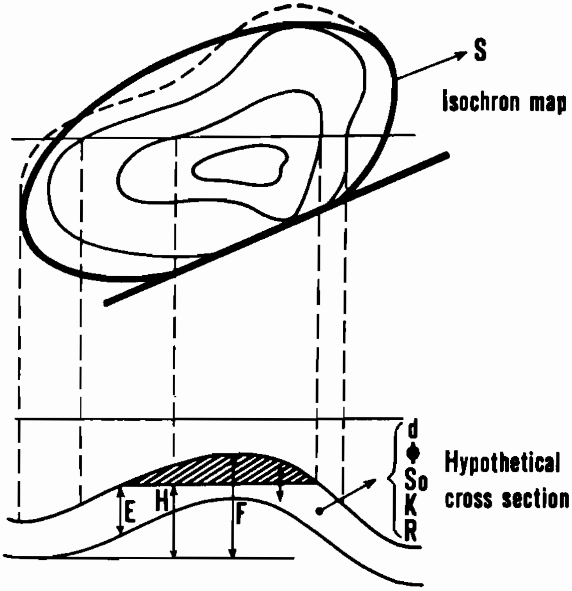


Figure 2. Trace of the "equivalent" paraboloid.

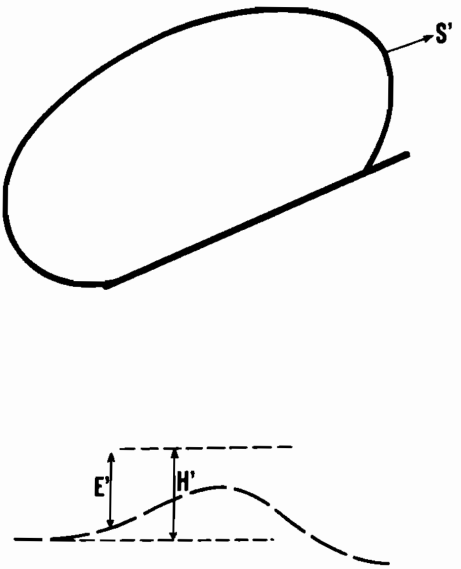


Figure 3.

Unfortunately, generally speaking, the geologist can only give, for all the parameters, an interval (minimum-maximum) in which he is "sure" the actual value will fall. Furthermore, he can have an idea of the probability distribution of the values within this interval. In fact, we usually use two simplified models, triangular distribution, and uniform distribution (see Figure 4).

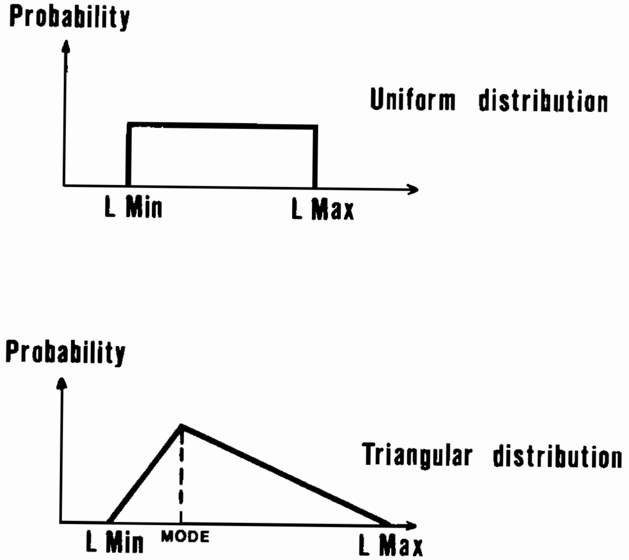


Figure 4. Statistical distributions.

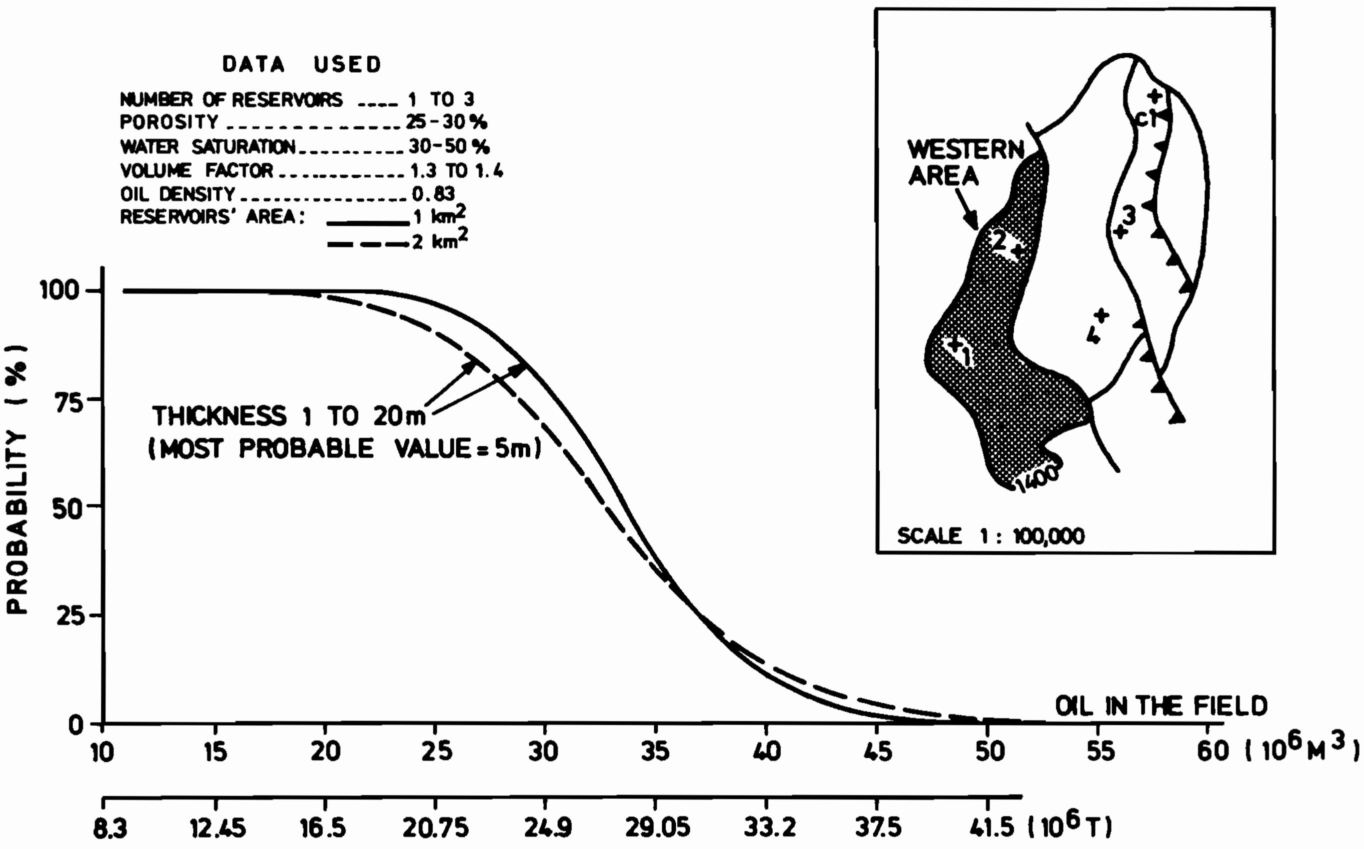


Figure 5. Oil distribution in field x.

It is possible, by knowing the probability distribution for each parameter, and the mathematical formula for reserves computation, to obtain the reserves estimate, using Monte Carlo simulation techniques. The results are synthesized in a distribution curve, and a cumulative distribution curve (see Figure 5), that answers the question: What is the probability that the reserves in the field are greater than a given value To?

REGIONAL EVALUATION

The two examples above dealt with field evaluation. But the geologist is, in fact, also concerned with evaluating a whole region, in which a certain number (unknown) of traps can exist.

The potential reserves of such a zone can be reached if individual field evaluations are available, by combining these results and using the individual success ratio for each trap. This leads to a cumulation curve for the whole region, and to a regional success ratio. It is also possible to introduce more sophisticated features into these models, such as the relationship between the presence of hydrocarbons in different traps with other parameters.

However, the lack of information often forbids use of such methods, and more global models are required. They still use Monte Carlo techniques, but they work on more synthetic parameters, such as:

- the ratio of the producing area within the zone,
- the mean hydrocarbon thickness in the producing area,
- the amount of recoverable hydrocarbons per volume of rock, and so on.

Each of these parameters is given by its probability distribution; it is then possible, once more, to give a result taking into account the uncertainty borne by the basic parameters. We shall briefly present one of these models.

The basic idea of this model is that it is fairly easy, by means of a structural or geomorphological study, to make a hypothesis about the traps' number and surface in a given region (still on a probabilistic basis). The same can be done for the success ratio (which will be considered, in this case, as the ratio between "full" traps and their total number).

From other sources, we can find the relationship between the traps' surface and the reserves (see Figure 6). This can be found from worldwide statistics, which can be filtered according to a specific geological context. Then, the simulation (see Figure 7) leads to an estimate of the reserves in the region. As for other models, a cumulative curve, which is the final result, can be drawn.

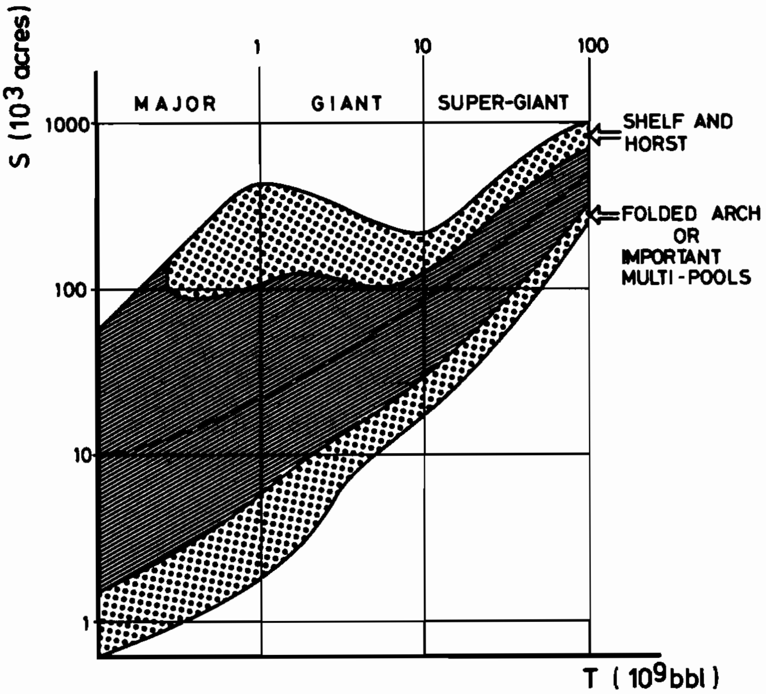


Figure 6.

Obviously, such a method has no better value than the value of the input parameters (although this can be said of any calculation), and must be used carefully. Particularly, it is important to check not only the results but also the hypothesis against the Petroleum Zones files. The main interest of such methods, as a matter of fact, is to help find the logical consequences of geologists' opinions.

CONCLUSION

The two methods we have discussed here seem to have different application fields. One, the Petroleum Zone concept, is fruitful in the early stages of exploration, when analogy is the only usable tool. The other, the probabilistic method, may be used when parameters are better known.

In actual fact we are often faced with cases which are not typical of one situation or the other. Thus, any practical study will be mainly a combination of both methods in order to better fit the tools to the problem to be solved.

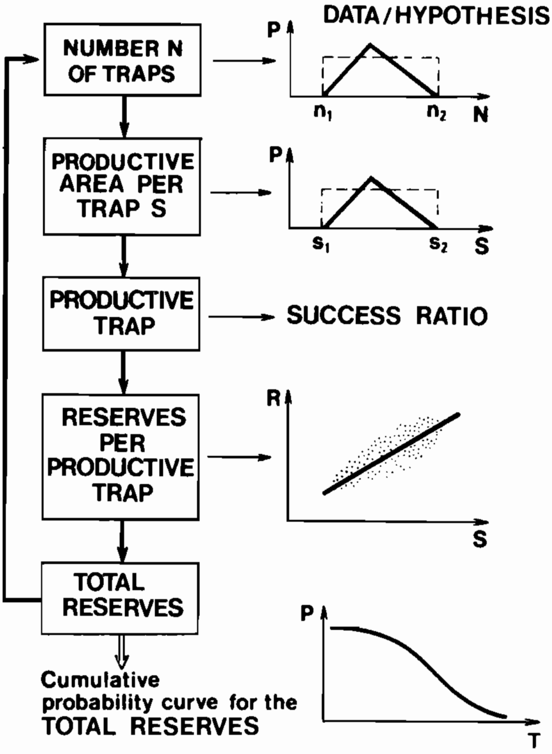


Figure 7. An example of regional evaluation.

THE NORTH SEA OIL PROVINCE: A SIMULATION MODEL OF ITS EXPLOITATION AND DEVELOPMENT*

Peter R. Odell and Kenneth E. Rosing

Simulation modelling has been used by our colleagues in the field of economic and social geography in many contexts (for example, land use patterns, urbanization, and locational problems of economic activities) over the past 10 or so years. These procedures have been generally used when a complex net of relationships exists, particularly over a time dimension, and it is not amenable to a probabilistic analytical solution. An alternative approach might be the derivation and solution of joint probability matrices culminating in a probability model capable of being tested inferentially (given the availability of real world data for comparison); however, with increasing order and increasing rank, the solution of such matrices becomes increasingly cumbersome. When the phenomena being investigated occur along a time axis, a simulation model, with dynamic attributes, may also more faithfully replicate the real world experience and give a more synthetic view, and hence enhanced understanding, than is possible through a static model.

For these reasons it was felt that the development of a simulation model offered the best potential for the prediction of the future of discovery and production from the North Sea oil basin from 1968 into the twenty-first century. Any such model must eventually be judged in terms of its correspondence with reality. Such testing will not be possible in the case of the present model for many years. However, we would argue that, because the model is based on a series of assumptions drawn from the development of other major oil provinces and because these assumptions are calibrated in light of the early history of the North Sea basin, such a correspondence will eventually be found.

The present development of the North Sea province (up to the end of March 1975) is shown in Figure 1. With proven economically recoverable reserves already amounting to over 20×10^9 barrels (some 3×10^9 tons), it is obviously a major province by any standards.[1] In addition the North Sea is a unique

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*This paper is based on a study made in the Economic Geography Institute of Erasmus University, Rotterdam, the full version of which has been published by Kogan Page, London, 1975, under the title The North Sea Oil Province: An Attempt to Simulate Its Development and Exploitation, 1969-2029.

[1] See an earlier appreciation of its significance in P.R. Odell, "Indigenous Oil and Gas and Western Europe's Energy Policy Options", Energy Policy, 1, 1 (June 1973).

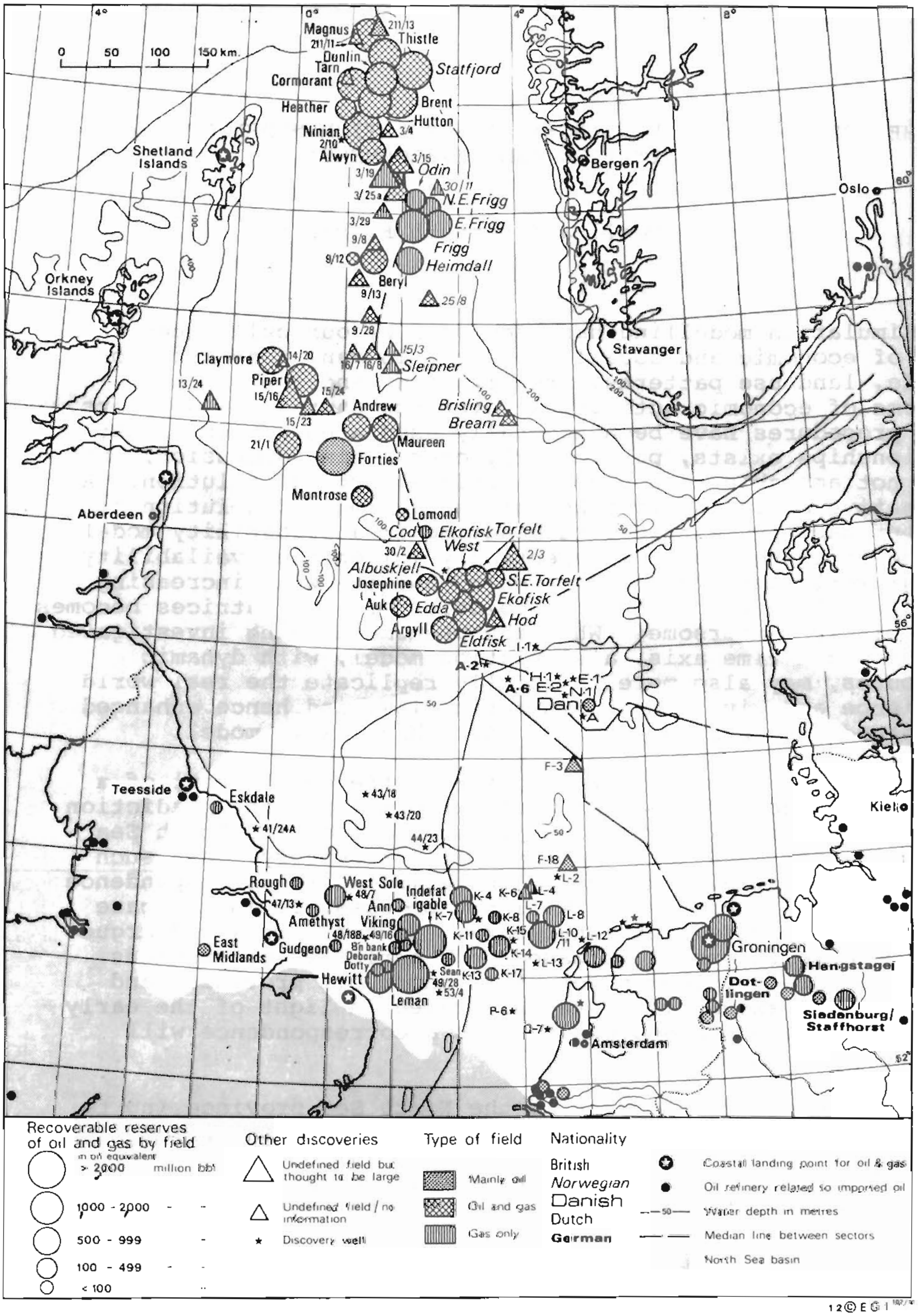

Figure 1. The North Sea basin: oil and gas discoveries to March 31, 1975.

occurrence, in that its development coincides in time with an increasing demand in Western Europe for an indigenous energy source and, perhaps even more important, it lies within a region of already high and intensive energy use.

In consequence, in the model we have assumed that all oil discovered and producible will be produced and marketed as rapidly as possible at a normal or super-normal profit. The province will thus be developed as rapidly as the constraints of offshore technology and hardware allow. Given this assumption the production potential becomes partly a function of the rates of discovery and appreciation of the discovered reserves and partly a function of the timing and speed of their depletion. Political considerations are not simulated in this version of the model.

In order to simulate the development, and thereby arrive at a prediction of the province's exploitation and depletion, a computer program was written to control the order and timing of simulated discovery and appreciation and to define the constraints for random variables.[2] The various assumptions were quantified and written into this program. We shall now turn our attention to these assumptions and their operationalization.

The average annual rate of discovery of initially declared reserves, a primary input, was defined as a function of the probable total number of wildcat wells, the variable success rate, and the various sizes of fields. There are 365 so-called "prime blocks" in the North Sea, which we assume require 3.3 wells per block for full exploration, and 261 "fair blocks", each requiring 1.8 wells per block (when all blocks are adjusted to British size).[3] This gives a total of 1,675 wildcat wells required for the full exploration of the part of the North Sea shown in Figure 2. As this map also shows, all but seven of these blocks lie within British or Norwegian waters. Legislation in these two countries requires that the licensee submit a work program of exploration prior to the granting of the license. If the full exploration work is not carried out the company must relinquish the area and the nation then may reallocate the area or do with it whatsoever it wishes. Therefore we may assume that these wildcats will be drilled unless the country decides not to allocate blocks for drilling and, since the law also requires the relinquishment of a substantial percentage

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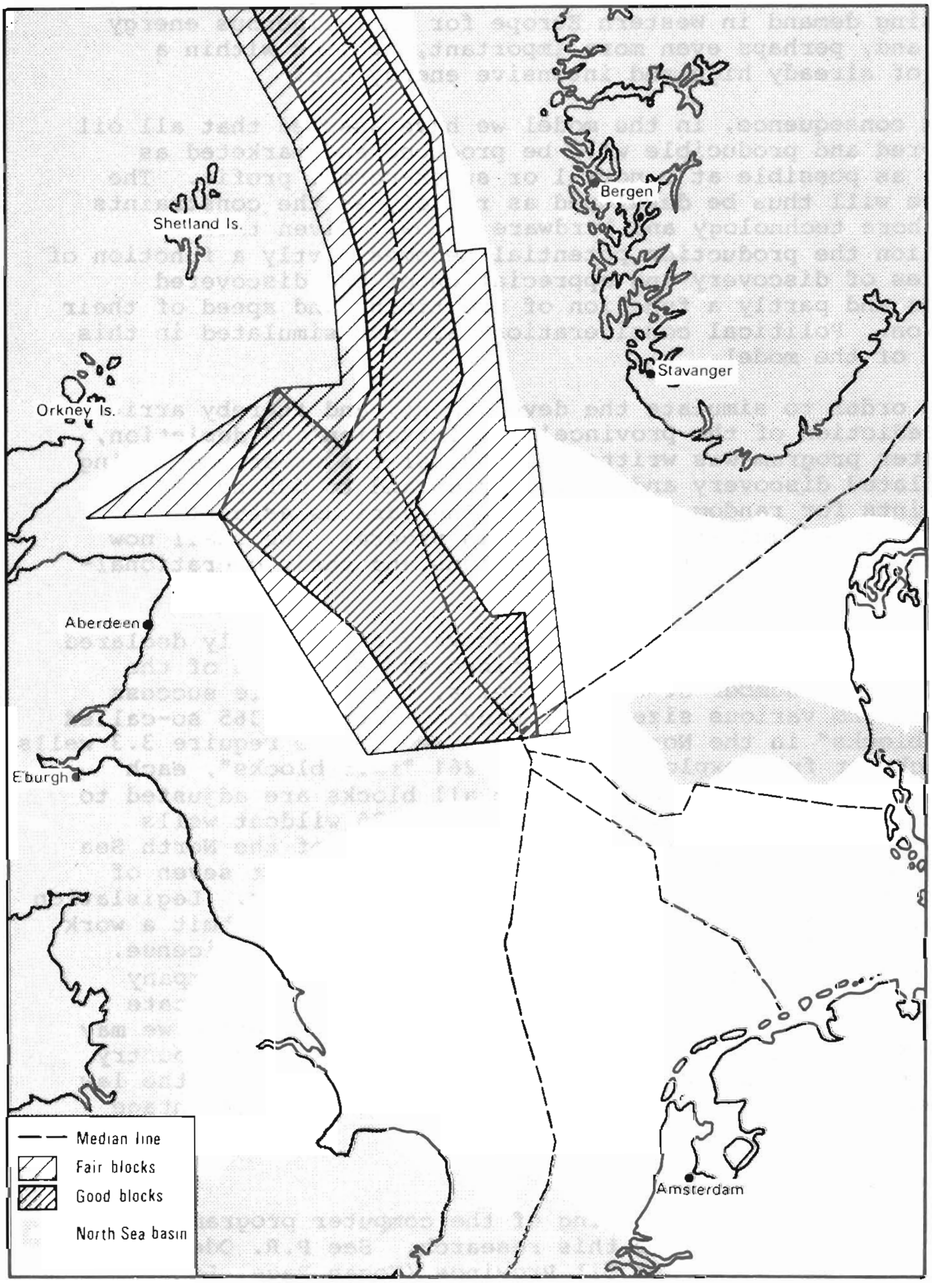
[2] A full, annotated listing of the computer program is given in the published report of this research. See P.R. Odell and K.E. Rosing, The North Sea Oil Province (Kogan Page, London, 1975).

[3] See the report The Outlook for Large Mobile Drilling Rigs on the European Continental Shelf, prepared by the Investment Research Division of Kitcat and Aitken, London.



1 2 © E.G.I. 100/74

Figure 2. The North Sea basin: designated good and fair blocks as considered in this paper.

of the area after a time period, that the timing of this exploration effort will be a function of the development of offshore drilling technology and the availability of hardware. Table 1 shows the expected buildup of wildcatting, given these factors, to a total of 220 wells by 1979.

There are, as shown in Figure 3, now 173 different companies and consortiums holding exclusive exploration rights on one or more blocks in the North Sea basin. These companies each work with a priority schedule and drill their largest, most promising structures first and smaller and less promising structures later. The success rate thus varies from year to year, but in the model we have assumed that the highest success rate has been reached (1:7 in 1974) and that it will now decline until it is uneconomic to continue exploration after 20 years. Additionally the success rate must be split between the probability of finding a field of the size expected and of finding a field in another size class. Table 1 displays the joint probability matrix which emerges from these assumptions and Table 2 shows how this is then worked out to arrive at an average expected discovery volume for each year.

A similar series of values were developed for the coefficient of variation of the average annual rate of discovery. This curve represents moderate certainty about the volume of finds in the early years, increasing certainty as the stratographic history becomes better understood, and decreasing certainty near the end of the period when the less attractive structures are being drilled. The standard deviation for each year was then calculated from the coefficient of variation and the mean.

Subroutine GAUSS,[4] a random number generator, was provided with these mean values and standard deviations and returned a value for each year from a normal probability distribution. This value was taken to be the volume of oil initially declared as recoverable reserves from all fields discovered in each of the 20 years of exploration. The volumes of oil discovered and the variability are displayed in Figure 4 which emerges from 100 iterations of the model.

When reserves are initially announced they are actually a probability statement based on test data. Over the years, with more drilling experience on an oil field and with production experience from the field, the variability of the probability field decreases and, generally, the estimate appreciates. The companies concerned also appear to be rather conservative in their public announcements of initial reserves as this is often commercially important and/or politically significant information.

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[4] "IBM System 360 Scientific Subroutine Package Version III, Program Manual", No. GH20-0202-4 (IBM, New York, 1970), describing program number 360A-CM-03X, p. 77.

Table 1. The development of exploration and field discoveries by class of fields (1969-1988).

Total Exploration Effort				Exploration Wells and Field Discoveries - by Year and Class											
				Exploration by Field Class											
				Class I Fields			Class II Fields			Class III Fields			Class IV Fields		
Year	Tot.No. of Wells	Prob. of Success %	No. of Wells by Objective	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields
1	8	6	Class Wells[1)]	8	5.0	0.4									
			Other Wells[2)]				8	1.0	0.8	8	0.0	0.0	8	0.0	0.0
2	14	8	C.W.	10	7.0	0.7	4	7.0	0.28						
			O.W.	4	1.0	0.04	10	1.0	0.1	14	0.0	0.0	14	0.0	0.0
3	20	10	C.W.	10	8.0	0.8	10	8.0	0.8						
			O.W.	10	1.0	0.1	10	1.0	0.1	20	1.0	0.2	20	0.0	0.0
4	26	12	C.W.	8	9.0	0.72	18	9.0	1.62						
			O.W.	18	1.5	0.27	8	1.5	0.12	26	1.0	0.26	26	0.5	0.13
5	34	12	C.W.	6	10.0	0.6	20	10.0	2.0	8	10.0	0.8			
			O.W.	28	1.0	0.28	14	1.0	0.14	26	0.5	0.13	34	0.5	0.18
6	45	14	C.W.	3	11.0	0.33	22	11.0	2.42	20	11.0	2.2			
			O.W.	42	0.8	0.34	23	1.0	0.23	25	1.0	0.25	45	1.2	0.54

[1)] Class wells: Wells into structures expected to produce a discovery of the class shown.

[2)] Other wells: Wells producing a field outside the class expected.

Table 1 (continued).

Total Exploration Effort				Exploration Wells and Field Discoveries - by Year and Class											
				Exploration by Field Class											
				Class I Fields			Class II Fields			Class III Fields			Class IV Fields		
Year	Tot. No. of Wells	Prob.of Success %	No. of Wells by Objective	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields
7	60	14	C.W.				24	11.0	2.64	36	11.0	3.96			
			O.W.	60	1.0	0.6	36	1.0	0.36	24	1.0	0.24	60	1.0	0.6
8	95	12	C.W.				17	10.0	1.7	53	10.0	5.3	25	10.0	2.5
			O.W.	95	0.67	0.62	78	0.67	0.52	42	0.67	0.28	70	0.67	0.49
9	135	12	C.W.				5	10.0	0.5	75	10.0	7.5	55	10.0	5.5
			O.W.	135	0.5	0.68	130	0.75	0.94	60	0.75	0.45	85	0.75	0.64
10	200	10	C.W.				2	8.0	0.16	93	8.0	7.44	105	8.0	8.4
			O.W.	200	0.4	0.8	198	0.53	1.04	108	0.53	0.57	95	0.53	0.5
11	220	10	C.W.							44	8.0	3.52	176	8.0	14.08
			O.W.	220	0.3	0.66	220	0.5	1.1	176	1.2	2.12	44	1.2	0.53
12	200	8	C.W.							24	7.0	1.68	176	7.0	12.32
			O.W.	200	0.3	0.6	200	0.3	0.6	176	0.4	0.7	24	0.4	0.1
13	160	8	C.W.							14	7.0	0.98	146	7.0	10.22
			O.W.	160	0.3	0.48	160	0.3	0.48	146	0.4	0.58	14	0.4	0.06

Table 1 (concluded).

Total Exploration Effort

Exploration Wells and Field Discoveries - by Year and Class

				Exploration by Field Class											
				Class I Fields			Class II Fields			Class III Fields			Class IV Fields		
Year	Tot. No. of Wells	Prob.of Success %	No.of Wells by Objective	No. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields	No.. of Wells	% Success	No. of Fields	No. of Wells	% Success	No. of Fields
14	120	7	C.W.							8	6.0	0.48	112	6.0	6.72
			O.W.	120	0.1	0.12	120	0.3	0.36	112	0.6	0.67	8	0.6	0.05
15	90	7	C.W.							3	6.0	0.18	87	6.0	5.2
			O.W.	90	0.0	0.0	90	0.3	0.27	87	0.7	0.61	3	0.7	0.02
16	75	6	C.W.										75	4.5	3.38
			O.W.	75	0.0	0.0	75	0.5	0.38	75	1.0	0.75			
17	60	6	C.W.										60	4.5	2.6
			O.W.	60	0.0	0.0	60	0.5	0.3	60	1.0	0.6			
18	50	5	C.W.										50	3.5	1.65
			O.W.	50	0.0	0.0	50	0.5	0.25	50	1.0	0.5			
19	40	5	C.W.										40	3.5	1.4
			O.W.	40	0.0	0.0	40	0.0	0.0	40	1.5	0.6			
20	25	5	C.W.										25	3.5	0.87
			O.W.	25	0.0	0.0	25	0.0	0.0	25	1.5	0.38			

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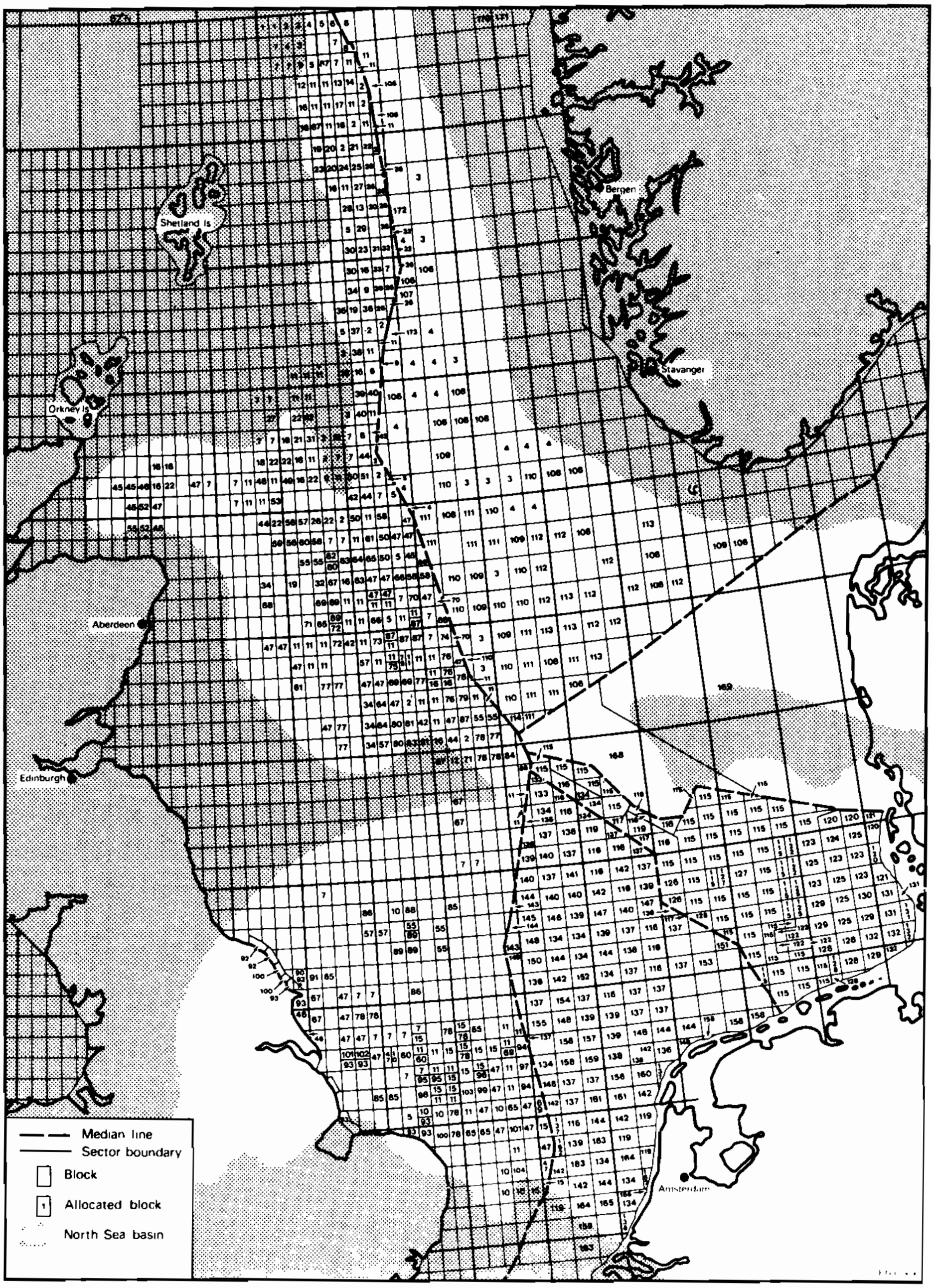

Figure 3. The North Sea basin: median lines, sectors and blocks.

The number in each block indicates a designated exploring company or group of companies. Each different number thus identifies a decision-making entity on the exploitation process.

Table 2. Derivation of mean curve of annually discovered reserves (in millions of tons).

	Number of Fields and Annual Reserves by Class of Fields										
	Class I		Class II		Class III		Class IV				
Year	No. of Fields	Reserves	No. of Fields	Reserves	No. of Fields	Reserves	Total No. of Fields	Effective Fields	Reserves	Total No. of Fields	Total Reserves
1 - 1969	0.4	80	0.08	8	-		-			0.48	88
2 - 1970	0.74	148	0.38	38	-		-			1.12	186
3 - 1971	0.9	180	0.9	90	0.2	10	-			2.0	280
4 - 1972	0.99	198	1.74	174	0.26	13	0.13	0.09	2	3.12	387
5 - 1973	0.88	176	2.14	214	0.93	47	0.18	0.14	3	4.13	440
6 - 1974	0.67	134	2.65	265	2.45	123	0.54	0.41	8	6.31	530
7 - 1975	0.6	120	3.0	300	4.2	210	0.6	0.45	9	8.4	639
8 - 1976	0.62	124	2.22	222	5.58	279	2.99	2.24	45	11.41	670
9 - 1977	0.68	136	1.44	144	7.95	398	6.14	4.61	92	16.21	760
10 - 1978	0.8	160	1.2	120	8.01	401	8.9	6.7	134	18.91	815
11 - 1979	0.66	132	1.1	110	5.64	282	14.61	10.96	219	22.01	743
12 - 1980	0.6	120	0.6	60	2.38	119	12.42	9.32	186	16.0	485
13 - 1981	0.48	96	0.48	48	1.56	78	10.28	7.71	154	12.8	376
14 - 1982	0.12	24	0.36	36	1.15	58	6.77	5.08	102	8.4	220
15 - 1983	-		0.27	27	0.79	40	5.22	3.92	79	6.28	146
16 - 1984	-		0.38	38	0.75	38	3.4	2.55	51	4.53	127
17 - 1985	-		0.3	30	0.6	30	2.6	1.95	39	3.5	99
18 - 1986	-		0.25	25	0.5	25	1.65	1.24	25	2.4	75
19 - 1987	-		-		0.6	30	1.4	1.05	21	2.0	51
20 - 1988	-		-		0.38	19	0.87	0.65	13	1.25	32
Totals	9.14	1,828	19.49	1,949	43.93	2,200	78.70	-	1,182	151.26	7,149

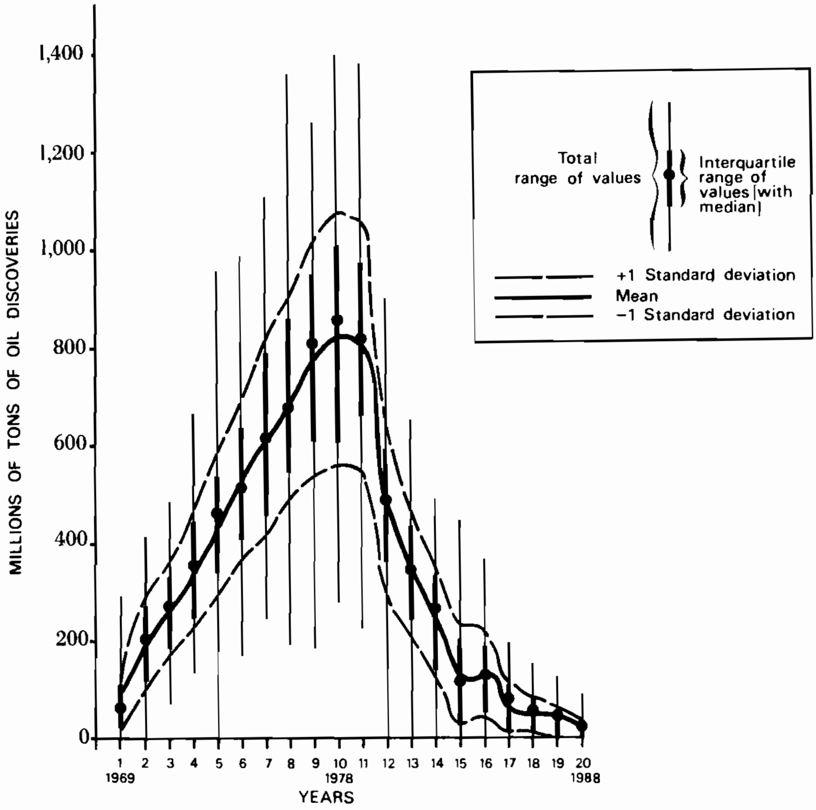

Figure 4. Results from 100 iterations of annual rates of discovery of initially declared recoverable reserves.

Notes to Table 2.

The number of fields in each class in each year is derived from Table 1. The following average sizes have been assumed for fields in the different classes. Class I--200 million tons; Class II--100 million tons; Class III--50 million tons; Class IV--20 million tons. Only 75% of Class IV fields discovered are considered to be effective on the assumption that the others will be too small to be profitable to develop.

Although further work remains to be done to validate the results of this analysis in respect of number of fields, field size and total reserves vis-à-vis the accepted lognormal distribution of oil fields within a province, it may be noted that a largest field with > 1,000 million barrels of oil reserves (as declared on initial discovery), a smallest commercial field with 100 million barrels and a total of 151 fields appears to be compatible with a lognormal distribution of fields in a province with total reserves of the size indicated in the final column of the table.

The phenomenon of reserves appreciation has been thoroughly studied in Alberta where a normal appreciation factor, relating twentieth-year knowledge to discovery-year estimate, has been found to be 8.89. On a worldwide basis such accurate analysis is not available, but a four to six-fold appreciation seems average.[5] In the North Sea itself the Ekofisk field has already appreciated by over 50% to 1,800 million barrels in four years and the Brent field by 125% to 2,250 million barrels in two years.

For these reasons we must include the dynamic process of reserves appreciation in any model such as this. Since developing technology may serve to decrease the appreciation factor for new provinces, and since this is a conservative model, a mean appreciation factor of 2 (doubling) has been used. As simulated in this model, the appreciation of a year's discovered fields can occur in three stages: the first, randomly from one to three years after the discovery year, the second, randomly two to six years after the first, and the third five to eleven years after the second. The volumes of the appreciations were related to the volume of the initial discovery, with the first appreciation being the largest and the third the smallest, so representing reality in successively smaller appreciations over time as the final limits of a field's ultimately producible reserves are approached. The total amount of appreciation of any one discovery could range from 40% to 160%. Subroutine RANDU[6] was used to generate a rectangular probability field with cutoff points as specified above to determine the volumes and timing. The volume and variability in appreciation from 100 iterations are shown in Figure 5. Figure 6 shows annual ranges of combined discovery and appreciation figures.

To simulate the production of each year's discovered or appreciated reserves a set of eight contrasting depletion curves, each covering a period of 20 years, were drawn and their volumes set equal to unity. One of these curves was randomly selected (RANDU) and the volume of the discovery or appreciation was multiplied by the height of the curve for each year. For simplicity the assumption was made that all fields discovered in one year would begin production at the same time; the lag between discovery and production was randomly chosen to be two to five years. A similar procedure was used for each of the three appreciations. The curve representing each discovery's and each appreciation's depletion was then plotted cumulatively as is shown in Figure 7.

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[5] See P.R. Odell, <u>Energy Needs and Resources</u> (MacMillan, London, 1974), for a detailed analysis of reserves appreciation.

[6] "IBM System 370", p. 77.

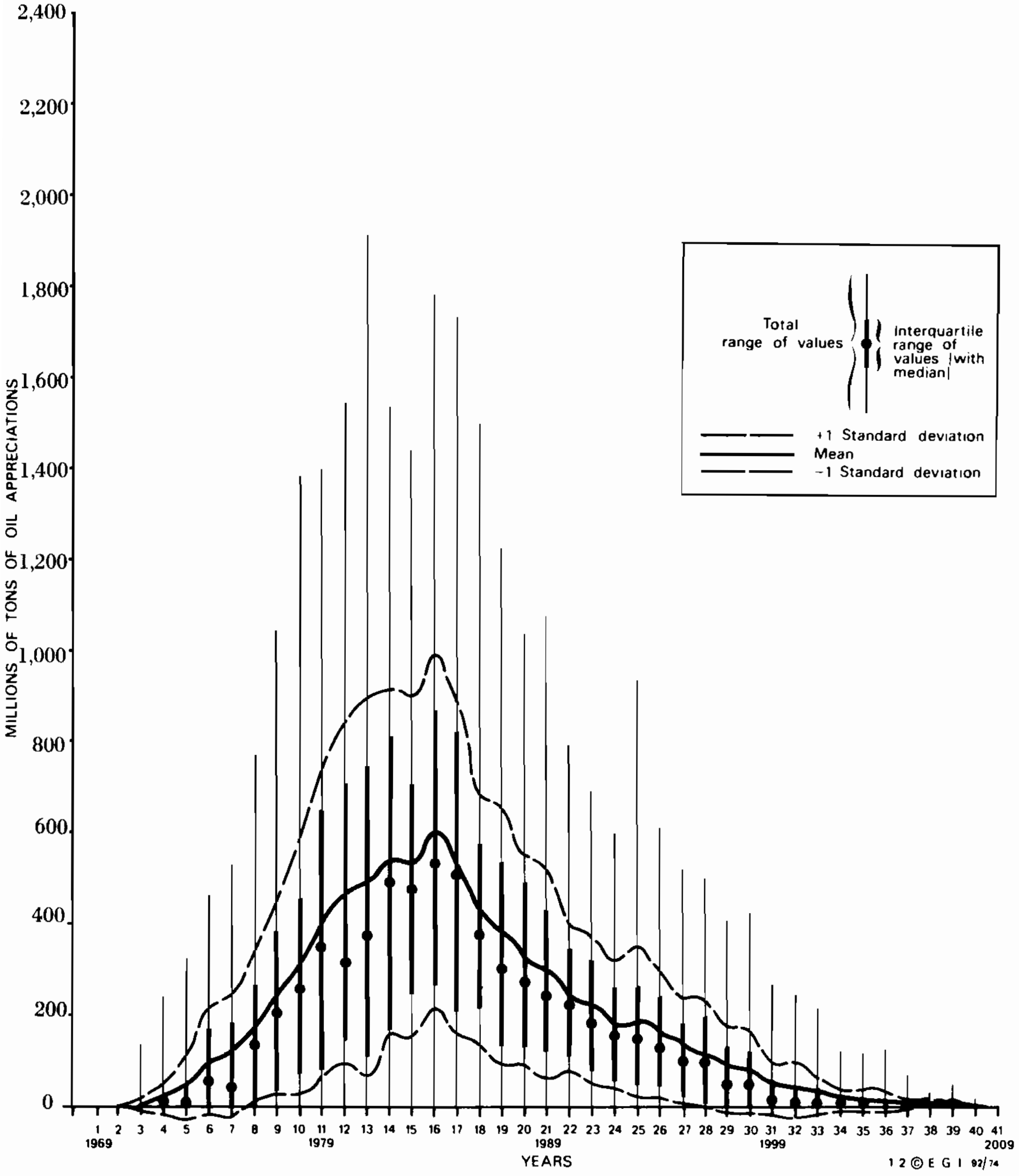

Figure 5. Results from 100 iterations of year-by-year reserves' appreciations 1969-2009.

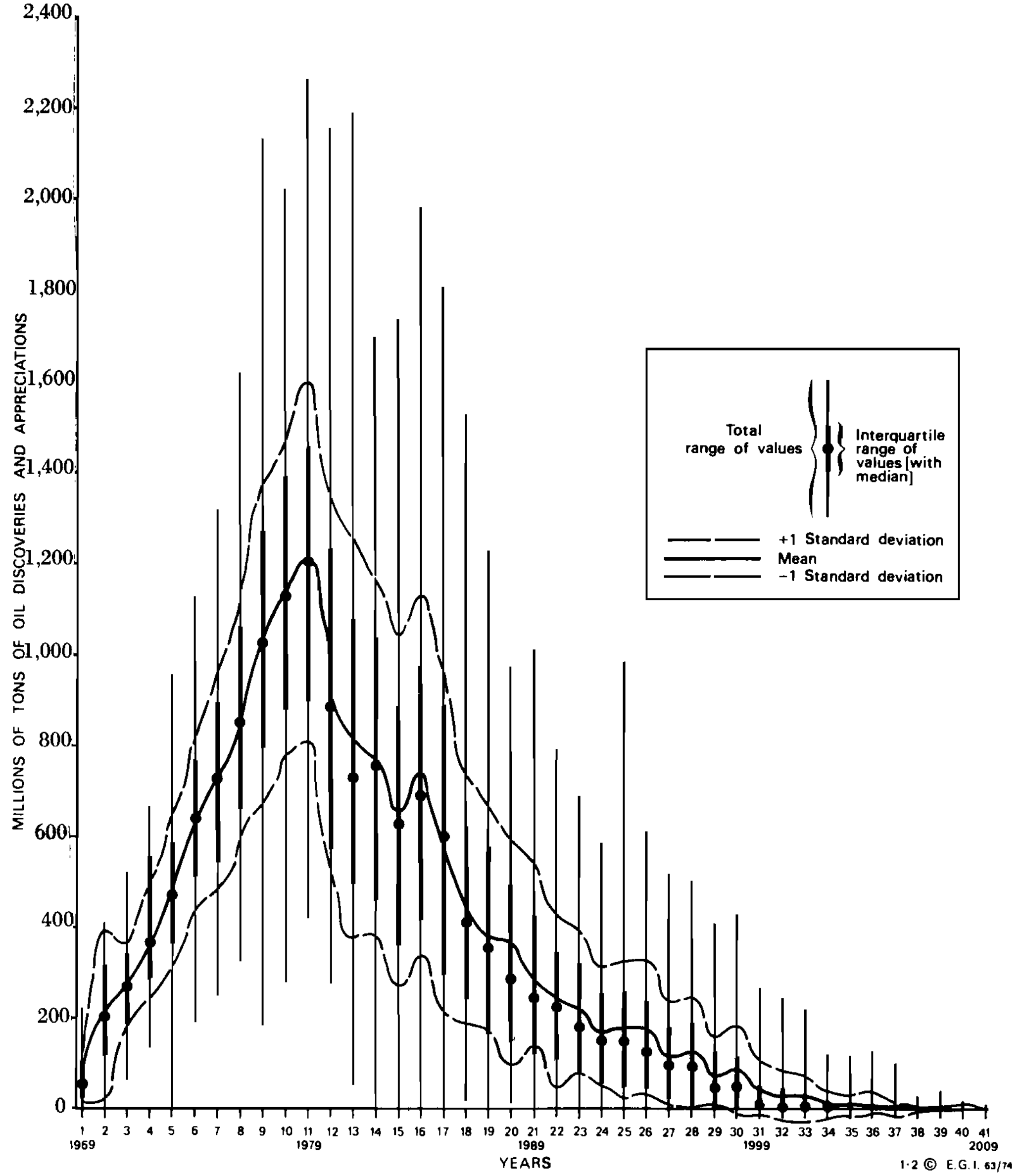

Figure 6. Results from 100 iterations of year-by-year discovery and appreciation of recoverable reserves 1969-2009.

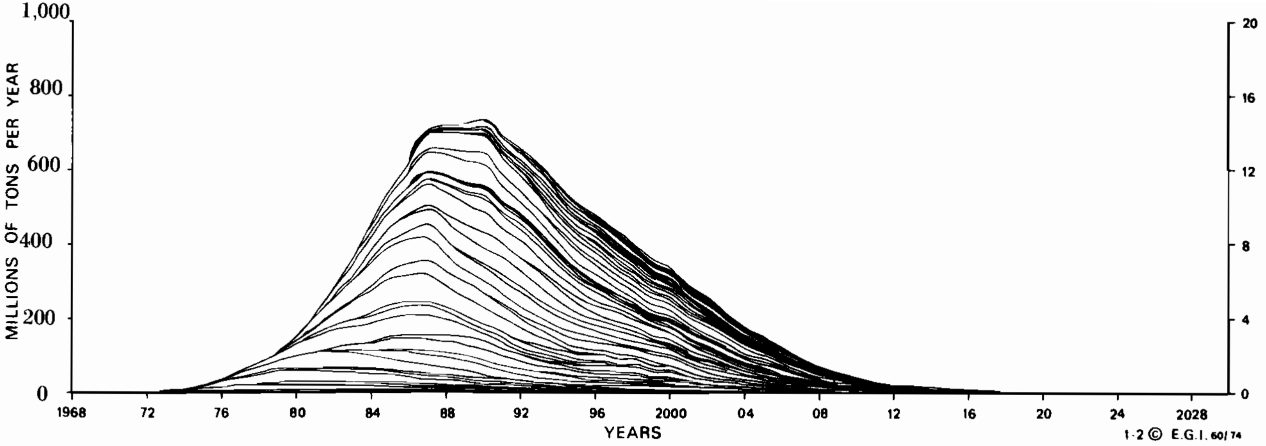

Figure 7. An individual iteration of the North Sea production model showing the buildup of production by the depletion of successive years' reserves discoveries and appreciations.

A full iteration can contain up to 80 curves. However, a 0.02 probability of any year suffering a disaster was allowed. In this case the discovered reserves were eliminated from the model together with all the appreciations associated with that year's discovery. In Figure 7 there is no discovery year 1986.

A feedback element for the loss of management confidence was also included. If for three consecutive years results were "bad", or for two consecutive years "very bad", then the average expected curve of discovery was halved for the rest of the iteration, in order to simulate the cutback in exploration expenditure. Checking then began for good years as well as bad and similar circumstances involving good years would result in the curve being multiplied by two to represent the return of confidence or if involving continuing bad years it would result in a further division by two.

The superimposed top lines from 100 iterations are shown in Figure 8. Each of these represents an estimate of the likely minimum level of production over the period. The bottom 10 curves were eliminated to arrive at the 90% confidence limit (so following the practice of oil companies) and the mean of the remaining 90 curves were calculated. In Figure 9 this mean curve is shown superimposed on the curve of 75% of the expected demand for oil in Western Europe over the rest of the present century.[7] Seventy-five percent has been used in this comparison because: a) certain areas of Europe, for example, southern France and Italy, will be more easily supplied with North African oil than North Sea oil no matter how successful the North Sea development is; b) some European countries have entered or are entering into long-term commitments to purchase oil from existing suppliers; and c) a certain amount of exogenous oil will always be required for refinery blending purposes with the light North Sea crudes in order to meet European product demand patterns. This last factor will become less important, however, as northwestern Europe increases its use of natural gas which, since it will be found associated with oil, will become more plentiful.

The mean result from the simulation model on the long-term oil potential from the North Sea basin indicates that it can indeed contribute 75% to the total demand for oil for the period from 1982 to 1996. This opens up the possibility that some constraints on the rate of the development of the basin might be appropriate, so as to keep the production potential much more closely related to the developing Western European demand position over this period and so enable oil to be "saved" for

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[7] P.R. Odell, "European Alternatives to Oil Imports from O.P.E.C. Countries; Oil and Gas as Indigenous Resources", in F.A.M. Alting van Geusau, ed., <u>Energy Policy Planning in the European Community</u> (Sijthoff, Leiden, 1975).

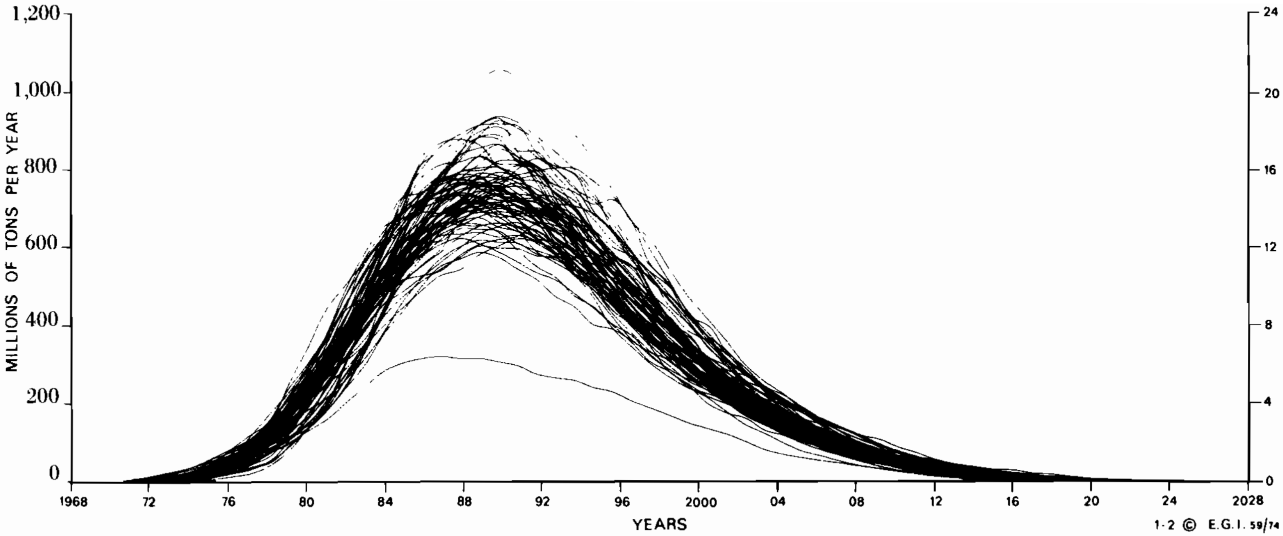

Figure 8. Results from 100 iterations of the production model. Note the "failed" curve. This represents the 1% probability of a curve of production as low as this.

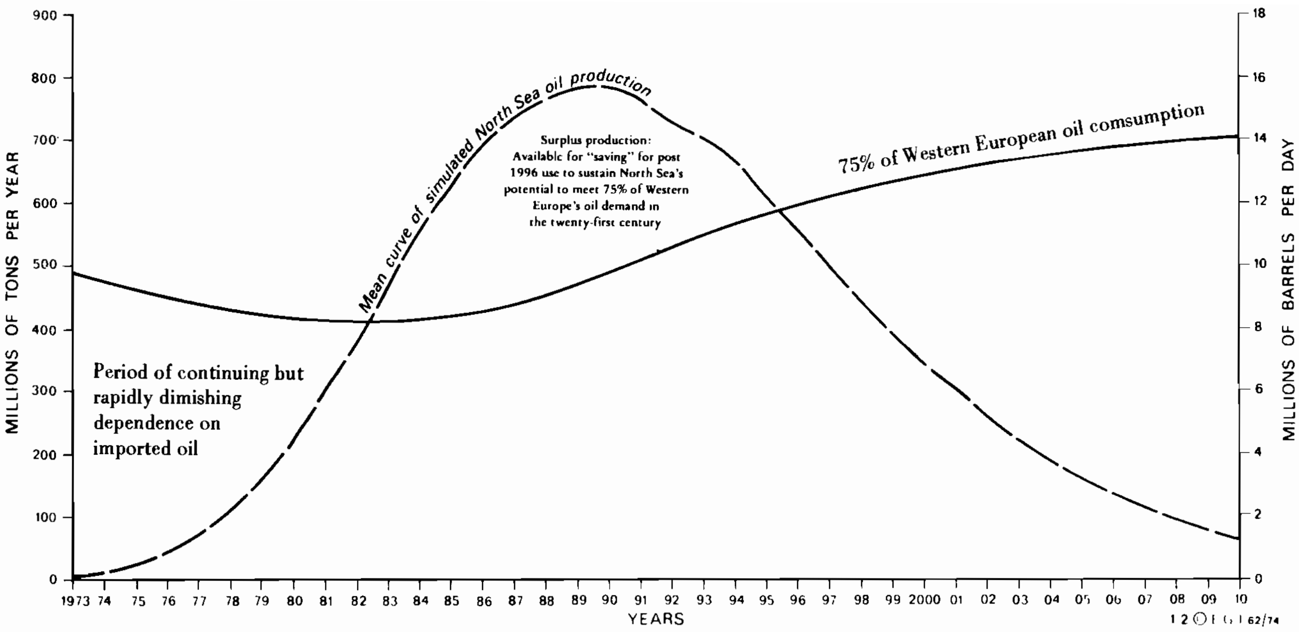

Figure 9. The mean curve of production potential compared with 75% of expected demand for oil in Western Europe.

use in the first quarter of the twenty-first century. Beyond that time it is probable that the Western European economy will become oriented to the use of other cheaper and/or preferred energy sources which, by then, will have been made available by technological developments. In brief, the North Sea oil production potential may well be great enough after 1980--given full and appropriately timed development, as well as the efficient use of oil implied in the demand curve in Figure 9--to see the whole of Western Europe through the post-oil age without any further large-scale dependence on supplies of foreign oil. It also undermines the validity of the now generally accepted view that a nuclear-power crash programme is required to ensure Western Europe's energy supplies for the medium-term future (see Table 3).

The model has predicted the potential ultimate reserves of the North Sea province to be over two and up to four times the volumes currently indicated by the oil companies. The latter figures are now being commonly used for planning purposes, but our investigation appears to indicate the need to examine a broader range of policy options for the future of Western Europe's energy supply than those usually envisaged by policy makers. The first requirement in looking at this broader range of options is an adequate international monitoring and evaluation system, at a northwestern European level, for the North Sea basin's development. Such monitoring of the basin's development would provide the essential device needed to give the information on which the shorter (five to ten years) policy options can be determined. Further evaluation, which could then be based on adequate information about the hydrocarbon potential, would then indicate options for the next two generations.

In this respect, the simulation model as presented in this paper can, hopefully, be used as the prototype from which to develop a more sophisticated and a more elegant approach to the longer-term potential from the province--not only for oil, but also for natural gas, the availability of which will, of course, be increasing at the same time given its occurrence along with oil, with a consequent joint availability of the two products. The simulations of future possibilities can provide a control against which actual developments can be examined for their significance, and so provide a tool for determining policies such as those, for example, that seek to vary the rate of development of the oil and gas resources of this major oil and gas province for political and economic reasons.

Table 3. Conventional and alternative views on Europe's energy supply 1975-2000.

	1975 Expected Approx.Use		1980 Estimates				1985 Estimates				2000 Estimates			
			Conventional		Alternative		Conventional		Alternative		Conventional		Alternative	
	mmtce$^{1)}$	%$^{2)}$	mmtce	%	mmtce	%	mmtce	%	mmtce	%	mmtce	%	mmtce	%
Total Energy	1,580	100	2,255	100	1,850	100	2,870	100	2,200	100	5,425	100	3,300	100
Oil-Total	920	59	1,500	66	785	42	1,845	64	800	36	Not Available		1,350	41
i) Indigenous	30	2	50	2	380	20	195	7	600	27			1,100	33
ii) Imported	890	57	1,450	64	405	22	1,650	57	200	9			250	8
Gas-Total	215	13	265	12	575	31	385	14	750	34			1,050	32
i) Indigenous	200	12	215	10	500	27	300	11	600	27			800	24
ii) Imported	15	1	50	2	75	4	85	3	150	7			250	8
Coal-Total	400	26	280	12	310	17	310	11	350	16			500	15
i) Indigenous	360	23	205	9	230	12	220	8	250	11			400	12
ii) Imported	40	3	75	3	80	5	90	3	100	5			100	3
Primary Electricity	45	3	210	10	180	10	330	12	300	14			400	12
Total Indigenous	635	40	680	31	1,290	69	1,045	37	1,750	80			2,700	81
Total Imported	945	60	1,575	69	560	31	1,825	63	450	20			600	19

Sources: OECD, EEC and various national estimates, prior to the oil crisis, for future energy supply patterns form the basis of the conventional estimates. The alternative estimates are the author's own from March 1974.

[1] Million metric tons coal equivalent.

[2] Columns do not necessarily add to 100 because of "rounding".

EXTRAPOLATING TRENDING GEOLOGICAL BODIES

Gregory B. Baecher and Jacques G. Gros

I. INTRODUCTION

The process of geological exploration often encounters formations or bodies which might be described as "linearly trending." Here, the word trending is not used in the sense of so-called trend surface analysis, but rather as a description of bodies whose planar shape can be approximated by lines or low-order curves. Examples are shoestring sands, buried reefs, some mineralizations, and high-permeability channels of subsurface flow (the last being of importance in civil construction; see Figure 1). The problem addressed in this paper is how the location of trending bodies in regions yet to be explored might be predicted on the basis of known locations in adjacent regions. In particular, an attempt is made to structure a rule-of-thumb approach on a rigorous foundation in the philosophy of exploration.

During the past 20 years, contributions have been made to the literature of decision analysis, search theory, and operations research generally which allow us to allocate exploration effort in ways which maximize the information we can expect to obtain. However, these methods require quantitative predictions: they require that predictions be encoded in probabilistic terms so that questions of the sort, "How much more probable is it that an ore body lies at point A than B?" can be answered. Certainly, evaluation of such probabilities is the foundation of exploration and the only reason geologists are the ones who carry it out. The purpose of the present paper is to attempt a quantification of predictions associated with one type of formation.

A Rule-of-Thumb Approach

It is dangerous to characterize rule-of-thumb approaches too narrowly; geologists tend to be independent sorts and there are many procedures for handling any specific problem. Nonetheless, a typical one for linear extrapolation is to assume that for short distances a body centerline may be approximated by a line or low-order curve, and to extend this line into unobserved regions as the likely continuation of the body (see Figure 2). Clearly, the faith one puts in this extrapolation diminishes the further it is extended. In a decision sense this line represents the locus of most probable locations of the body as one moves away from the observations, and is the line along which further exploration would initially take place.

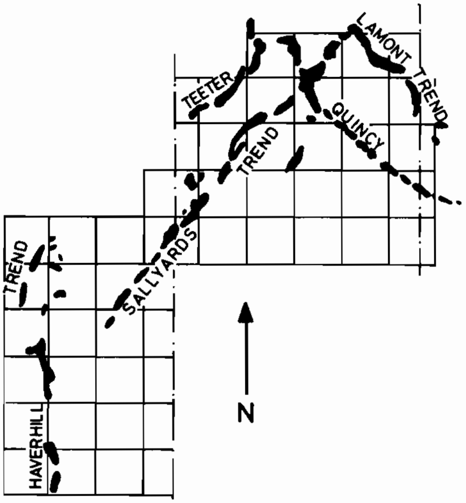

Figure 1. Shoestring-sand pools of Kansas (after Levorsen, 1954).

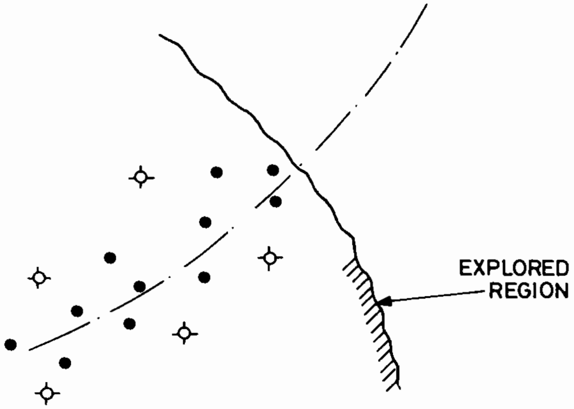

Figure 2.

The line or curve fitted to observed locations depends on the geologist's experience and his understanding of fundamental geological processes. While this heuristic approach is not based directly on geological theory (that is, it is not a random process model), knowledge of the theory leads one to intuitively suspect certain forms of spatial behavior over others, and thus the approach does represent informed geological opinion.

The relationship between informed geological opinion, uncertainty, observations, and spatial modelling is largely neglected in the literature. So, before proceeding to quantification, the philosophical basis of exploration upon which the present work is predicated should be discussed.

II. EXPLORATION PHILOSOPHY

Conclusions drawn from the results of exploration contain much more than the physical records themselves. Patterns recognized, maps drawn, similarities inferred, these all transcend the observations actually made. Hypotheses are the product of exploration. Exploration uncertainties manifest themselves in the degree to which hypotheses either are or are not confirmed by exploration data. Therefore, geological mapping is not merely a faithful reporting of instrumental observations, but is an interpretive, inductive task reflecting currently held concepts of geological structure (see, for example, Harrison, 1963).

Hypotheses arise and are given initial credibility through a process which is entirely subjective. They are generated by a process of discovery (much discussed in the philosophy-of-science literature), and assigned a priori degrees-of-confirmation based primarily on extra-evidential factors.[1] In entirety this process is simply inductive reasoning. Although a priori degrees-of-confirmation are subsequently modified as new data become available, their foundation is always and purely subjective. Thus, as the uncertainties of exploration are predicated on the subjective process of inductive reasoning, they too are fundamentally subjective. One has experience and knowledge of geology which causes one to suspect conditions not directly manifested in exploration data, and the uncertainties one associates with these hypotheses cannot be objectively derived from the records of exploration.

As data from exploration accrue, initial degrees-of-confirmation are modified by the extent to which the predictions following from each hypothesis are consistent with observation. A method for doing this analytically is Bayes' Theorem. Let there be some set of alternative hypotheses, $H_1,\ldots,H_n$, with respect to subsurface conditions at a site; and assume that the a priori degree-of-confirmation assigned to each is $p^o(H_i)$ (that is, the probability of hypothesis H_i being correct). Given a set of observations $\underline{z}$, by Bayes' Theorem the a posteriori degree-of-confirmation of each hypothesis is

$$p'(H_i|\underline{z}) = \frac{p^o(H_i)\ L(\underline{z}|H_i)}{\sum_{i=1}^{n} p^o(H_i)\ L(\underline{z}|H_i)} \qquad (1)$$

in which $L(\underline{z}|H_i)$ is the likelihood of the observations, $\underline{z}$, conditioned on H_i (that is, the probability of observing $\underline{z}$ were hypothesis H_i correct), and the denominator is simply a normalizing constant. Clearly, as the number of times this process is iterated increases, the importance of $p^o(H_i)$ in establishing $p'(H_i|\underline{z})$ decreases. The degree-of-confirmation, given a hypothesis, comes to depend more and more on observations alone.

Subjective Probability

Structuring inductive tasks in terms of Bayes' Theorem indicates that we are approaching exploration problems from a degree-of-belief perspective on probability; our description of interpreting exploration data indicates that we are approaching them subjectively. The task here is not to repeat arguments for and against belief and frequency--these are voluminously argued in other places (for example, Savage et al., 1962)--but there are operational arguments as well as philosophical ones for adopting a subjectivist approach, and these may provide justification to those more skeptical of "Bayesian" analysis.

First, subjective approaches include the prior feelings and intuition of the exploration geologist directly in the analytical model. These feelings are important sources of information which other approaches do not consider analytically.

Second, subjective approaches allow the inclusion of components of uncertainty (for example, model selection) which otherwise must be dealt with judgmentally. They provide rigorous procedures for aggregating uncertainties from several sources in evaluating total uncertainty.

Third, predictions which result from subjectivist models are expressed in terms of probabilities of hypotheses or events and can be directly incorporated in decision-making. This allows use of sophisticated methodologies developed in decision analysis, search theory, and other branches of operations research.

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[1] Some of these are the simplicity or aesthetic appeal of a hypothesis, its conformity to larger sets of hypotheses, and lack of better hypotheses. A review of inductive philosophy is given by Salmon (1966).

Fourth, geological structure is a highly complex phenomenon of which we have random process models for only the simplest cases.[2] A subjectivist approach allows us to employ heuristic models and assign levels of credibility to them within the analytical framework. Also, empirical evidence in other fields (for example, see Murphy and Winkler, 1974) indicates that subjective forecasts may even be more accurate than the best random process models in treating certain types of predictions.

Lastly, in subjective theory probability is defined with respect to the individual. Recent work (Morris, 1974) allows us to coalesce the feelings of more than one geologist into a priori probabilities, and thus both allocate initial effort and make predictions on a broad expert base which has been rigorously aggregated.

Accepting the subjective approach for quantitative analyses of exploration requires placing numbers on a priori feelings: quantifying a priori subjective probabilities. This quantification does not imply objectivity; it is merely a process of scaling subjective feelings on a rigorously based metric so that feelings may be analytically combined with other parts of exploration.

The theory of subjective probability and techniques for assessment are topics which cannot be adequately presented here. The literature of statistical decision analysis and behavioral decision theory, however, contains extensive work on these topics, and Grayson (1960) has presented a well-known discussion of subjective probability within the context of oil and gas drilling.

Models and Model Selection

The selection of models with which to analyze geological data and make predictions is, like exploration itself, a subjective task. The geologist reviews his experience with geologically similar formations and assigns (explicitly or implicitly) degrees of appropriateness to each of several models he might employ. He applies the models deemed most appropriate to the existing data, and then reassesses the weight attached to each by how well it "fits" the data. The process is the same as for evaluating alternative hypotheses. In making subsequent predictions one evaluates uncertainty by compounding uncertainties in the validity of the model with uncertainties in its predictions. In other words, the probability of an event, $\mathcal{E}$, becomes

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[2] What we have here called random process models are often called *structural models.* That is, they are models based on first principles of the physical system. We use the first name to avoid confusion with "structural" geology, however.

$$\Pr[\mathcal{E}] = \sum_i \Pr[\mathcal{E}|M_i]\Pr[M_i] \quad , \tag{2}$$

in which $\Pr[\mathcal{E}|M_i]$ is the probability of the event as predicted by the ith model and $\Pr[M_i]$ is the probability of the ith model being correct (assuming the $\Pr[M_i]$ independent).

Models applied to predicting spatial properties may be based either on an understanding of fundamental geological processes (for example, the physics of sedimentation) or on heuristic rules inferred from experience. When quantified as stochastic relationships the former are referred to as random process models, while the latter will be referred to here simply as heuristic models. Random process models stem from theories of geological processes which lead deductively to spatial properties; heuristic models stem from no identifiable geological theory and are justified only in that they adequately fit (and predict) observations. This should not be taken to mean that random process models are universally preferred, because operationally heuristic models may be more useful.

Random process models require that geological processes be well understood, and that the set of controlling variables be both identifiable and small. In practice, these conditions are not often met, and geologists themselves are generally unable to formulate conceptual models in terms of first principles (Krumbein, 1970). Practical limitations of random process models are that the mathematics of the models rapidly become intractable, and controlling variables are often unmeasurable. In matters of scientific inquiry, models based on first principles are clearly preferable to heuristic ones, but in exploration this is not necessarily the case: models which work (that is, which yield valid predictions for whatever reason), and are simple enough to apply, are favored.

The degree-of-belief one has in the validity of particular models, just as the degree-of-confirmation he assigns to hypotheses, is a complex function of evidential and extra-evidential factors. On the one hand, the better the performance of a given model with past data, the more faith one places in it; while on the other hand, the more compatible a model is with larger sets of geological theories, the more faith one places in it. These tendencies sometimes pull in opposing directions. The stability of one's belief in a model clearly relates to its foundation in theory. Heuristic models are quickly discarded when they do not fit data in new situations; for random process models this is not the case.

The tendency in fitting heuristic models, particularly for trend extrapolation, is to make them as simple as possible; this means as low-order as possible. Linear or quadratic trends are usually preferred to 10- or 12-degree trends. Simplicity is not merely a prejudice of geologists, but reflects experience (that is, it is evidential). High-order curves and surfaces have sufficient flexibility that the probability distributions of their predictions decay more rapidly than experience suggests they should: we appear to be able to make more confident and further-extended predictions than high-order trends imply. Thus one generally avoids high-order trends as having little a priori validity or usefulness in practical problems.

Summary

We have tried to present a short discussion of the logic of inference in exploration. In particular, we have tried to emphasize the following points:

1) Exploration is an inductive rather than deductive undertaking whose results transcend the physical record of explorations.

2) Uncertainties in the conclusions drawn from exploration are of subjective origin, and should be treated by subjectivist probability theory.

3) There is a fundamental difference between models which predict spatial properties based on heuristic reasoning and those which do so by modelling geological processes.

III. QUANTITATIVE ANALYSIS

The present approach to predicting the location of trending bodies is an analytical formulation of the heuristic centerline extrapolation technique; it is not a random process model of the spatial properties of geological bodies based on genetic concepts of sedimentation, implacement, etc. Therefore, it is not so much a model of geology as it is a model of spatial relationship based on empirical experience with other similar formations. However, the model does provide an accounting of uncertainties from various sources and thus provides insight into the dispersion of certainty with which predictions can be made away from observations.

We assume that on the basis of previous drilling and exploration some region within which the trending body lies has been explored, and that from this exploration two types of information are available. First, we know that the body exists at several discrete points in the horizontal plane (see Figure 3); second, we have information on which some subjective feeling for the orientation of the body, exclusive of boring locations, can be based. (For example, we may have relevant geomorphological information, cross-bedding orientations in core samples, grain-size changes at progressive locations, etc.)

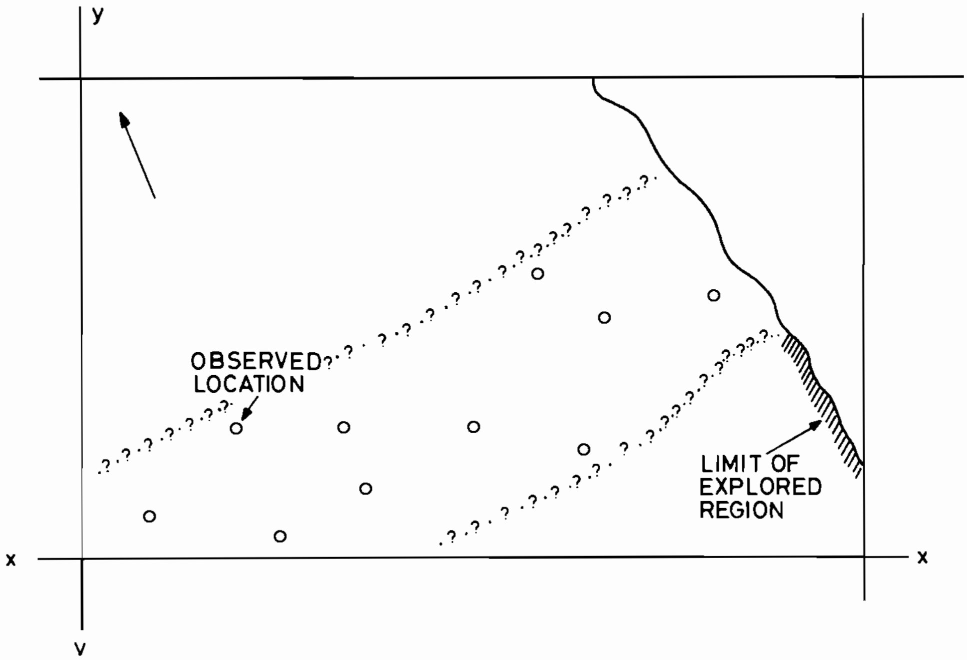

Figure 3.

Based on information of the latter type, a priori feelings about the trend and width of a body may be evaluated using techniques of subjective probability theory. Then, using known locations of the body as data, the probabilities both of the centerline trend and of the width are updated to give a posteriori probabilities from which predictions can be made.

Given that probability distributions on centerline trend and width have been updated, probabilities that the body exists at unobserved locations can be evaluated by a procedure shown schematically in Figure 4. Let the probability density function of the intersection of the centerline with the line $x = x_o$ be $f(y'|x_o)$. The conditional probability that the body exists at some point (x_o, y_o) is simply the probability that the distance between (x_o, y_o) and the centerline is less than half the body width,

$$\Pr[x_o, y_o | y') = \Pr\left[|y_o - y'| \le \frac{w}{2}\right] \quad . \tag{3}$$

But as the centerline location is itself uncertain, the probability must be weighted and integrated over possible centerline locations, or

$$\Pr[x_o, y_o] = \int_{y'} \Pr\left[|y_o - y'| \le \frac{w}{2}\right] f(y'|x = x_o)\, dy' \quad . \tag{4}$$

So, once the probability functions of width and centerline location are determined, probabilistic predictions of body location on the basis of any particular trend model can be generated by equation (4).

Probability density functions (pdf's) of centerline location and body width can be evaluated for a particular trend model by performing a (Bayesian) regression on known locations. Once this is done, model uncertainty can be accounted for by evaluating the posterior probability of each model and forming a so-called composite Bayesian model.

Centerline Distribution: Bayesian Regression

Let the known locations of the body be represented by the set of data points $(\underline{x}, \underline{y})$, and the trend model be

$$\underline{y} = \underline{\beta}\underline{\underline{X}} + \underline{e} \quad . \tag{5}$$

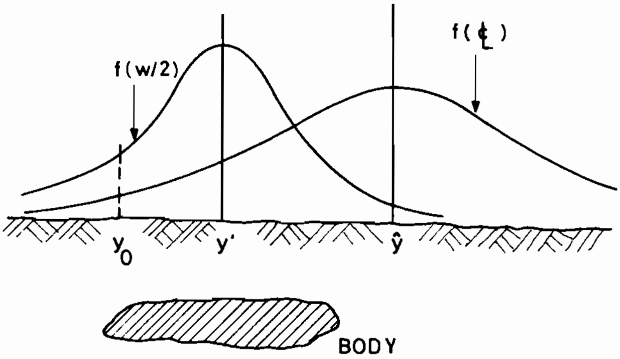

Figure 4.

Here, $\underline{y}$ is the vector of y-components of the data set, $\underline{\underline{X}}$ is a matrix of functions of the x-components, $\underline{\beta}$ is the vector of regression coefficients, and $\underline{e}$ is an error term with zero-mean and variance σ^2. For example, for the model,

$$y_i = \beta_1 + \beta_2 x_i + \beta_3 x_i^2 + \cdots + e_i \quad , \tag{6}$$

$$\underline{y} = (y_1, y_2, \ldots, y_n)$$

$$\underline{\beta} = (\beta_1, \beta_2, \ldots, \beta_k)$$

$$\underline{\underline{X}}^t = \begin{bmatrix} 1 & x_1 & x_1^2 & \cdots & x_1^{k-1} \\ 1 & x_2 & x_2^2 & \cdots & x_2^{k-1} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_n & x_n^2 & \cdots & x_n^{k-1} \end{bmatrix}$$

By the Bayesian argument, prior probabilities on $\underline{\beta}$ and σ are updated to yield posterior probabilities on the basis of the likelihood of observations conditioned on $\underline{\beta}$ and σ. That is, probabilities are updated on the basis of conformity between observations and predictions. If we let $f^o(\underline{\beta},\sigma)$ be the prior joint pdf of the regression parameters, then the posterior joint pdf of $\underline{\beta}$ and σ by Bayes' Theorem is

$$f'(\underline{\beta},\sigma|\underline{\underline{X}},\underline{y}) \propto f^o(\underline{\beta},\sigma)\ L(\underline{\underline{X}},\underline{y}|\underline{\beta},\sigma) \quad . \tag{7}$$

If for the prior distribution $f^o(\underline{\beta},\sigma)$ we use the so-called "uninformed" prior,[3]

$$f^o(\underline{\beta},\sigma) \propto \frac{1}{\sigma} \tag{8}$$

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[3] We have chosen here to use "uninformed" or flat priors simply for convenience of presentation. In reality, the geologist's opinion of local geological structure would enter the analysis through $f^o(\underline{\beta},\sigma)$. Informed priors are discussed in Appendix C.

(that is, $\underline{\beta}$ and ln σ uniformly distributed), and if for the error term, $\underline{e}$, we assume a zero-mean normally distributed random variable, then one can show (Zellner, 1971) that the posterior distributions of $\underline{\beta}$ and σ and simple functions of $\underline{\beta}$ and σ belong to well-known families of distributions (see Appendix A). In particular, the distribution of interest in extrapolation is the centerline pdf. From equation (5), centerline location conditioned on x is simply a weighted sum of the random variables $\underline{\beta}$, and can be shown to be distributed as a univariate Student t (Zellner, 1971):

$$f(y'|x_o) \propto \left\{\nu + \frac{(y - \hat{y})^2}{S^2 c}\right\}^{-(\nu+1)/2} , \qquad (9)$$

in which ν is degrees-of-freedom, S^2 is a squared error term from the data set, and c is a constant depending on values of the data set and x_o. The term $\hat{y}$ is the expected location of the centerline.

Model Uncertainty

Beyond uncertainties inherent in estimating model parameters there are also uncertainties in which model of centerline trend to fit. For example, should a linear trend be used, or is some low-order curve a better representation? The importance of including model uncertainty in prediction is that it is a substantial component of total uncertainty, and that this increased uncertainty leads to an increased rate of decay in the probability density of predicted location (that is, a more rapid "broadening" of the pdf), and thus shortens the length to which extrapolations can be made.

The approach to model uncertainty used here is that suggested by Benjamin and Cornell (1970) and by Wood (1974), in which a weighted sum of the prediction of each model is formed using posterior model probabilities as weights.

Adopting the "linear" model of equation (6) to predict centerline trend, the shape of the extrapolation is described by k, the order of polynomial. Allowing the prior belief in the validity of k_i to be $p^o(k_i)$, posterior probabilities are updated in the normal way:

$$f'(\underline{\beta},\alpha,k_i|\text{data}) \propto f^o(\underline{\beta},\alpha,k_i)\ L[\text{data}|\underline{\beta},\alpha,k_i] \quad . \qquad (10)$$

Then

$$f'(\underline{\beta},\alpha|\text{data}) = \sum_{i=1}^{3} f'(\underline{\beta},\alpha,k_i|\text{data})$$

$$= \sum_{i=1}^{3} f'(\underline{\beta},\alpha|k_i,\text{data})\ p'(k_i|\text{data}) \quad ; \qquad (11a)$$

where

$$p'(k_i|\text{data}) \propto p^{o}(k_i) \int_{\underset{\sim}{\beta}} \int_{\alpha} L[\text{data}|\underset{\sim}{\beta},\alpha,k_i]\ f'(\underset{\sim}{\beta},\alpha|k_i)\ d\underset{\sim}{\beta}\ d\alpha \quad . \tag{11b}$$

<u>Width Distribution</u>

For convenience, we assume that the probability density of body half-width is distributed as the Maxwell distribution,

$$f(w|\sigma) = \frac{\sqrt{2}\ w^2}{\sigma^3\ \sqrt{\pi}} \exp\ (-w^2/2\sigma^2) \quad , \qquad \text{for } w \geq o \tag{12}$$

with parameter σ.

If we assume that the known locations of the body are randomly (that is, uniformly) distributed across the width of the body, then the pdf of the "error" term away from the body centerline (see Figure 5a) is

$$f(e|w) = \frac{1}{w} \quad , \qquad \text{for } o \leq e \leq w \quad . \tag{13}$$

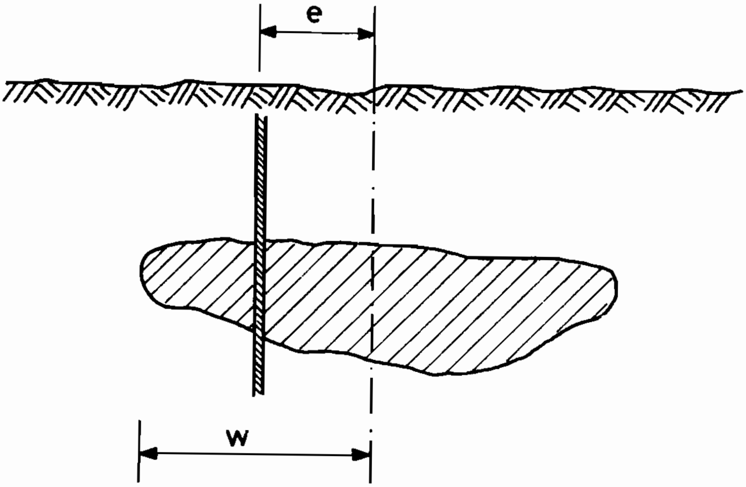

Figure 5a.

The marginal distribution of e is (see Appendix A)

$$f(e) = \int f(e|w)\ f(w)\ dw = \frac{\sqrt{2}}{\sigma\ \sqrt{\pi}}\ e^{-w^2/2\sigma^2} \quad , \tag{14}$$

which can be seen to decay as a one-sided normal distribution with variance σ^2. This is, of course, our justification for using the Maxwell distribution to begin with. With this distribution on width, "error" about the centerline is normally distributed and the results of Normal Bayesian regression can be directly employed.

Body Length

The model proposed thus far does not account for the finite length of geological bodies; it assumes them to be infinite. Therefore, probabilities which result from this model must be modified.

From past experience one has some idea of the distribution of lengths of similar bodies, and this information can be modelled by a probability density function, $f(\ell)$. Here, we will assume $f(\ell)$ to be lognormal, as this distribution family adequately fits many geometric properties of geological formations. Since we know that the body whose location is being predicted is at least of length l_o (see Figure 5b), by Bayes'

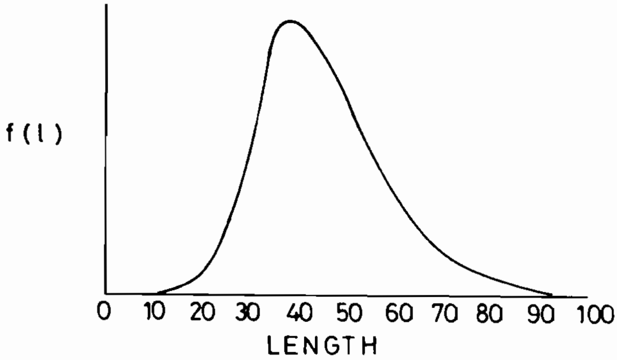

Figure 5b.

rule the conditional probability density of it being of length ℓ' is

$$f'(\ell'|\ell_o) = \begin{cases} \dfrac{f(\ell)}{\int_{\ell_o}^{\infty} f(\ell)\, d\ell} & \text{for } \ell \geq \ell_o \\ 0 & \text{otherwise} \end{cases} .$$

Assuming that the planar shape of the body is independent of its length (an assumption which may be questionable), the probability of its being located at any point is simply the product of the model prediction and the probability of its extending to or beyond the point in question,

$$\Pr[x_o,y_o] = \Pr[x_o,y_o|\ell \geq \ell'] \int_{\ell'}^{\infty} f'(\ell'|\ell_o)\, d\ell \quad .$$

IV. EXAMPLE PREDICTIONS

The present procedure for extrapolation was applied to the data shown in Figure 6 (a second data set and prediction is shown in Appendix B). Three simple trend models were fitted (linear, quadratic, cubic), assuming equal a priori model probabilities and Maxwell-distributed width.

Figure 7 shows the marginal posterior distribution of the regression coefficients $\underline{\beta}$ for the linear model (those for the quadratic and cubic models being harder to plot here), and Figure 8 shows the marginal posterior distributions of width for each of the models. Extrapolation predictions for each model are shown in Figure 9a, b, c, respectively; and the composite prediction, in Figure 10. Figure 11 shows the composite prediction modified by consideration of finite length.

The most striking feature of these extrapolations is how rapidly the certainty of location prediction decays away from the data set, an observation which is not so clearly demonstrated when non-quantified approaches are used.

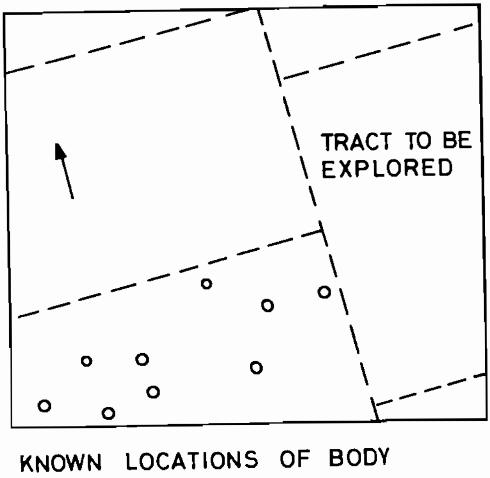

Figure 6.

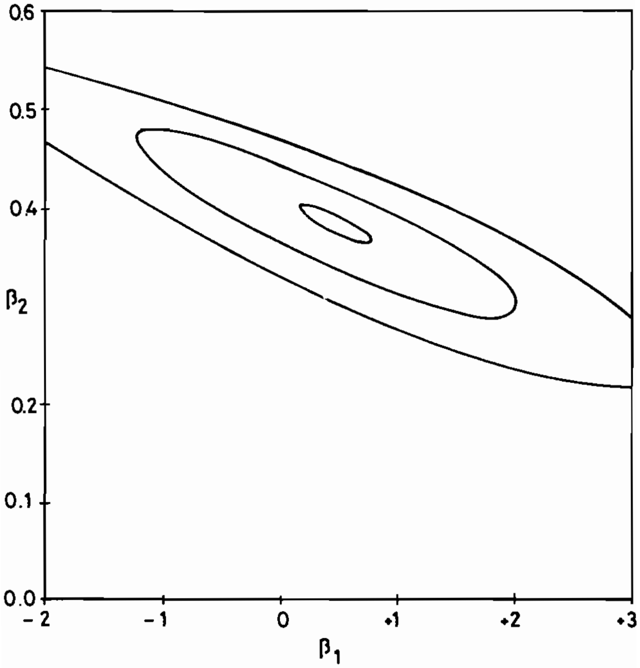

Figure 7. Posterior distribution of $\underline{\beta}$ linear model.

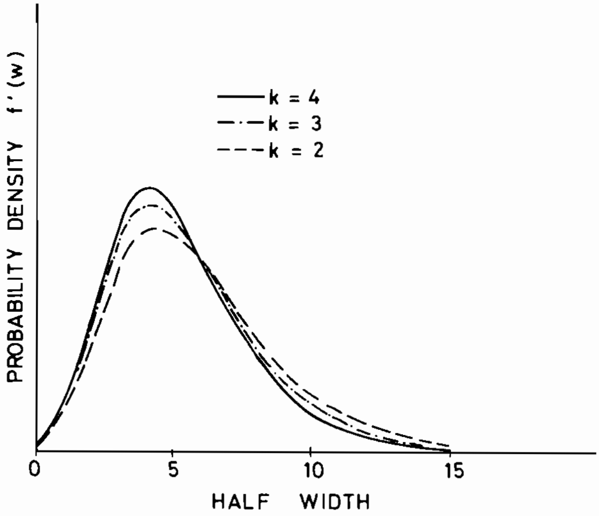

Figure 8. Posterior distribution of half width.

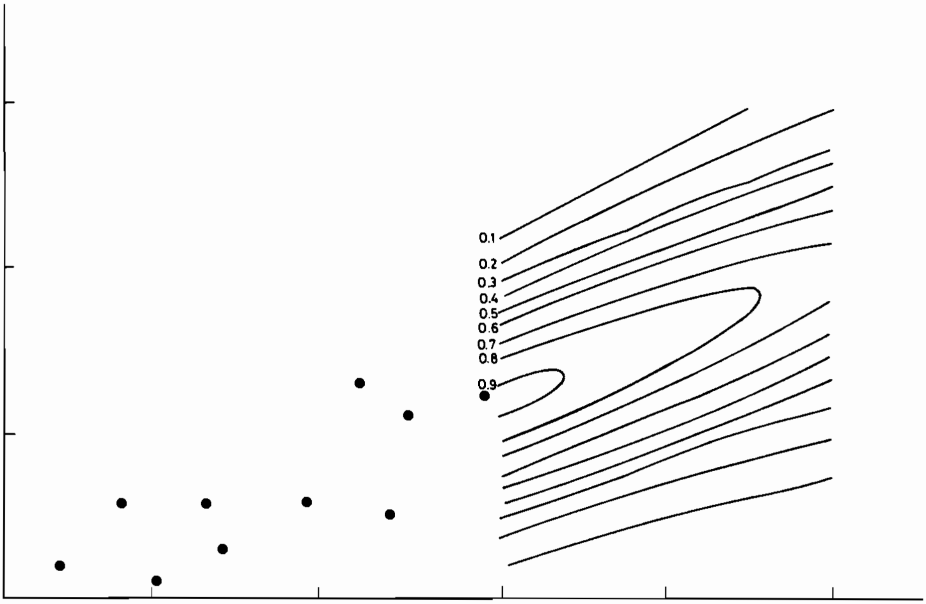

Figure 9a. Linear model.

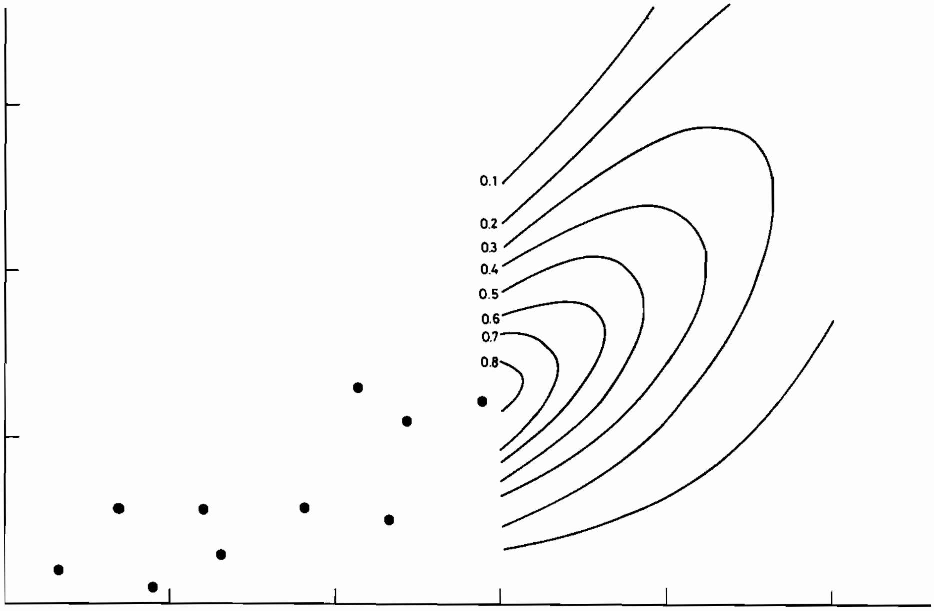

Figure 9b. Quadratic model.

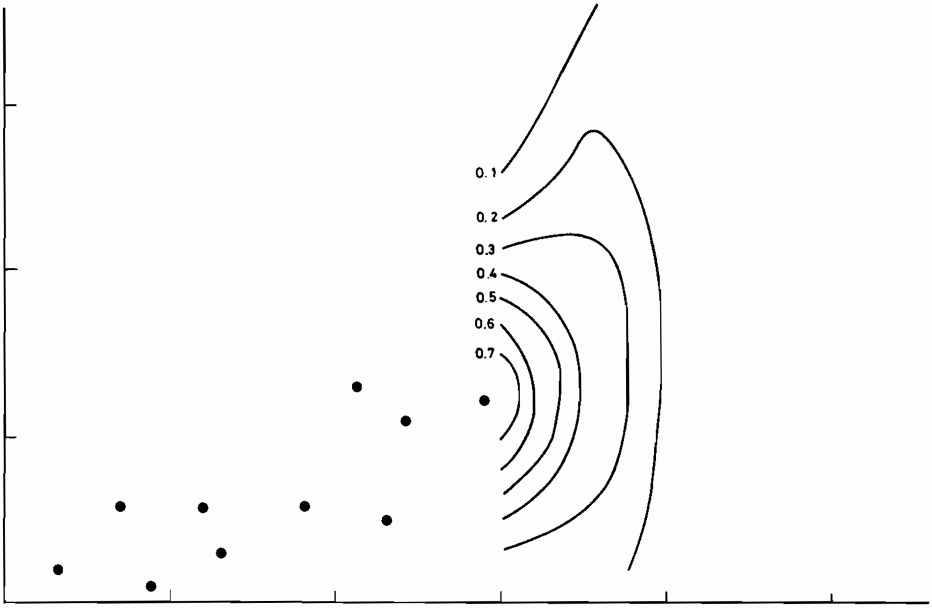

Figure 9c. Cubic model.

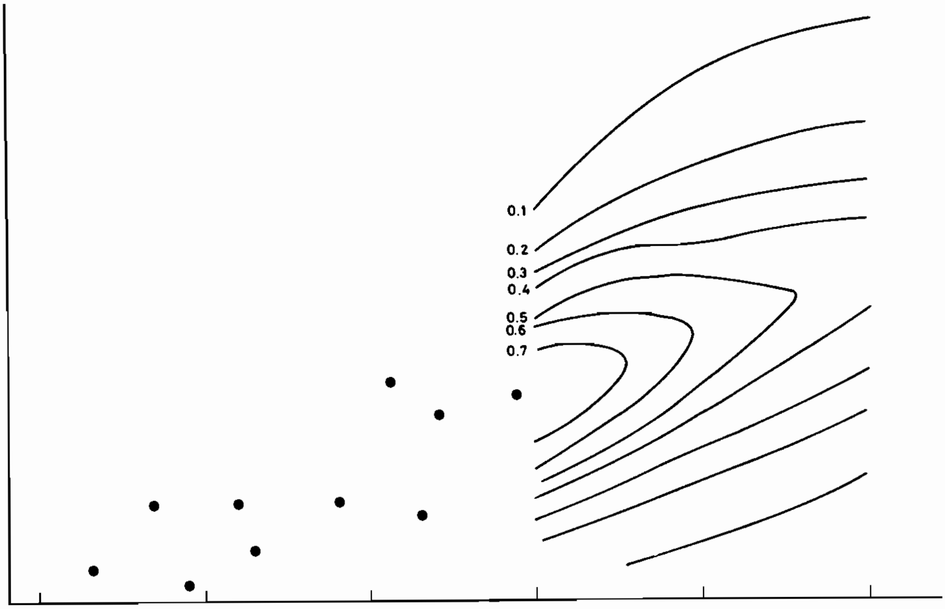

Figure 10. Composite.

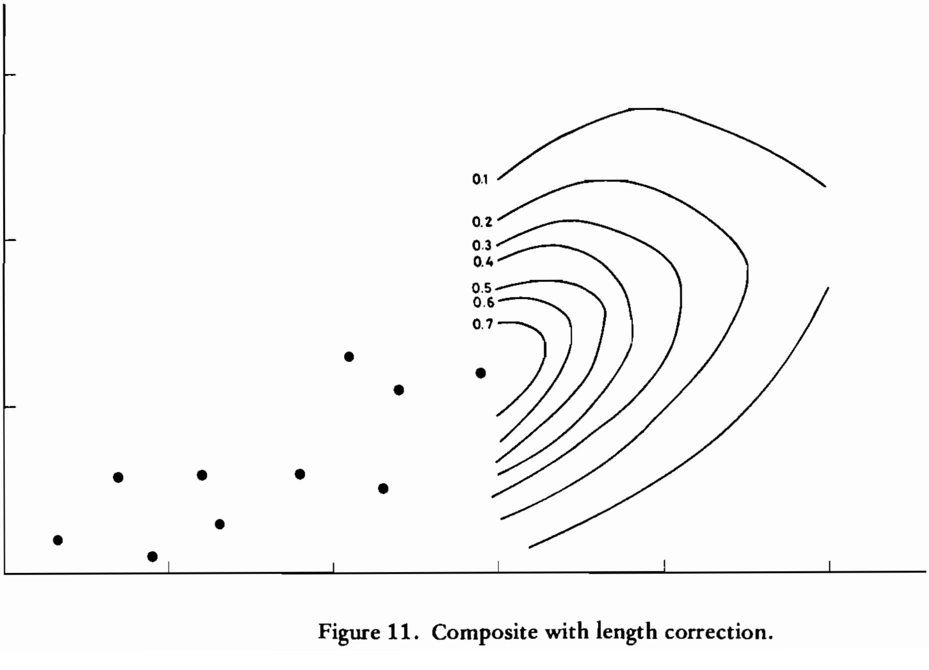

Figure 11. Composite with length correction.

V. LIMITATIONS AND ERRORS

This model is an attempt to quantify the sorts of spatial predictions which exploration geologists routinely make on the basis of observations. The model is not refined, and it clearly suffers the limitations of the heuristic technique on which it is based. On the other hand, the model has analytical shortcomings as well as geological ones, and these are what we turn attention to here.

To begin with, the model assumes that the x-components of known locations are independent, but in reality this is not so. Just as one considers present information when locating the next well or observation, so one considered it in the past. Thus, observations are biased toward lying on a straight line or low-order curve; that is precisely the way they were sequentially placed by whoever was making the decisions.

Second, the analysis neglects part of the location information we have. While reconnaissance information (for example, geophysical data, etc.) can be included in establishing prior probabilities, "dry wells" or locations where the body is known not to exist are neglected. This causes the model to generate predictions which are too diffuse.

Third, the distribution model for width is inadequate because it also neglects information and because account should be taken of width-model uncertainty as well as centerline-model uncertainty. Box and Tiao (1973) suggest a way of doing this. Since, as before, we have information on where the body is not, the width distribution should have an upper bound--which the Maxwell distribution does not.

Next, there is no reason to believe that the body has constant width. The assumption makes regression easier, and this is the reason it is made, but real formations have varying widths. As long as there is no trend of width with length, however, the assumption of uniformity is probably not too bad. If there is a trend--and finite length means that at some point there must be--the predictions may be substantially in error.

Finally, the procedure for updating model probabilities still requires thought. Here, likelihoods were calculated on the basis of "fit" of a centerline trend to observations. For a large number of observations (that is, relative to the trend order, k), higher-order curves will always fit better than lower-order ones. Yet, as we said earlier, empirically we know that high-order curves are too flexible and their predictions overly diffuse. When the number of data points, n, is small, this problem does not necessarily occur because the degrees-of-freedom ($\nu = n - k$) is substantially affected by changes in k (for example, see Appendix C).

VI. LOCATION PREDICTIONS AND DECISION MAKING

In this last section, as an addendum, we will briefly discuss the place of quantified predictions in decision making for geological exploration. In general, there are two types of decisions which might be made with spatial predictions. One is the exploitation decision: where should a new producing well be placed, or where should a well point be located to drain a pervious stratum? The second is the allocation of exploration effort: where should observations be made, or how closely spaced should geophysical traverses be placed? These decisions have different objectives and do not necessarily lead to similar optimizations. For example, the optimal location of an exploitation well might not be the same as the optimal location for gathering information on structure. Here we will describe the exploitation decision as it is analytically simpler, yet highlights the role of quantified predictions.

Assume that the decision to be made is where to place a well for production of some resource or for dewatering a construction site; and assume that this is a one-stage decision (that is, information gathering has already been finished). A decision tree for this decision is shown in Figure 12. Let the cost of drilling, c, be independent of location, and let the value of hitting oil, water, or whatever, be a function, g(d), of the distance from the closest "producing" well. (In other words, assume that two wells in proximity draw on the same volume of resource and thus have lower individual yields than two more distant wells; see Figure 13.)

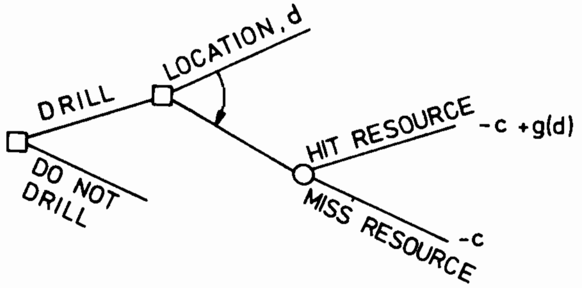

Figure 12.

Taking the predictions of Section IV, let the locus of points of maximum probability of the body's location away from the data set be represented by line J (Figure 14). The decay in probability along this line is shown in Figure 15. Using

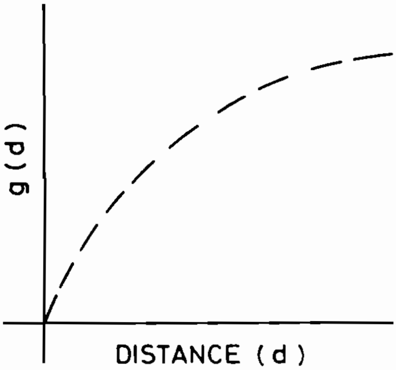

Figure 13.

expected value as the criterion of decision,[4] we can graph the objective function over distance along J as

$$E[\text{value}] = (-c) + g(d) \times \Pr[\text{hitting body with resource}] \quad .$$

Combining yields a maximum at d_*, which if greater than zero would be the optimal location for drilling based on model predictions.

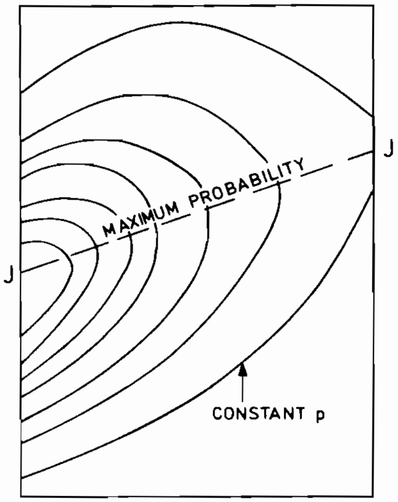

Figure 14.

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[4] This of course assumes a linear objective function which is expected monetary value. Clearly this may not always be the case. But the problem may be overcome by introducing utility functions, which Grayson (1960) has discussed in a geological context.

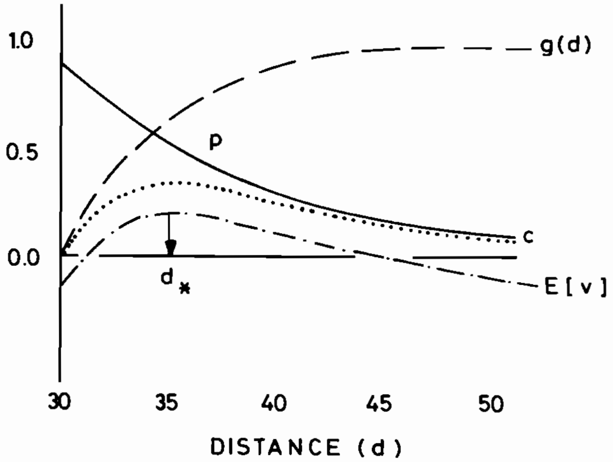

Figure 15.

VII. CONCLUSIONS

We have presented an analytical model for quantifying location predictions of linearly trending geological bodies, so that these predictions might be included in larger decision models for exploration. The model requires further refinement, but illustrates how the geologist's subjective judgment may be included in quantified approaches to optimizing exploration strategies. The model also sheds light on traditional questions in exploration, such as how far trends may be extrapolated away from observations. Our hope in presenting this work is that it will contribute to the larger task of the development of a general theory of rational exploration based on the subjective judgments of geologists.

APPENDIX A

Mathematical Structure of Analysis

WIDTH DISTRIBUTION

The probability density of width is assumed to be distributed as the Maxwell distribution with unknown parameter σ

$$f(w|\sigma) = \frac{\sqrt{2}\, w^2}{\sigma^3 \sqrt{\pi}} \exp\,[-w^2/2\sigma^2] \quad . \tag{A1}$$

Further, assuming that borings intersecting the body are randomly distributed across the body width, the probability density function of the distance, e, between a boring and the centerline is

$$f(e\ w) = \frac{1}{w} \qquad o \le e \le w \quad . \tag{A2}$$

Hence,

$$f_e(e) = \int f(e|w)\ f(w)\ dw \tag{A3}$$

$$= \int_{w=e}^{\infty} \frac{1}{w}\ \frac{\sqrt{2}\, w^2}{\sigma^3 \sqrt{\pi}}\ \exp\,[-w^2/2\sigma^2]\ dw$$

$$= \frac{\sqrt{2}}{\sigma \sqrt{\pi}}\ \exp\,[-w^2/2\sigma^2] \quad , \tag{A4}$$

which decays as a (one-sided) normal distribution. This distribution corresponds to that of the error in locating the centerline.

A Bayesian regression to estimate parameters of the centerline is performed on known locations of the body using a zero-mean normally distributed error term with variance σ^2, and an a priori pdf on the regression parameters,

$$f^o(\underline{\beta},\sigma) \propto \frac{1}{\sigma} \quad . \tag{A5}$$

This is the so-called "uninformed" prior based on uniform distribution of $\underline{\beta}$ and $\ln \sigma$. Using the notation of Section III, the posterior distribution of the parameters $(\underline{\beta},\sigma)$ is

$$f'(\underline{\beta},\sigma|\underline{\underline{X}},\underline{y}) \propto f^{o}(\underline{\beta},\sigma)\ L(\underline{\underline{X}},\underline{y}|\underline{\beta},\sigma) \tag{A6}$$

$$\propto f^{o}(\underline{\beta},\sigma) \prod_{i=1}^{n} f_e(y_i - \underline{\beta}\underline{x}_i|\underline{\beta},\sigma) \tag{A7}$$

$$\propto \frac{1}{\sigma^{n+1}} \exp\left\{-\frac{1}{2\sigma^2}\left[\nu s^2 + (\underline{\beta} - \hat{\underline{\beta}})^t \underline{\underline{X}}^t\underline{\underline{X}}(\underline{\beta} - \hat{\underline{\beta}})\right]\right\} , \tag{A8}$$

in which ν is the degrees-of-freedom,

$$\nu = n - k \quad , \tag{A9}$$

$$\hat{\underline{\beta}} = (\underline{\underline{X}}^t\underline{\underline{X}})^{-1}\ \underline{\underline{X}}^t\underline{y} \quad , \tag{A10}$$

and

$$s^2 = \frac{(\underline{y} - \underline{\underline{X}}\hat{\underline{\beta}})^t\ (\underline{y} - \underline{\underline{X}}\hat{\underline{\beta}})}{\nu} \quad . \tag{A11}$$

The centerline passing through any line $x - x_o$ is a weighted sum of the random variable $\underline{\beta}$,

$$\bar{y} = \beta_1 + \beta_2 x_o + \beta_3 x_o^{\ 2} + \ldots \quad ; \tag{A12}$$

and given the posterior distribution of equation (A8), Zellner (1971) shows this weighted sum to be distributed as a univariate Student t,

$$f(\bar{y}|\underline{\underline{X}},\underline{y},\underline{x}_o) \propto \left[\nu + \frac{(\bar{y} - \hat{y})^2}{s^2 C}\right]^{-(\nu+1)/2} \quad , \tag{A13}$$

in which

$$\hat{y} = \underline{x}_o\hat{\underline{\beta}} \tag{A14}$$

and

$$C = \underline{x}_o(\underline{\underline{X}}^t\underline{\underline{X}})^{-1}\ \underline{x}_o \quad . \tag{A15}$$

The procedure for using the pdf of centerline location along any line $x = x_o$ in conjunction with the pdf of width to predict body location is described in Section III.

Three simple trend models were fitted to the data (linear, quadratic, and cubic) with equal a priori probabilities (that is, 1/3). These probabilities were updated using Bayes' Theorem to arrive at posterior model probabilities, then used in forming the weighted or composite model for predictions:

$$p'(k) = \frac{p^{o}(k)\ L(\underline{\underline{X}},\underline{y}|k)}{\sum_{k=1}^{3} p^{o}(k)\ L(\underline{\underline{X}},\underline{y}|k)} \tag{A16}$$

in which

$$p^{o}(k = 2) = p^{o}(k = 3) = p^{o}(k = 3) = \frac{1}{3} \tag{A17}$$

and

$$L(\underline{\underline{X}},\underline{y}|k) = \mathop{\pi}\limits_{i=1}^{n} f_t\left[\frac{\underline{y}_i - \underline{x}_i\hat{\underline{\beta}}}{\sqrt{h_{ii}}}\right] , \tag{A18}$$

where the conditional distribution of the observations is Student t with ν degrees-of-freedom, and h_{ii} is the (i,i)th element of the inverse of H,

$$H = \frac{1}{s^2}\ (\underline{\underline{I}} - \underline{\underline{X}}(2\underline{\underline{X}}^t\underline{\underline{X}})^{-1}\ \underline{\underline{X}}^t) \quad . \tag{A19}$$

The weighted sum of the model predictions is formed as in Section III, to generate final predictions.

The probability distribution of body width inferred from each of the models is computed using the marginal posterior distribution of σ and the relationship,

$$f(w|\underline{\underline{X}},\underline{y}) = \int_{\sigma=0}^{\infty} f(w|\underline{\underline{X}},\underline{y},\sigma)\ f(\sigma|\underline{\underline{X}},\underline{y})\ d\sigma \tag{A20}$$

$$= \int_{\sigma=0}^{\infty} \frac{\sqrt{2}\ w^2}{\sigma^3\ \sqrt{\pi}}\ \exp(-(w^2/2\sigma^2)) \left[\frac{2(\nu s^2/s)^{\nu/2}}{\Gamma(\nu/2)}\right] \frac{1}{\sigma^{\nu+1}}\ \exp(-(\nu s^2/2\sigma^2))\ d\sigma \tag{A21}$$

$$= \frac{(\nu s^2/2)^{\nu/2}}{\Gamma(\nu/2)}\ \frac{\sqrt{2}\ w^2}{\sqrt{\pi}} \left[\frac{\Gamma[(\nu+3)/2]}{[\frac{1}{2}(\nu s^2 + w^2)]^{\frac{\nu+3}{2}}}\right] . \tag{A22}$$

APPENDIX B

A Second Numerical Example

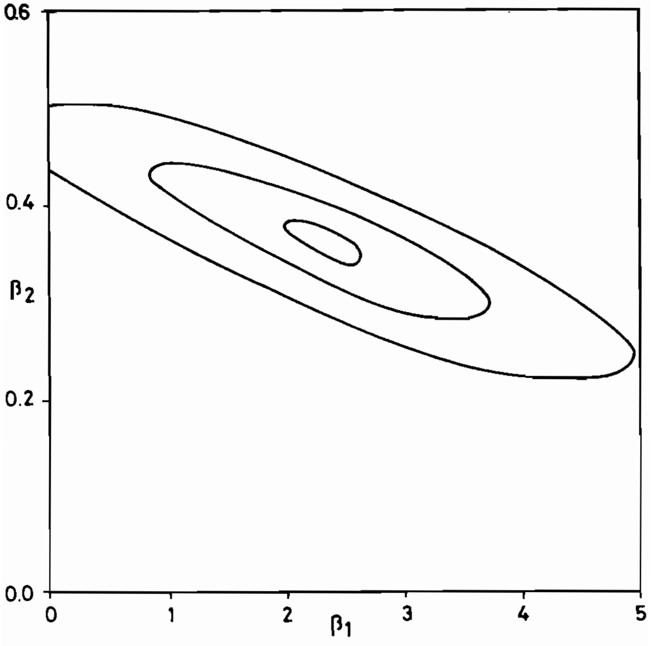

Figure B1. Posterior distribution of $\underline{\beta}$ linear model.

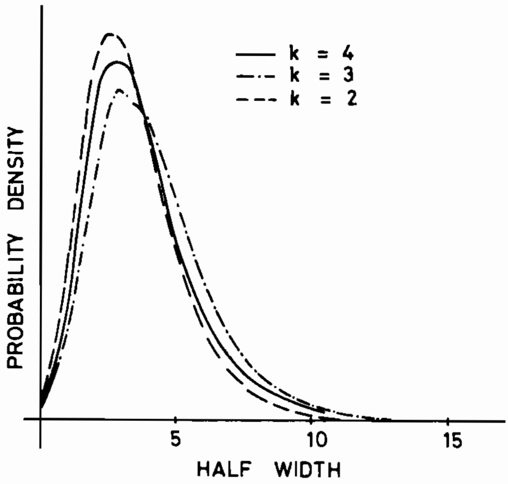

Figure B2. Posterior half width distributions.

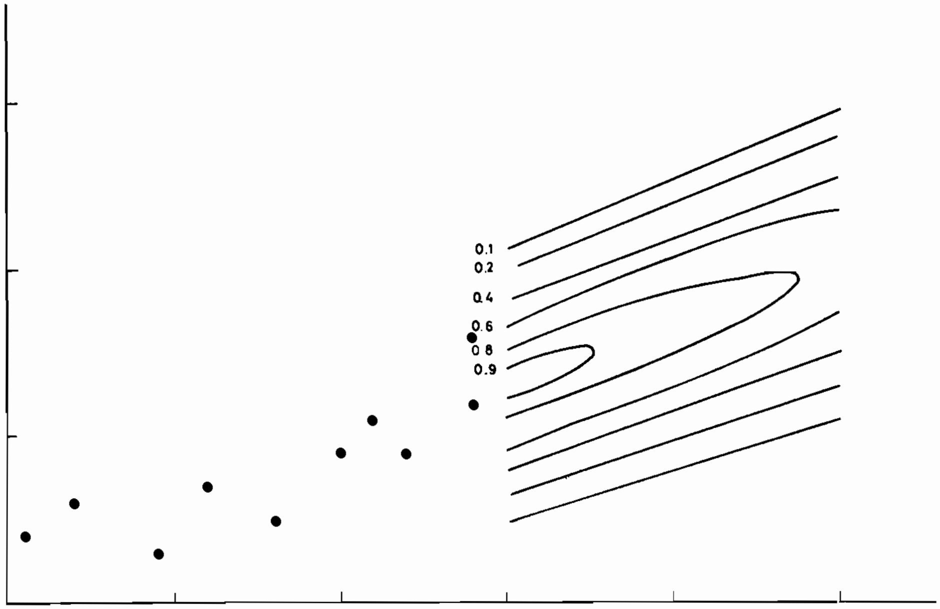

Figure B3. Linear model.

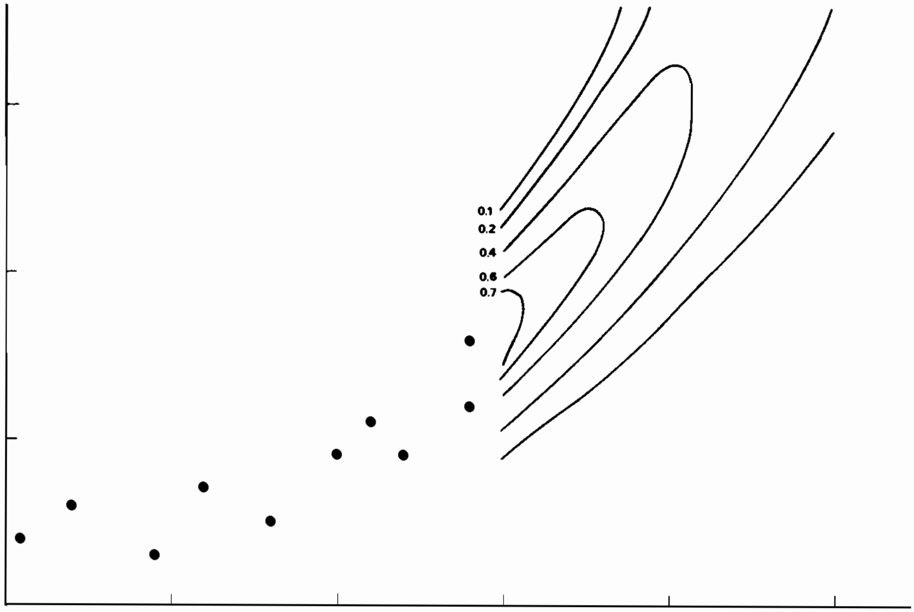

Figure B4. Quadratic model.

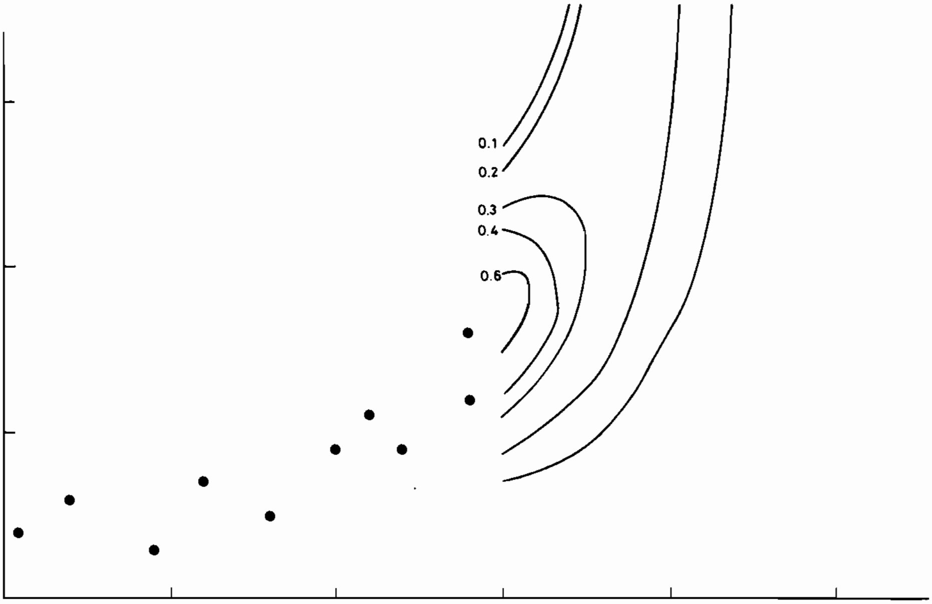

Figure B5. Cubic model.

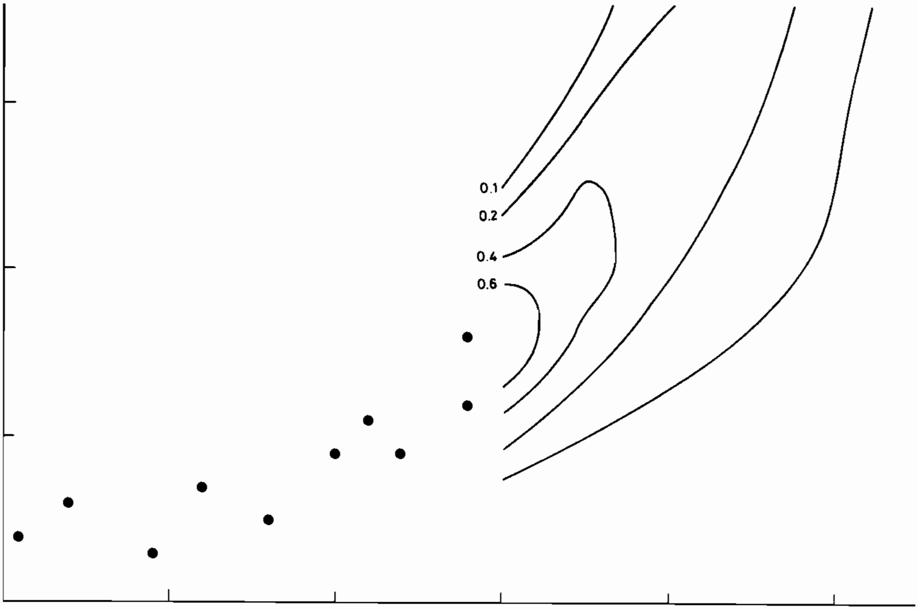

Figure B6. Composite.

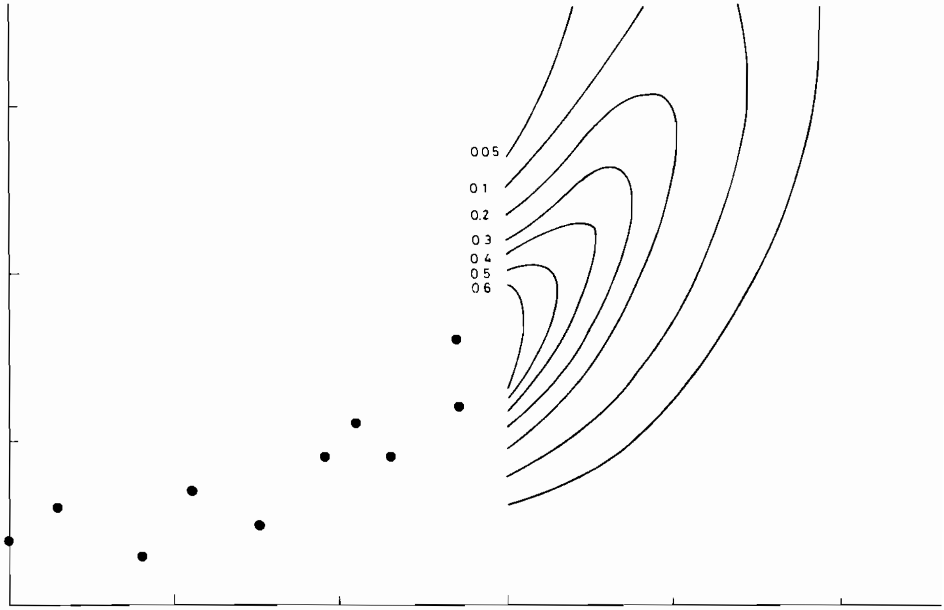

Figure B7. Composite with length correction.

APPENDIX C

Informed Priors

The use of noninformative or diffuse priors in Bayesian analysis has been a source of controversy, and indeed a point of major criticism of Bayesian methods by members of the frequentist school. This controversy is discussed in several places (for example, Jeffreys, 1966; Savage et al., 1962; Zellner, 1971), and so will not be summarized here.

When prior information on feelings does exist, some prior pdf on $\underline{\beta}$ and σ which accounts for this information should be used (that is, rather than "uninformed" priors). Since the procedure for updating a prior distribution on $\underline{\beta}$ and σ by sample data rapidly becomes intractable unless the shape of the prior distribution is judiciously chosen, one is well advised to select this distribution in coordination with the likelihood function. One such distribution is the conjugate of the likelihood function which has the property of closure under Bayesian updating. That is, a conjugate distribution is one which when updated by the likelihood function yields a distribution of the same family, but with different parameters. Zellner shows that for normal multiple regression the conjugate distribution is

$$f(\underline{\beta},\sigma|\underline{\underline{X}},\underline{y}) \propto \frac{1}{\sigma^{n+1}} \exp\left[-\frac{1}{2\sigma^2}(\underline{y}-\underline{\underline{X}}\underline{\beta})^t(\underline{y}-\underline{\underline{X}}\underline{\beta})\right] , \qquad (C1)$$

or the same as the posterior distribution generated using the "uninformed" prior.

Assessment of subjective probabilities in terms of this distribution is clearly complicated, but as a first approximation, marginal distributions of $\underline{\beta}$ and σ might be assessed independently. The marginal distribution of $\underline{\beta}$ is multivariate normal, which for multivariate assessments is easier than most; and the marginal distribution of σ is inverted-gamma, which being univariate is at least straightforward. It is also conceivable that specialized methods of assessment, by sketching ranges and most-probable axes on a map, say, could be developed.

APPENDIX D

Symbol List

C	constant = $\underline{x}_o(\underline{\underline{X}}^t\underline{\underline{X}})^{-1}\ \underline{x}_o$
c	cost of drilling
e	error term
$f^o(\cdot)$	prior probability density function
$f'(\cdot\|\cdot)$	posterior probability density function
$g(d)$	relationship of production to distance
k	order of polynomial
$L(\cdot\|\cdot)$	likelihood function
M_i	model number i
$p^o(\cdot)$	prior probability
$p'(\cdot\|\cdot)$	posterior probability
pdf	"probability density function"
$Pr[x_o,y_o]$	probability body located at point (x_o,y_o)
s^2	sum of squared errors in regression
$(\underline{\underline{X}},\underline{y})$	data set: known body locations
y'	random location of body centerline given x
$\hat{y}$	expected location of centerline given x
$\underline{z}$	data set = $(\underline{\underline{X}},\underline{y})$
$\underline{\beta} = \{\beta_1,\ldots,\beta_k\}$	regression coefficients
$\hat{\underline{\beta}}$	most likely value of regression coefficients
$\Gamma[\cdot]$	gamma function
σ^2	variance of error about center, and parameter of width distribution

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EVALUATION OF GEOTHERMAL LOW ENTHALPY RESOURCES

Jean Patrice Herault

INTRODUCTION

The evaluation of geothermal low enthalpy energy resources in France comes within the scope of the Bureau de Recherches Géologiques et Minières (BRGM). This paper offers an outline of the method that is currently being developed for this evaluation.

Whether there is a limitation on the lifetime of some geothermal high enthalpy fields is still a question, but we must consider that, concerning geothermal low enthalpy fields mainly constituted by sedimentary formations in mean temperature gradient areas, the geothermal resource is a limited resource, unrenewable like most other natural resources. This results from the large difference between the heat quantity drawn out during exploitation and the heat supply corresponding to the natural heat flow, when reinjection of produced water is needed to maintain reservoir pressure or is obligatory to prevent superficial water pollution. The aquifer is gradually cooled around each injection well and will not return to its initial temperature for several thousand years. This is the situation with nearly the whole low enthalpy French geothermal resources.

In view of these considerations, the problem of evaluating geothermal low enthalpy resources could seem like the evaluation of any mineral resource; however, technical and economic motives require the development of specific methods. In the case of geothermal low enthalpy energy, the production costs, which have to be compared with the cost of substitutes to determine exploitable resources, depend not only on aquifer characteristics and production conditions and, more basically, on the potential demand characteristics: localization, level of heat needs, seasonal variation of needs, technologies employed. This is the reason the method that the BRGM is developing distinguishes two consecutive levels of analysis. The first consists in studying potential resources: this study is only done in physical terms and aims to gather basic data about hot aquifers for all the French territory. The second level of analysis consists in determining the extent of recoverable resources in given economic conditions and at a fixed date. This determination is made in each area having potential resources by comparing for every heat demand the cost of geothermal supplies and the cost of conventional substitutes.

If the assumption that geothermal energy is employed whenever it is competitive can be made, then it is possible to estimate the proportion of the energy market which can be supplied by geothermal low enthalpy energy. We will discuss this later.

DETERMINATION OF POTENTIAL RESOURCES IN PHYSICAL TERMS

This problem need not be expanded upon since it brings into play well-known classical methods. Besides, it is outside the author's specialization. It must just be said here that in France most of the formations that could constitute geothermal reservoirs luckily have already been studied in the course of oil prospecting works. Data collected during deep exploratory drilling, although not always convenient for prospecting geothermal resources (for instance short water flow tests, even if they exist, are often difficult to interpret) constitute a very good starting point. It will be noticed that currently no large investments are foreseen in France for geothermal low enthalpy prospecting, because on the one hand the areas whose characteristics are not well known cannot have great possibilities, and on the other hand the cost of exploratory drilling is much too high compared with the expected advantages. The French Ministry of Industry, however, has set up a financial system to cover the risk of failure in drilling, consisting of a government loan for the first well of geothermal heat sources, that is paid back only in case of success. This system permits exploration when the possibility of failure is not too high.

In a first stage, the current studies of the BRGM have been focused only on aquifers whose characteristics seem a priori favourable for geothermal exploitation: temperatures > 45°C to 50°C, good permeability, thickness > about 10 m. Three categories of potential resources can be distinguished as a function of kind and quality of available data (see Figure 1):

a) Proved Resources--These resources are constituted by aquifers for which all data necessary to run a mathematical model simulating the propagation of thermal fronts around injection wells, like those currently being developed by the BRGM, are available.

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[1] CADOUDAL: mathematical model for simulating the propagation of the thermal fronts generated by a recharging-discharging well pair into aquifers with uniform regional flow and with heat transfers in the cap and bed rocks.

METERNIQ: mathematical model for simulating the propagation of thermal fronts generated by several production and injection wells into aquifers with uniform regional flow and with heat transfers in the cap and bed rocks.

STENHDAL: mathematical model for simulating the propagation of thermal fronts generated by several production and injection wells into heterogeneous aquifers with heat transfers in the cap and bed rocks.

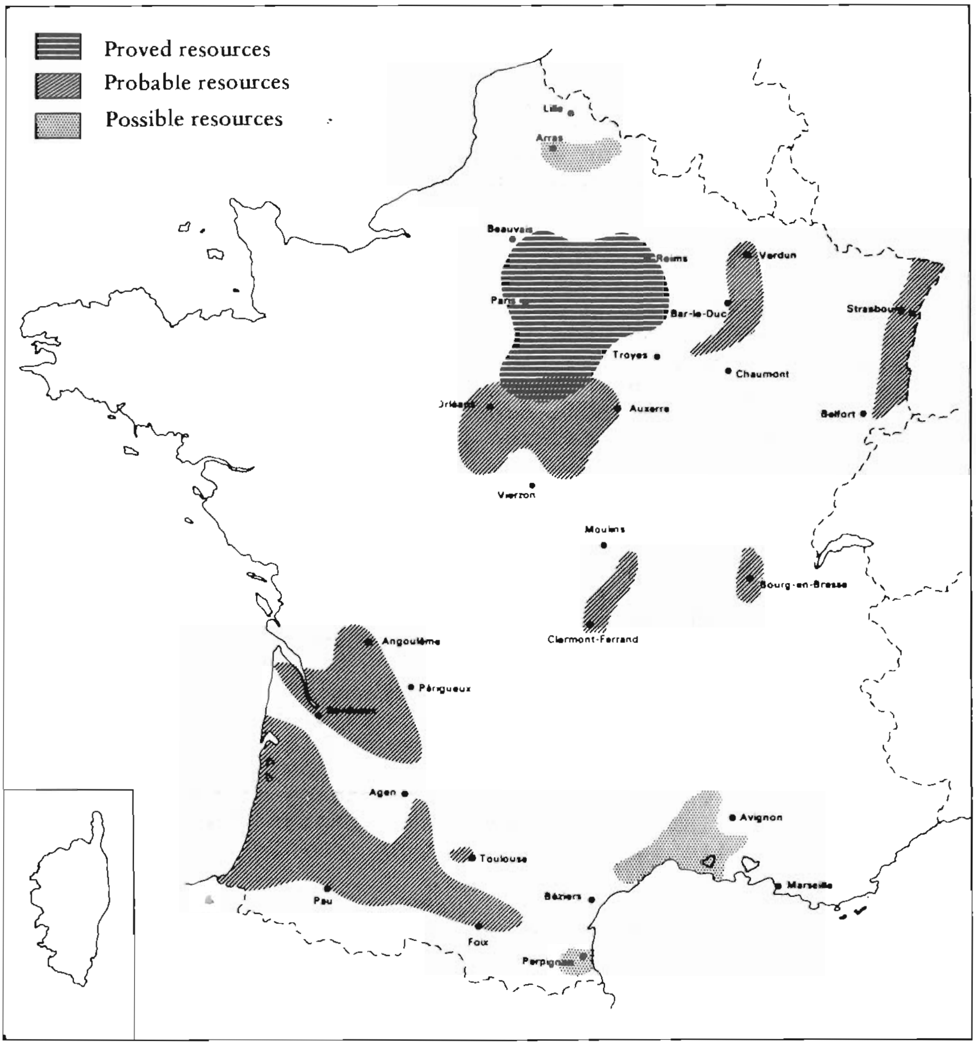

Figure 1. French geothermal low enthalpy resources. (Temperatures > 45° - 50°C).

Particularly, the following data must be available:

- characteristics of the reservoir (lithology, porosity, permeability, thickness, depth);
- characteristics of the fluid (viscosity, pressure, chemical composition).

Iso-value curves or at least probable mean value zones then can be drawn for each parameter. Two formations in the Parisian Basin belong to this category: Albien and Dogger.

b) Probable Resources--This concept is used for resources for which available data are not sufficient to allow a reliable simulation of thermal front propagation. Assumptions can be made in most cases, but they are always hazardous. The risk of failure in drilling is worth taking when the expected costs of heat are quite competitive, more especially since drilling can provide most of the lacking data.

c) Possible Resources--This category comprises contingent resources situated in some complex tectonic areas. In these areas, formations could be good reservoirs but their localization is difficult and their characteristics are generally not well known. For these resources, only very interesting operations can justify exploration survey expenditures.

This determination of potential resources allows computing, for all the proved resources and a large part of the probable resources of the upper limit of yearly producible energy when assuming a homogeneous distribution of production and injection wells according to a regular pattern; the spacing of wells is determined as a function of the possible discharge and the chosen life of exploitation with a constant temperature of produced water.

It stands to reason that such an evaluation is far higher than any realistic estimate. A second level of analysis is hence necessary to heed the potential demand.

DETERMINATION OF RECOVERABLE RESOURCES IN ECONOMIC TERMS

Contrary to the first level of analysis, whose method is currently being applied to the Parisian Basin (and for which a publication is forecast in late 1975 or the beginning of 1976), this second level exists only at the project stage. Therefore the method outlined below cannot be held to be operational; but its application to the Parisian Basin is planned for the beginning of 1976 and will be extended to other areas as the determination of potential resources proceeds.

Though the economics of geothermal heating need not be elaborated here, it seems necessary to give some information about this problem which explains the choices we have made:

- The basic investment, formed by a production and injection well pair, is indivisible. If a drainage pump is used the output can be set within a large range with but little effect on investment costs though a somewhat larger effect on production costs. The cost of water at the bore is a discontinuous function of the output.
- Investments for the transmission of hot water are rather expensive so that in most cases lengths of pipes more than a few kilometres are not economic.
- The power of the installation is highly dependent on the nature of heat needs and the employed technology of utilization: this problem is easy when heating a fluid between two constant temperatures (for instance, the heating of hot tap water), but it is more complex in the case of building heating, which needs to heat a fluid between a variable temperature and a constant temperature (for instance, the preheating of fresh air) or between two variable temperatures (for instance, in hot water heating systems). In the latter case, the investment cost of the geothermal heat source is a non-linear function of its maximal power, and its available power depends on the outside temperature.
- The total cost of geothermal heat produced is formed for the largest part by capital costs and fixed costs; proportional costs are rather low. Consequently, the unit cost of geothermal heat is a rapidly decreasing function of the load factor of the geothermal heat source, that depends on the ratio between the power of the geothermal source and the total power of the heating installation in a given climate.

In brief, the characteristic parameters of heat installations using a geothermal source (and especially in the case of building heating) are not independent, so that it is difficult to estimate their value for a competitive installation design except for a few simple cases where competitiveness or non-competitiveness is obvious. We think, in the general case, that the computation of these values is necessary to compare for one heat demand the cost of geothermal energy with the cost of classical energies. Thus the method evaluation chosen is based on a micro-economic approach, global projections seeming inadequate to us.

For this purpose, we intend to develop a simplified mathematical model to optimize the main characteristics of heat installations using a geothermal source so that it will be possible to determine whether each heat demand can be a geothermal energy demand when the total cost of produced heat of the geothermal solution is lower than that of classical solutions.

It may seem very ambitious to do such a job that gives the impression of being gigantic, at least in collecting indispensable data, but it is actually possible to define the part of the heat market that is likely to need study. Considering that the temperature of hot aquifers does not exceed 100°C except in Alsace and in the Limagne of Allier, all of the market needing higher temperatures must be excluded; possibilities for electric power production using two fluid cycles, which are the only ones fitting geothermal low enthalpy energy, need not be examined because the forecast costs are quite non-competitive.

Only very few industrial processes are of interest for the geothermal low enthalpy market; the main channels for this energy are constituted by building heat (including greenhouse heating) and hot tap water heating. For this kind of demand, considering the indivisibility of the basic investments, we can reduce the part of the heat market to be studied to the potential district heating market.

A distinction must then be introduced between new buildings and existing buildings. For the new building market, the only problem--though it is a very difficult one--lies in the spatial localization of the projections and in the assumptions that have to be made about densities, both for new areas and for urban areas being redeveloped. For the existing buildings, two cases arise:

- In the case of low temperature installations such as floor and ceiling radiant heating systems or warm air heating systems, the possibility of using a geothermal source is quite easy to study.

- In the case of classical central heating systems with radiators, the substitution of geothermal energy could perhaps be economic if the heat requirements were reduced by the use of outside insulation systems; the problem cannot at present be settled.

In consideration of all these elements, it seems that the number of demands that would have to be studied for a 10-year projection in the Parisian Basin would not exceed about 1,000: this number is high but not excessive.

The last problem raised by the method is the discussion of the following assessment: when a heating system using a geothermal source is competitive, it will be realized. This assessment assumes rational economic behaviour by decision makers and a marginal effect of all the decisions on the different markets (investment goods and financial markets).

Actually, financial problems (interest rate and borrowing possibilities) owing to the existence of specialized markets, administrative standards such as price ceilings for certain buildings, or a tendency towards the reduction of the size of building programs are not favourable to technical solutions that involve high investments, even if these solutions are the best when reasoning with pure economic arguments.

On the other hand the most suitable technological systems for geothermal heating are either old systems such as radiant floor heating systems or warm air heating systems, which are little appreciated by common opinion, or new systems. These are often combinations of classical systems, but they also need architectural changes to improve comfort, and are not always appreciated by the building societies which prefer the well-known classical solutions. A fuller study is necessary to evaluate the present and the expected weight of these different factors and their effect on decisions to realize geothermal heating systems.

Lastly, ecological problems must be mentioned though they currently seem negligible.

HUBBERT ESTIMATES FROM 1956 TO 1974 OF US OIL AND GAS

M. King Hubbert

The study of US petroleum resources, whose totals have been reported by Rose, represents perhaps the most important development in the US Geological Survey (USGS) during the last 15 years. As Rose has pointed out, official estimates by the USGS made during the period 1961-1974 have been about 650 billion barrels of crude oil for the entire USA and adjacent continental shelves, or about 600 billion barrels for the conterminous States, whereas my studies from 1956 to 1974 have given consistent estimates of about 170 to 175 billion barrels for the lower 48 States and adjacent continental shelves.

The results of the recent intensive study made by Rose and his staff in the Oil and Gas Branch of the USGS have given estimates of the ultimate amount of crude oil to be produced in the entire USA and adjacent continental shelves in the range of 224 to 301 billion barrels (the published report, Miller et al., 1975, Table 1, gives 218 to 295 billion barrels), the lower figure having a 95% probability and the higher one only 5%. This lower figure is in substantial agreement with my estimate of 1974 (Hubbert, 1974, Table 7, p. 155) of 213 billion barrels.

Since my methods are totally different, I am giving the following summary of my methods of analysis and of the results obtained.

Figure 1 (Hubbert, 1962, Figure 21; 1974, Figure 23) is reproduced from a paper given before an audience of petroleum engineers in 1956 (Hubbert, 1956). At that time, in the 97 years since the initial discovery of oil, the USA had produced 52.4 billion barrels of crude oil. Contemporary estimates by leaders of the petroleum industry of the ultimate amount of oil to be produced in the lower 48 States and adjacent continental shelves ranged from about 150 to 200 billion barrels.

In my analysis, I showed that the area beneath the curve of annual production versus time is a graphical measure of cumulative production. One grid square in the figure corresponds to 25 billion barrels. Hence, for 150 billion barrels, the complete-cycle curve would encompass six grid squares; for 200 billion barrels the area would be eight grid squares. The two curves in Figure 1 are drawn accordingly. For 150 billion barrels the peak in the production rate would have to occur about 10 years after 1956; for 200 billion barrels about 15 years. Therefore, the peak in production should probably occur within the interval 1966-1971.

This prediction proved to be somewhat startling to the petroleum industry and a source of some dismay. It also inspired a succession of much higher estimates, but based upon negligible new information. These are shown in Figure 2 (Hubbert, 1962, Figure 21; 1974, Figure 24). These escalated to about 400 billion barrels, and finally after five years, the USGS trumped them with 590 billion barrels for the conterminous States.

A comparison between the Hubbert 1956 estimate and that of the USGS of 1961 is shown in Figure 3 (correction of Hubbert, 1974, Figure 25). The USGS estimate is equivalent to a prediction that the peak of crude oil production in the USA would not occur until about the year 2000.

Because the foregoing estimates were all in some measure subjective, development of a method of analysis based solely upon the publicly available data of the US petroleum industry was sought. Available data included cumulative production, Q_p, from 1860 to date,

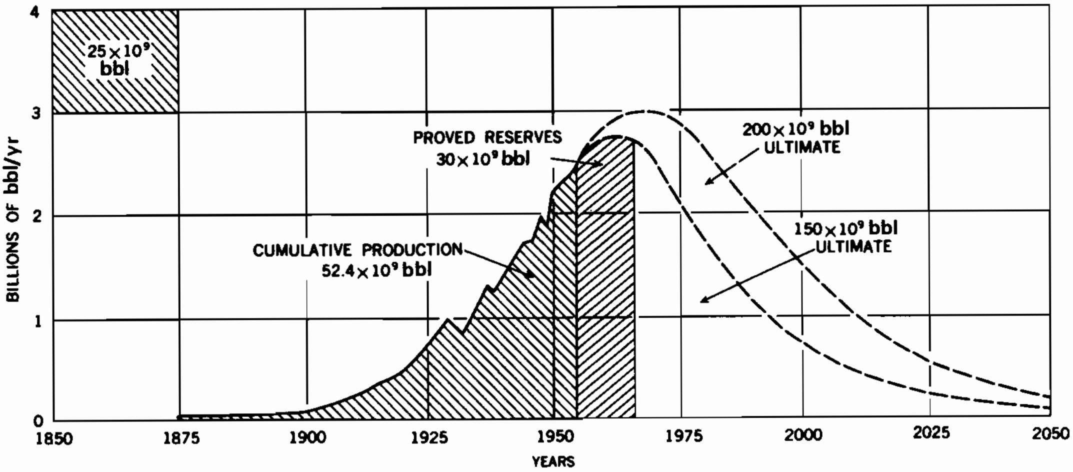

Figure 1. Hubbert prediction of 1956 of future production of crude oil in the conterminous United States and adjacent continental shelves (Hubbert, 1956, Figure 21; 1974, Figure 23).

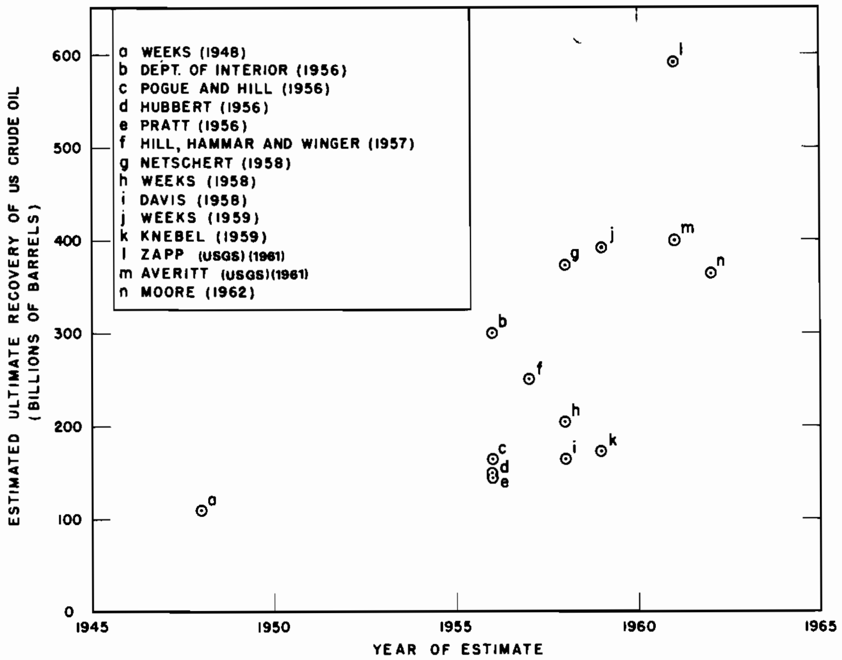

Figure 2. Estimates of ultimate crude oil production in conterminous United States published between 1948 and 1962 (Hubbert, 1962, Figure 21; 1974, Figure 24).

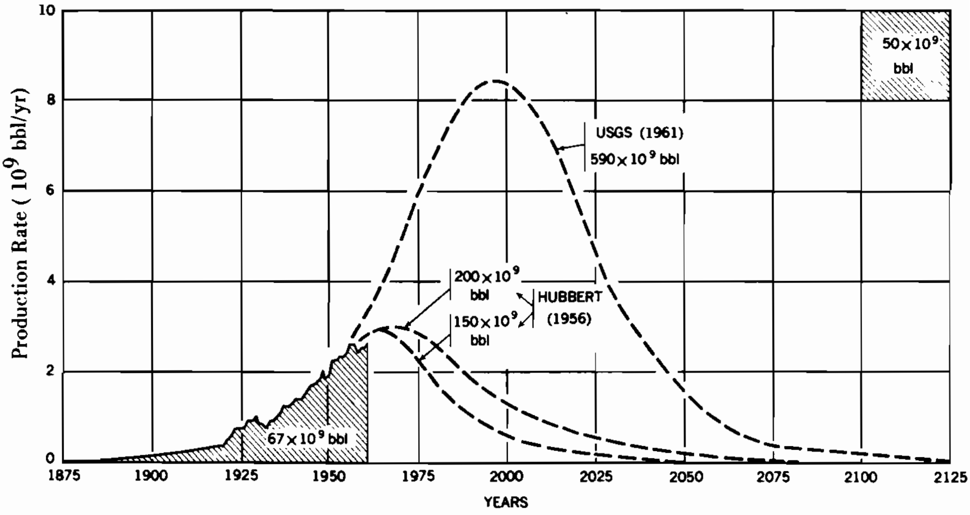

Figure 3. Comparison of complete cycles of US crude oil production based upon estimates of 150-200 and 590 billion barrels for Q_∞ (correction of Figure 25, Hubbert, 1974).

proved reserves, Q_r, since 1937, and approximate data annually since 1900. Finally, cumulative proved discoveries, Q_d, are defined by

$$Q_d = Q_p + Q_r \quad . \tag{1}$$

The approximate behavior of these three quantities during the complete production cycle is shown in Figure 4 (Hubbert, 1962, Figure 22; 1974, Figure 26). The actual data as of 1972 are shown in Figure 5 (Hubbert, 1974, Figure 36). Here it is seen that by 1972 proved reserves were 10 years past their peak, and cumulative discoveries had passed their inflection point at about 1957. The best mathematical fit for these curves gave 170 billion barrels for Q_∞, the ultimate cumulative production--the same figure obtained by a similar analysis in 1962.

The time derivative of equation (1) is

$$dQ_d/dt = dQ_p/dt + dQ_r/dt \quad . \tag{2}$$

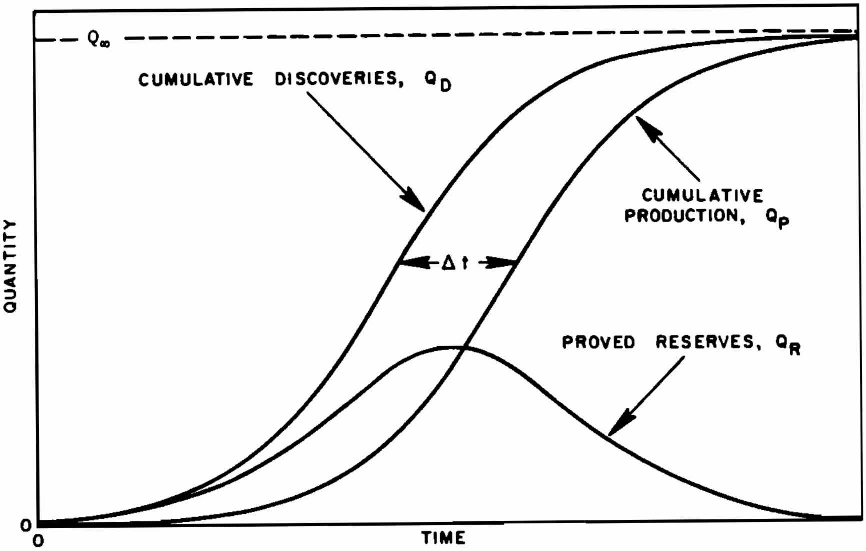

Figure 4. Variation with time of proved reserves, Q_r, cumulative production, Q_p, and cumulative proved discoveries, Q_d, during a complete cycle of petroleum production (Hubbert, 1962, Figure 22; 1974, Figure 26).

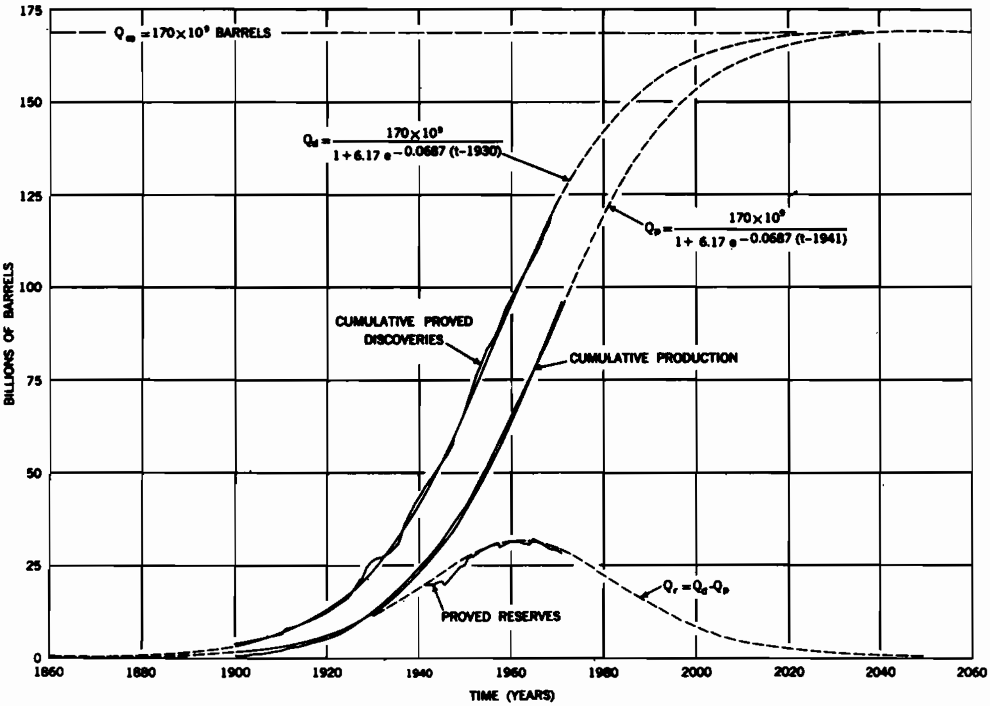

Figure 5. Logistic equations and curves of cumulative production, cumulative proved discoveries, and proved reserves for crude oil from the conterminous United States 1900-1971 (Hubbert, 1974, Figure 36).

The derivative curves are shown graphically in Figure 6 (Hubbert, 1962, Figure 24; 1974, Figure 27). It will be noted that when proved reserves reach their peak

$$dQ_r/dt = 0 \tag{3}$$

and

$$dQ_d/dt = dQ_p/dt \quad . \tag{4}$$

Hence, when the dQ_r/dt curve crosses the zero line, the curves dQ_d/dt and dQ_p/dt cross one another.

The curve of the computed mathematical derivative, dQ_d/dt of the discovery curve with actual data superposed, is shown in Figure 7 (Hubbert, 1974, Figure 38). It is seen that the

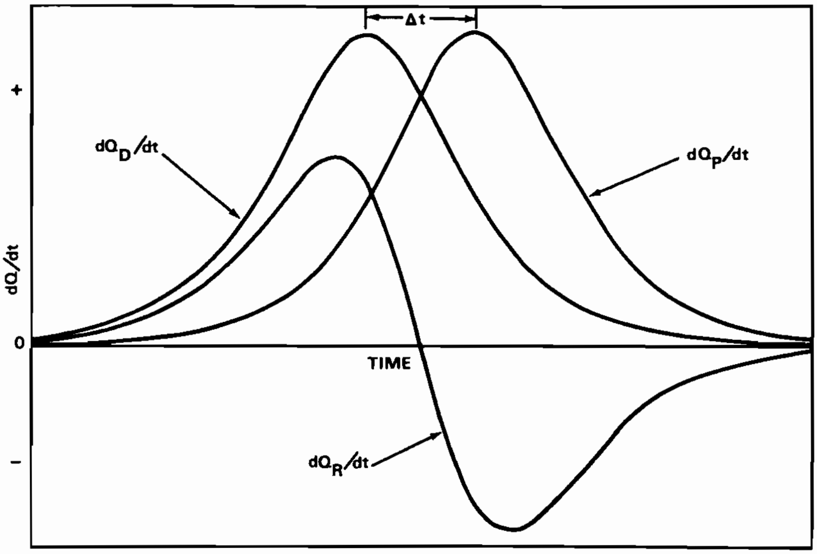

Figure 6. Variation of rates of production, of proved discovery, and of rate of increase of proved reserves of crude oil or natural gas during a complete production cycle (Hubbert, 1962, Figure 24; 1974, Figure 27).

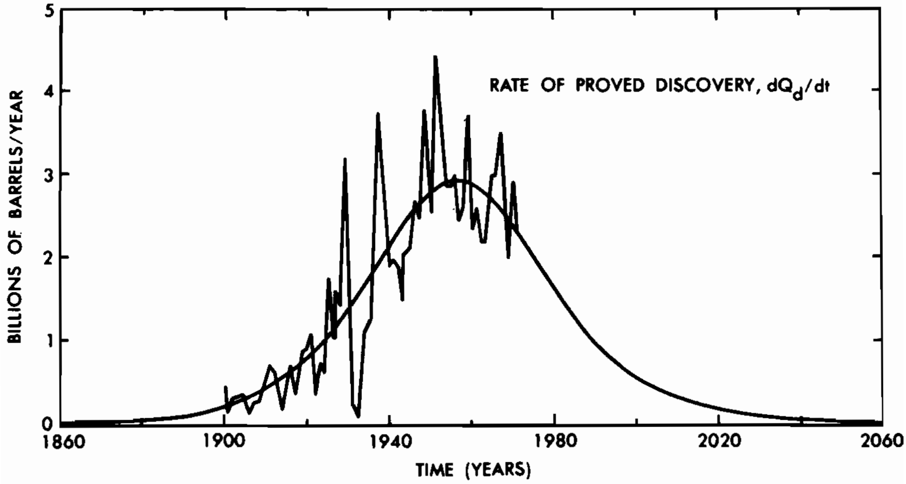

Figure 7. Comparison of annual proved discoveries of crude oil in the conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974, Figure 38).

rate-of-discovery curve passed its peak in the second half of the 1950 decade, and has been declining ever since.

The curve of the rate of increase of proved reserves is shown in Figure 8 (Hubbert, 1974, Figure 40). This curve crossed the zero line in 1962 and is now near the bottom of its negative loop.

Finally, the curve of the rate of production, dQ_p/dt, is shown in Figure 9 (Hubbert, 1974, Figure 39). This has an aberration owing to successive Middle East disturbances since 1956. The peak production rate, slightly eccentric with respect to the mathematical curve, occurred in 1970. The mathematical curve reached its maximum about 1968.

Based upon the foregoing analysis, the curve of the complete cycle of crude oil production in the conterminous states is shown in Figure 10 (Hubbert, 1974, Figure 51). Here, the 67-year period from 1932 to 1999, is the time during which the middle 80% of Q_∞ will be consumed. A child born about 1930 will see the US consume most of its oil during his lifetime.

A different method of analysis is shown in Figure 11 (Hubbert, 1974, Figure 50). This consists in plotting the discoveries per foot of exploratory drilling, dQ/dh, versus cumulative feet of drilling, h. In the figure, the separate columns are averages for each 10^8 ft of drilling. Cumulative discoveries to about 1972 by $17 \cdot 10^8$ ft of drilling amounted to 143 billion barrels. Extrapolation of the negative-exponential decline curve approximating the actual data gives an additional 29 billion barrels of crude oil, or a total of 172 billion barrels for Q_∞--a result in close agreement with that obtained earlier by other methods.

ESTIMATES FOR THE WORLD

I have not personally made world estimates for petroleum, but those shown in Figure 12 (Hubbert, 1974, Figure 67) made by Richard Jodry of Sun Oil Company are in substantial agreement with other recent estimates. The Jodry estimates total 1952 billion barrels. Rounding this off to 2000 billion barrels, and computing the complete cycle of world production gives the results shown in Figure 13 (Hubbert, 1974, Figure 68). This is based upon the assumption of an orderly evolution of petroleum production. Should production be constrained at near present levels, the area under the top part of the curve would be displaced to the declining phase.

According to this curve, the peak of world production rate will probably occur about 1995, and the period for the middle 80% will be the 56-year interval from about 1965 to 2021. A child born now will see the world consume most of its oil during his lifetime.

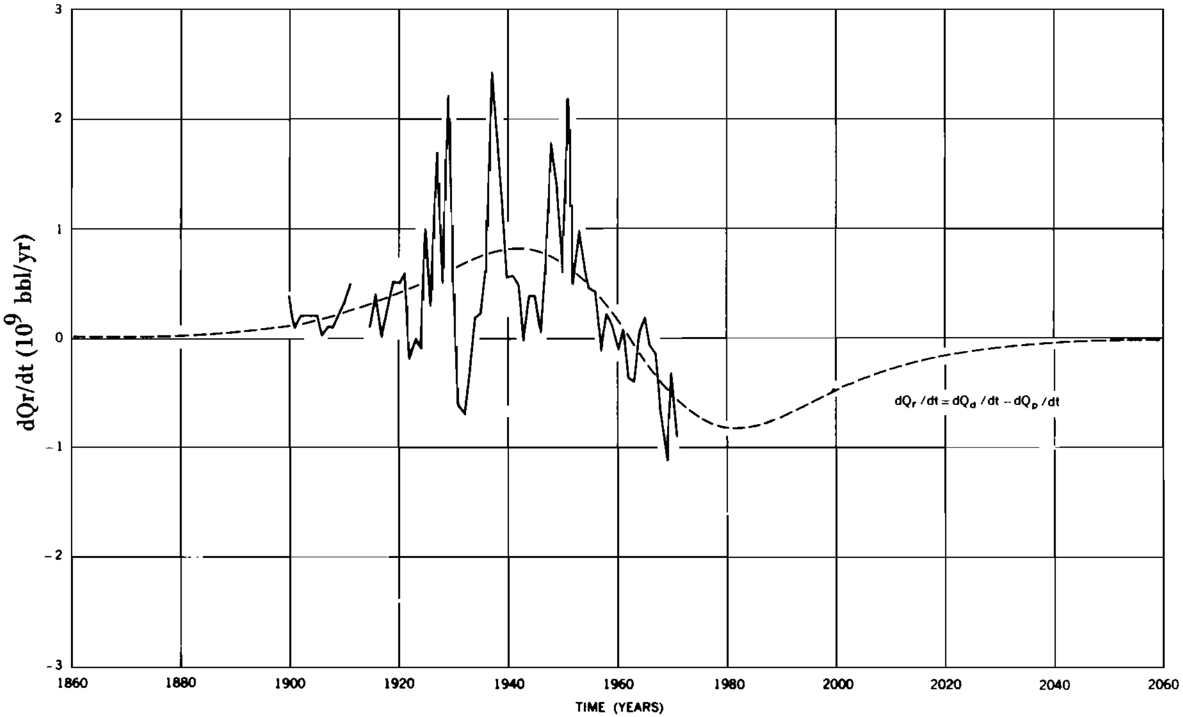

Figure 8. Comparison of annual increases of proved reserves of conterminous United States, 1900-1971, with theoretical curve derived from logistic equations (Hubbert, 1974, Figure 40).

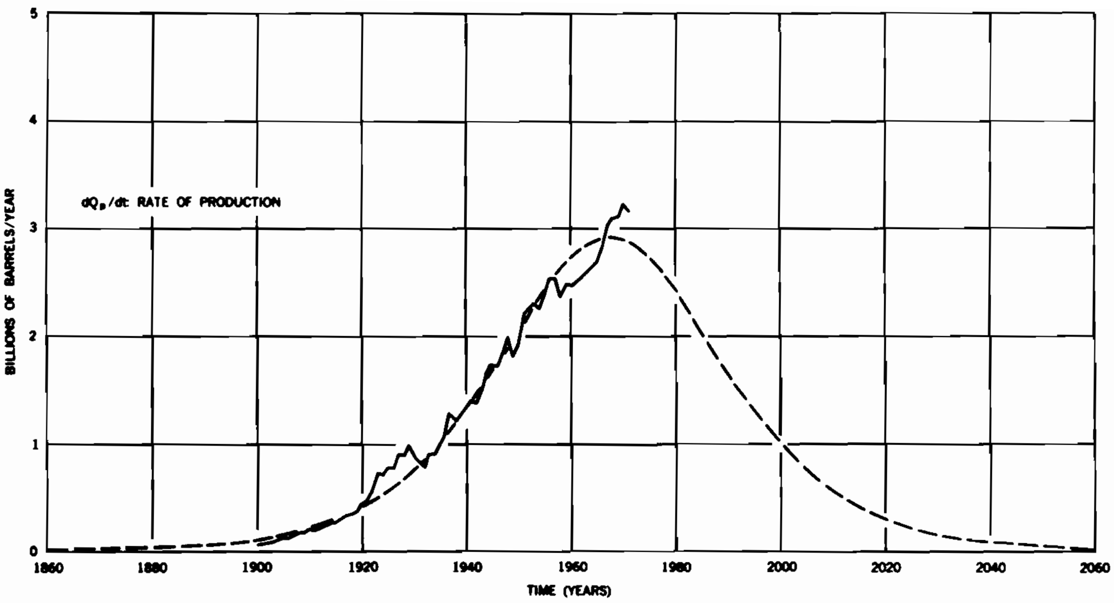

Figure 9. Comparison of annual crude oil production in conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974, Figure 39).

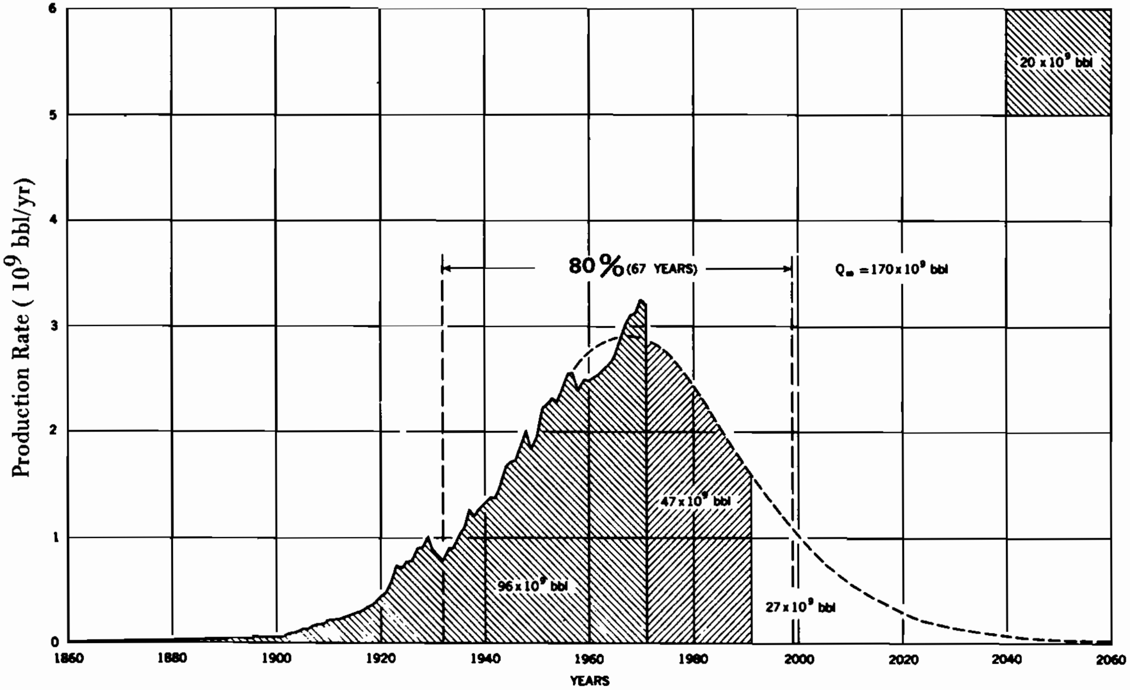

Figure 10. **Complete cycle of crude oil production in conterminous United States as of 1971 (Hubbert, 1974, Figure 51).**

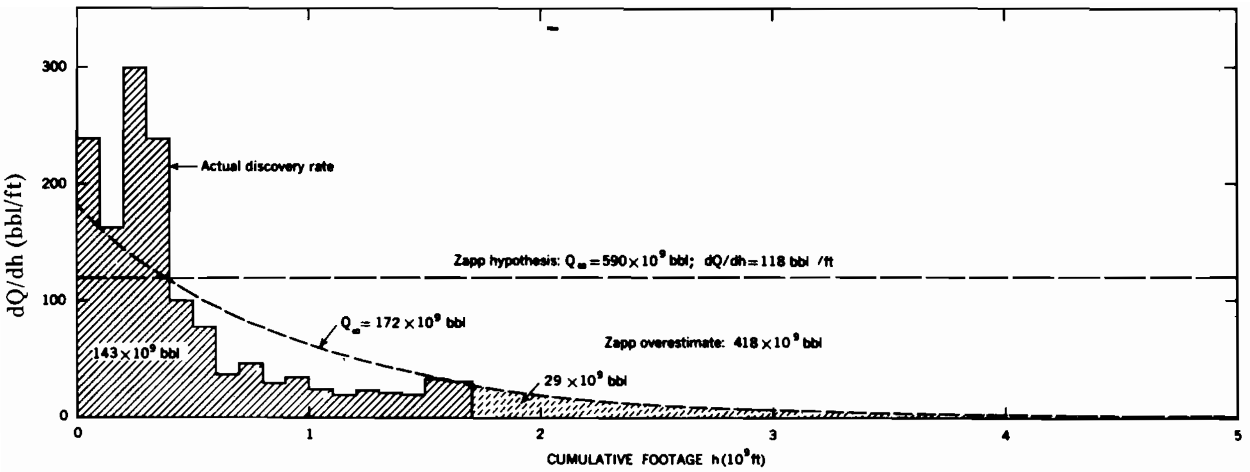

Figure 11. **Estimate of ultimate crude oil production of conterminous United States by means of curve of discoveries per foot versus cumulative footage of exploratory drilling, and comparison with Zapp hypothesis (Hubbert, 1974, Figure 50).**

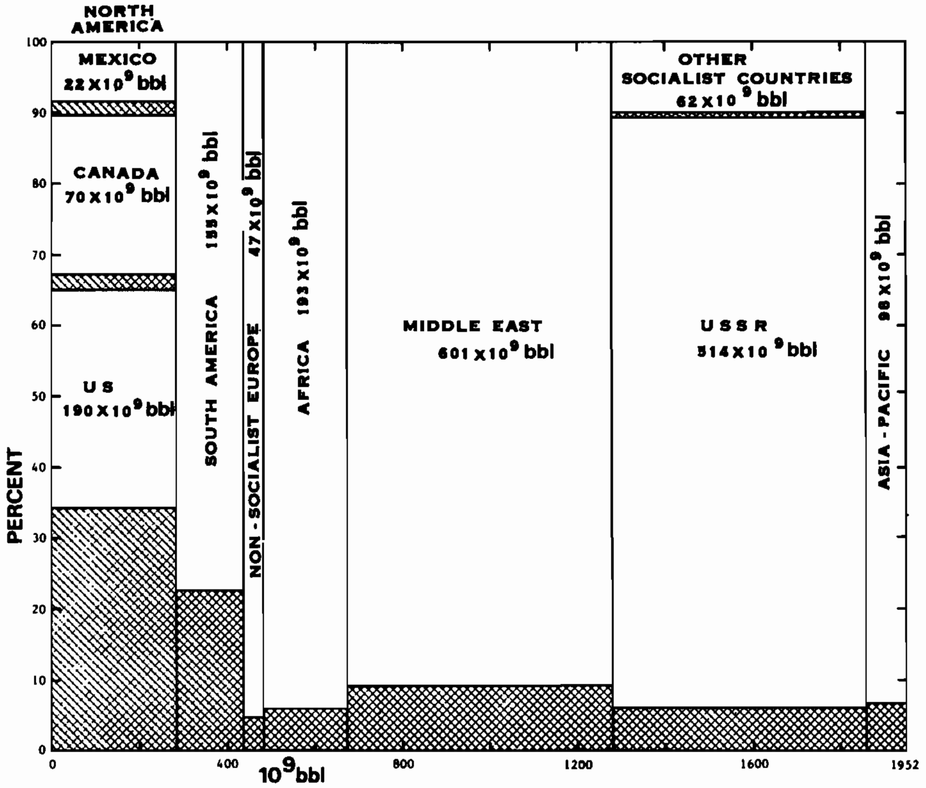

Figure 12. **Graphical representation of Jodry estimate of world ultimately recoverable crude oil. The shaded areas at the foot of each column or sector** represent quantities **consumed already (Hubbert, 1974, Figure 67).**

Finally, to appreciate the brevity of the epoch of the totality of fossil fuels in human history, consider Figure 14 (Hubbert, 1972, Figure 20; 1974, Figure 69). Here, on a background of human history from 5000 years ago to 5000 years in the future, the epoch of the fossil fuels comprises principally the brief interval of only about three centuries, and is hence but an ephemeral event in the totality of human history, an event nonetheless that has exercised the most disturbing influence experienced by the human species during its entire biological existence.

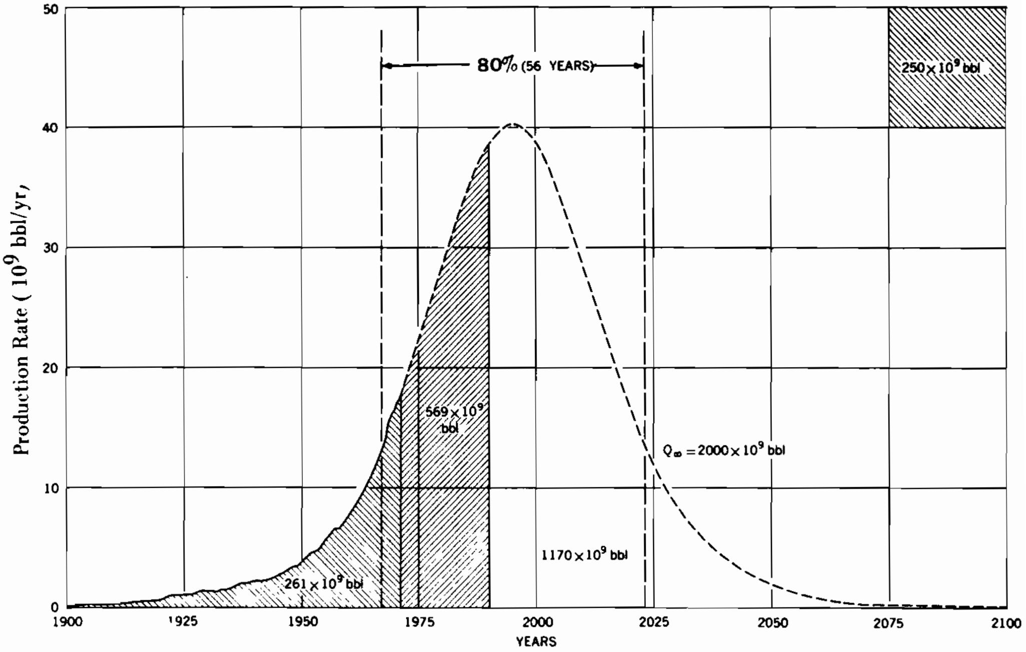

Figure 13. Estimate as of 1972 of complete cycle of world crude oil production (Hubbert, 1974, Figure 68).

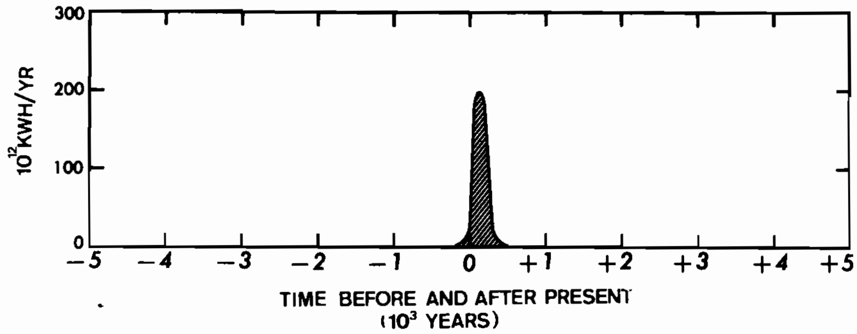

Figure 14. The epoch of fossil fuel exploitation as seen on a time scale of human history from 5,000 years ago to 5,000 in the future (Hubbert, 1972, Figure 20; 1974, Figure 69).

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DISCUSSION

Bauerschmidt: I think these statistical methods are fine, but they cannot give us proof that we will have such development in the future. If you look at the curves from the beginning, then we will have growths and declines as before, and then big jumps come again. I am not sure, therefore, whether this decline will hold in the future and that we have had the peak already. Another question concerns the recovery factor. I did not hear much about it. The recovery factor must go up, and will go up. I have talked with several people from the oil industry who told me that we can have a recovery factor of much more than 30%, that it might go to 40%, 50%, or 60%. This is important.

Masseron: I think that the recovery factor can be increased, as you say, in the future--by the end of the century--so that we can reach perhaps a better figure than Sickler's, something, one day, between 50% and 55%, or even 50% and 60%.

Khazzoom: Mr. Kaufman, how many Monte Carlo trials were performed?

Kaufman: The graphs displayed were each computed from 1000 Monte Carlo trials. One trial consists of one complete replication of the discovery process.

Khazzoom: And what you plotted was expected?

Kaufman: The expected size of the first discovery, the second discovery, third discovery, and so on. In the Resource Analysis Group simulation, designed for probabilistically aggregating subjective probability distributions for some 80 US petroleum provinces, we performed 10,000 Monte Carlo trials for each province. Consequently, the Monte Carlo sampling variability is virtually negligible.

Roadifer: How did you arrive at the number of fields (in the North Sea), that is, at the number of accumulations being 303?

Kaufman: By examining the behavior of the likelihood function. Crudely speaking, this is the probability of observing what one did observe regarded as a function of the parameters to be estimated. A maximum likelihood estimate of a parameter is a value that maximizes the likelihood function, i.e. that maximizes the probability of observing what one did observe.

For a fixed value of N, we computed the value of the likelihood function for a large set of values of μ and σ^2 and plotted these values on the μ - σ^2 plane. Graphs of points having equal values of the likelihood function are plotted as shown in our paper. They are called isocontours and are roughly elliptical in shape. We found for each value of N, that within the range of validity of our approximation to the density of observations, a single value of μ and σ^2 maximized the likelihood function. We repeated this computation for many values of N, shown in the table displaying maximum likelihood estimates of μ and σ^2 for fixed N and the corresponding values of the likelihood function.

For N between 200 and ∞ there are two local maxima of the likelihood values regarded as a function of N. One is at N = 303, the other at N = ∞. The first is a plausible number for N in the absence of additional information, the second is not. Furthermore, there is no guarantee that we have found a joint maximum likelihood estimate for μ, σ^2, and N. One could in principle search over the three-dimensional parameter space to find a joint maximizer of the likelihood function. We plan to do a nonlinear least squares analysis to pin down more satisfactory estimates of μ, σ^2, and N jointly. I recommend doing estimates several ways, cross-checking one method against another. One could go one step further and bring expert opinion to bear so as to get a priori probability judgments on N. This is a third way of estimating. The North Sea data were used to illustrate one method of estimating we are employing. I am hoping to collaborate with the Geological Survey of Canada in a restudy of the Western Sedimentary Basin. We will then be able to see how these methods work in the context of a very systematic geological and statistical study of this region.

Roadifer: You had a population of 24 discoveries?

Kaufman: That is all we had to work with.

Roadifer: Did you assume that these were in any particular place in the log normal distribution? Did they perhaps occupy the upper end?

Kaufman: I would expect a priori that the sizes of the first fields would be larger than the mean size of the last 24 fields. If the probability of discovery of a field is proportional to its size and discovery is like sampling without replacement, then the larger fields composing the right tail of the empirical frequency distribution of all fields in the North Sea have high probability of being discovered early in the game.

Roadifer: Your model would strongly favor a few large fields at the upper end of the distribution.

Kaufman: That is exactly what happens for a single play. However, the North Sea is in fact composed of several plays and is only used here as an illustrative example. We are planning, as I said earlier, to do a study of individual plays in western Canada. We also have detailed well and pool information for the Williston Basin in Montana, North Dakota, and South Dakota and we will use individual plays in this basin to test further our modeling assumptions.

Brinck: Do you believe your basic assumptions one and two to fairly represent or simulate the actual conditions from which the observed discovery sequence (large deposits generally first) has to be explained?

Kaufman: If by "simulate actual conditions" Brinck means do these assumptions accurately describe the detailed physical activities carried out in reconnaissance surveys, detailed local surveys, geological and geophysical interpretation of data, and drilling, the answer is of course not. A useful model is a compromise between the extremes of overwhelming descriptive accuracy--which renders it useless as a predictive tool--and simple assumptions adopted mainly for analytical tractability. In our case, these assumptions do reflect essential features of observed discovery size data and so are "actual conditions", that is, there are statistical regularities that characterize the discovery process and the assumptions state what they are.

Brinck: Are repeated runs (Monte Carlo simulation) really essential to bring out this particular feature of your model?

Kaufman: Monte Carlo simulation is not necessary at all if one can do a thorough mathematical analysis of the model. By this I mean a calculation of the probability density of observed sizes, of the marginal moments, and of the conditional moments. This we can now do. Simulating values of these quantities is useful as a check when one can do these calculations and indispensible when one cannot.

Brinck: How often then would it be reasonable to expect confirmation for this theory from the historical development of particular oil producing areas, representing only one run each?

Kaufman: Empirical validation of assumptions one and two cannot be done with data from a single play. If, however, many plays are available it is possible to do meaningful statistical testing of the assumptions. The Western Sedimentary Basin of Canada alone has about 37 plays in it, and we have studied them to this end. Onshore and offshore USA has on the order of 600 plays, a portion of which can be studied in a similar way.

If Brinck has a telephone line to the Lord and can call him up any time to resolve future uncertainties in this uncertain world, I will agree that he can predict perfectly and has no need for probabilistic sampling methods. Petroleum exploration in particular appears to many of us to be "random" in many of its aspects, since we do not have perfect knowledge a priori as to how it will evolve in any given basin. Hence, those of us without such a telephone line are led to making assumptions about "distribution patterns and sampling methods" based on what data we have seen.

Ross: I wonder how sensitive your estimates are to the input assumptions. The point is not whether your estimates depend on the input assumptions--they obviously do--but how sensitive they would be to something like the log normal distribution.

Kaufman: The results do depend on the form of the probability distribution characterizing the deposition pools. A distribution that is highly skewed with a fat right tail--the log normal distribution or a stable distribution, for example--gives qualitatively different results from, say, the exponential distribution. Fat tailed distributions result in the mean size of discovery as a function of the discovery number behaving as shown in our paper: as the discovery number increases, there is a rapid decline in expected size at first, then a slow decline. If the exponential distribution is assumed to characterize the size distribution of pools as deposited by nature, the mean size of discovery declines linearly with successive discoveries.

Nordhaus: Is it possible to link what is essentially the micro-geological work with the global problems being investigated here by modeling the distribution of field size in much the same way as the distribution within fields? Is there any work going on?

Kaufman: You mean within plays?

Nordhaus: What is the possible technique essentially to resolve some of the debates that have been going on here about the distribution of future field sizes? They are also more important than the variants of that since it is uncertain.

Kaufman: The more I listen to geologists the more I conclude that the best way to proceed is to take them seriously when they say that geology in different plays is really different, and proceed by directly aggregating micro-units rather than building a synthetic global description of how discoveries worldwide behave. I think this approach is now feasible because of the rate of increase in the richness of statistical information of precisely the kind that we need to carry it out. It certainly is possible to implement this approach within the USA. Every US Major and many large Independents have sufficient information to make this approach feasible--but none of their information has been made publicly available.

Gros: Mr. Roadifer, how good are your probability assessors? For instance, after obtaining the five fractiles, what percentage of the time does the actual value exceed the subjective value that has 0.01 probability of being exceeded. A paper by Alpert and Raiffa suggests that people think they know twice as much as they actually do know when doing such an assessment. They suggest either a learning period is required, or that special procedures should be followed when fitting probability densities to the five points to compensate for the bias of the assessment process. Which technique, if either, is followed by your organization?

Roadifer: The way we collected the data was to organize a very small group of people, three people, who visited every operating office in our company, which in that particular case covered North America, and we could do the same thing for the world. The three people talked to specialists or experts (explorationists) in every area in every play. Then we took the data and checked them against national and continental averages. When they did not make sense on first inspection, they were discussed on the spot. Then we ran it all through the computer and got the results, and went back and talked to all these people again to see whether we had any differences (between the monitor group and estimates) that were not resolvable. And finally, we made about three passes for review and computer runs for every one of the plays, and we compared the computer runs across boundaries, etc. In fact, what we did was to follow a modified Delphi technique, where we questioned a very large number of experts and used their expert opinions based on real data and incorporated them in the probabilistic model.

Gros: So, you were pretty satisfied with the state of your distribution?

Roadifer: Yes, compared with other assessments. Now we have not gone through the exercise some people suggest of rolling back time by taking a basin and stripping out all of the wells, stripping off the knowledge, and trying to start from scratch. We wanted the very best data that we could get, and then we modified the data only if we had to.

Clegg: We have an exercise going on in my company at the moment looking at people's ability to provide subjective probabilities in a number of areas. But our experience, on some very limited information, is that in fact people who think they are experts turn out to be wrong, and the actual outcome of the particular event is outside the 5% and 95% range they give. And the more expert they think they are, the worse they can be. This leads me to a couple of points in Roadifer's paper where he was talking about the uncertainty ratio. Presumably, if the people who think they are experts--the geologist who has made a special study of the area, for example--come up with a relatively small uncertainty, they are quite likely to be wrong; and the man who is not an expert may come up with a very much broader range that will probably encompass what actually comes about. So I have a question really to put to both you and Roy: Have you in fact looked back at the subjective probability estimates that you obtained from people to see whether in fact they are meaningful and what sort of performance they have given? Because, it seems to me, if you cannot do that to support it, there is little point in going through the very extensive analysis.

Roadifer: We did not judge individuals so harshly as to give them an uncertainty ratio; we gave that to the output estimates only. In fact, we did make a very detailed study of the individuals and they can be identified by their input curves. They have been segregated into optimists and pessimists and so forth by looking at what they have done so that, finally, you can judge the estimator, especially if you meet him personally, you can get a very definite feel for what kind of person he is and what kind of estimates he gives you. Now leading on to actually examining the results, I may cite an example of one case on the Gulf coast of the USA where we looked at the uncertainty ratios of our output estimates and found that the uncertainty of our estimates comes out higher onshore than offshore. We said obviously there must be something wrong because we know a great deal more about the onshore than about the offshore. In going over the example in a very detailed review we established that the future potential of the onshore really was in very poorly known trap styles that were very deep and that in fact we knew less about the future potential onshore than about the offshore. So yes, we have checked that in very strenuous detail.

Roy: One of the things that is critical to this and somewhat gets around the problem you bring up is the attempt to break the assessment down into this fairly large number of component parts, so that an individual assessor cannot very easily tell what the answer is going to be. This then gets away a little bit from that expert problem where a person is sure that there are x billion barrels or whatever in this area, and brings it back down to more components, where they still have expert judgment. I think that they may be more rational than some of the others.

Kaufman: The situation is not so critical as Clegg reports because people can be trained to validate subjective probability empirically. There is a considerable work going on in this area. I have a question about the presentations of both Roadifer and Roy simultaneously, relating to possible probability dependences between the quantities assessed. It is certainly plausible and possible that certain of the engineering and geological components analyzed individually are highly correlated. My question is, does the Monte Carlo procedure that you used take into account the possible correlation between the individual components that went into that simulation? For example, average net feet of pay may, in certain kinds of trapping mechanisms, be highly correlated with areal extent.

Roadifer: I cannot say exactly that in our own case there were no correlations, but these are essentially independent parameters or factors. There is a dependence, as you say, between area and trap configuration, and if you do not believe it, look at a family of reefs. The extent of fill in a reef, for example, because of its configuration, is a very steep-sided trap, and we dealt with areal fill up. I think that the Canadian Survey has dealt with vertical fill whereas we dealt with areal fill, so that in a reef our areal fill would tend to be much higher, for example, than in a structural play. So, yes, there is some relationship.

Kaufman: Is this reflected in the Monte Carlo situation?

Roadifer: I cannot answer that. I have no data.

Roy: We try to avoid the obvious correlations as much as possible. But there are some, and it is a problem.

Ross: One way of debugging or verifying the whole process is to play the game, or take a play that has been developed and is now virtually finished, say over the last 20 years. Give your experts all the information that was available 20 years ago, turn the crank, and see how they do.

Sickler: They know the answer.

Ross: Let all the information of a fairly obscure, not large, play fall together with the hope that they are good enough experts, but not good enough to recognize the data, and then give them the data that is from 15 years ago, 10 years ago, and see what they do. To me, this is a way in which, if you could repeat the experiment several times, it might be a good way to see whether there are significant inconsistencies in the process.

Sickler: We have used this method for at least five or seven years already, so we have considerable experience with it. Firstly, the observation that the geologist cannot rig the method is not true. It takes about six months to a year, and for some geologists 1.5 years, to understand it completely, and they can get any answer they want by playing the parameters. Therefore, subjective things come in again. Secondly, we found that trying to let a geologist estimate chance factors does not work at all. They seem to analyze what they do in a logarithmic way rather than in a linear way. When they say something is good, or something is bad, or something is medium, then the medium is not halfway between good or bad, but distributed logarithmically. Having geologists estimate normal chance factors in a way as you put down here in our experience does not lead to good results.

In the majority of cases you will get the result that you experienced too: they will look at the results, and they will say they do not like them. We arrived at a more subjective way of doing it and let the geologists judge all these parameters, such as those you put up and a few more, but without the chance factors. But they could say, for instance, the cap rock is favorable, while we think it is unfavorable, etc. From experience and from calibration from existing basins we know approximately what kind of chance factor a geologist has in mind when he says the thing is favorable, unfavorable, or 50-50. By using chance factors that are calibrated on existing basins you get far better results that geologists believe. But it is a process that takes a number of years.

Next I want to comment on the presentation by Odell. Firstly, I think that the majority here will agree with me that to compare the North Sea with the Persian Gulf geologically does not make much sense. Also, we think the North Sea development will go a bit differently. I refer again to my table for reserves that I used during my talk. You can see here that for Europe we have a range of 37 to 67 billion barrels. This, of course, is mainly North Sea. We believe that to be the picture up to the year 2000 or 2020 or something like that.

We do believe that because, even if there were far more oil than that, constraints put in the way of normal economic development, for instance, governmental action--several of the governments have declared that they do not want production to grow "unlimited"--produce certainly in the case of the North Sea a constraint on the technological side. One cannot simply build sufficient platforms, be they of steel or concrete, or drilling rigs and so on, to produce peaks in the production as Odell predicts. The constraint is the very high cost of production, so economically the industry is not inclined to go for very high peak production. They would rather use the facilities spread out over a longer period--and then, of course, these high prices that should really encourage development of the North Sea, of course, generate a high income. This income is then taken over by the States surrounding the North Sea who do not put the money back into the energy development.

So the margin left for the energy developers is not very large even if there is a high price. That is the reason we think that the North Sea potential will develop approximately according to this scheme. It is far more modest. It takes into account more the reality in the political factors and in the construction constraints and so on. The highest production, as we see it within the low estimate, gives a peak of around 4 to 5 million barrels a day in 1983 or so, and in case there are more reserves and in case things are a bit more encouraging than assumed, we perhaps can go on to 6 million barrels a day and then, if there is still more than that, that will be used mainly to keep this production constant. This is for the economic benefit of the industry, I feel, because the facilities are used to a much greater extent, especially the very expensive pipelines; it is also a benefit for the governments: the Norwegian government, which is not in favor of high-peaked production rates anyway, will be happy too. They will perhaps encourage keeping production level to generate a constant income. So we think that this perhaps is an optimistic scheme, 6 million barrels a day for a rather long time.

Häfele: A question to Odell: Was I right in calculating that your grand total in the North Sea was of the order of 100 billion barrels, instead of 37-67?

Odell: The output of the model indicates a 90% probability of about 78 billion barrels. At the other end, the 10% probability is of 138 billion barrels, and the mean figure was 109 billion barrels.

Häfele: Do you feel that you could explore these resources at $8 a barrel, assuming that there is no inflation? I mean $8 a barrel in 1975 dollar terms.

Odell: Insofar as we also have a cutoff in the model of all fields of less than 100 million barrels, and the industry still indicates that a field with 100 million would be commercial at $8 a barrel, and provided the governments are not too rapacious, the answer is yes.

Häfele: Or, in other words, what is the floor price that you are after, or below which you cannot do it anymore?

Odell: We have not calculated this. My own feeling for it emerging from our studies is that it is of the order of $6 to $7 a barrel.

Häfele: And what is your point of comparison?

Odell: A normal profit tax of 50%.

Clegg: So you can develop at a cost of $3 a barrel?

Odell: No, that is not correct. With a price of $6 a barrel and an allowed cost of $5 there is only a profit of 50 cents. It is not a 50:50 split of the total income as it is not a production sharing agreement. So we are talking in terms of a 50% tax rate on a profit margin of maybe a dollar, which gives a cash flow to the company of $5.50 a barrel.

Clegg: But that is nonsense economically because of the sums of money involved.

Odell: At $5.50?

Clegg: Well, at a dollar's profit.

Odell: We are talking about cash flows.

Clegg: You were talking about tax on the profit, not the cash flow.

Sickler: The dollar profit is far too low.

Odell: In relation to what? It depends on your investment per barrel, so again what per barrel investment are you judging is necessary?

Sickler: In case you are talking about small fields, you will spend $6 to $8 on technical cost per barrel.

Odell: The last investment cost per barrel given by BP was in relation to the Forties Field. That was £1100 per barrel per day of producing capacity. And in answer to what it would be now in the light of inflation over the last two years is around £1700 to £1800.

Clegg: You have not thought about inflation in detail. May I just add to that and say that as far as I know, the figures for the Forties Field--that is one of the three largest fields in the North Sea--is currently running at something like £1500 per barrel per day. I suspect that the Ninian Field is estimated to cost £1.1 million to develop and will produce something say between 300,000 to 400,000 barrels per day. So you are getting up to $6000 or $7000 per barrel per day. And in terms of the operating costs, I cannot tell you exactly.

Masseron: Four to five dollars per barrel?

Clegg: Yes, I suppose that is correct.

Masseron: In the North Sea case we must, like Häfele and Sickler, consider taking out something like $7 to $8 per barrel for the small field. And the problem, of course, is political and economic: Is it possible for any kind of group, state, or private company to develop with such a cost? Are there any comments on this particular point?

Sickler: It is surely possible to develop oil at a cost of $7 or $8 per barrel provided that the right tax incentive is given. Now, talking to governments and perhaps coming to the point that the governments do not get any information, as is sometimes mentioned, I do not think that is true at all. We, Shell and BP I think, have talked extensively with the British government when it came up with this PRT tax, and the government received cash flow calculations. Everything the government asked for they got over a period of more than a year. The same is true in Norway, where the government produced a new tax law in November 1974. We in the industry went to the government and presented them with a large amount of data and calculations, actual facts, and the Norwegian government knows what it all costs in Norway, and the same is true for the UK. So all this information is available in the ministries.

Roadifer: I would like to comment on behalf of the companies--not with regard to economics, but with regard to the estimating of undiscovered potential. It was asserted earlier that we (the companies) have a very definite practice of estimating what is economically attractive for us now, and I say that it is not true. We also plan for the future. In fact, we can plan much further ahead than many governments, and we do have the potential estimate not just for today and tomorrow but for 20 and 25 years down the road. We are not looking only at the short future.

Hubbert: I am almost completely ignorant of this North Sea case, except what I read in the current literature. But what puzzles me is that I can see very little geology, very little evidence of geophysical and seismic exploration. I do not know how to estimate things without such information. I have read two or three papers by Odell, and I have never discovered what actual data he uses, and I still do not know how he gets his answers.

Odell: The problem of Hubbert in respect to this is exactly the same as the problem he has in respect to all the other kinds of probability analysis that have been presented here. You have here the basic difference of opinion. On the one hand, we have those who argue that you can predict on the basis of what you have drilled and the core samples you have examined and what you can extrapolate from that. On the other hand, we have those, including myself and others that have presented papers this morning, who indicate that there is certain evidence from the data that have been accumulated in the history of the industry that enable one to extrapolate in probability terms. I think this is quite a fundamental difference in outlook and this is not specific, I think, to Hubbert's comments on this model.

Hubbert: I recall an earlier paper by Odell on this same subject I read a few weeks ago, in which the word "assumption" occurs on almost every page.

Odell: I cannot confirm it says "assumption" on every page, but perhaps Hubbert has a better memory than I. But certainly we clearly defined all assumptions and we clearly stated that those assumptions had been made. We then reminded the readers of this fact, with a list at the end of the paper of all the assumptions that had been made. It is a probabilistic model, and we come back to the basic difference of opinion about how you progress knowledge on an "unknown" like the future reserves of oil on a subject that is a very important component for the future development of Western Europe.

Clegg: May I ask Odell a question, because this is an important subject that he has raised--the future development of Western Europe--where obviously the implications for the European countries are extremely great, and I think it would be wrong to degenerate into an argument about what companies will and will not supply.

I would like to ask you to clarify one thing about the way in which you have approached the calculation, because there is not very much in the paper about it, and that is the way in which you have derived the success ratio that might be achieved in the future for the drilling that is going to take place. I get the impression that you have looked at the historical data and have said that they are probably as good as they are going to be and they are going to get worse. We would contend, I think--and there would be strong geological evidence--that the initial results that you get will be very heavily biased and that the sort of curve shape that you get will be quite different from what you might expect by drawing something nice and smooth. This is point one.

Point two is that, looking at the results you have supplied, you have taken a population in which you are looking at a number of samples--I do not know how many wells have been drilled, 100, 150--you are looking at those and say: here is a population that I have sampled and I infer something about the probabilities of success in the future from those figures. You must look at the confidence limits associated with these projections. We would suggest to you that if you had included those you would have come up with a very, very much wider range of possible outcomes than you have, and this is only to be expected. After all, you have very little data on which to go (which you are continuously complaining about) but you are coming up with something that does not have such a large spread of results. And I would contend that if you had put all these things in and taken account of them you would come up with a very much wider spread that would have made your results appear quite different.

Odell: Briefly, that is correct. The assumption about the success rate is what has happened so far. A further assumption is that the best that will be achieved, and thereafter a decline in the rate of success through to the 20th year. As far as the degree of confidence around the parameters is concerned, we did not individually attach degrees of confidence to each of the parameters. From the matrix that we worked through from a number of wells, success rates, likely size of fields, we came to an evaluation of what we called the "normally expected rate of discovery of reserves" per year. Variability was then introduced in that stage. What we are now looking at as a result of discussions we have had since this model was exposed to public criticism is the kind of suggestion that Clegg has just made; that is, every individual variable in the model should in fact itself be subject to variability and confidence limits before moving on to the next stage. This will obviously extend the range of variability built into the model.

Dunham: Could Herault tell us roughly how many years' life he expects for a typical aquifer in the Paris Basin, supposing that it is fully exploited through this technique? Perhaps it is too early to ask this question, but I would be interested in even a tentative answer.

Herault: At present, the distance between the wells is computed for 30 years' life.

COAL RESOURCES

"Coal is a fine fuel, but we do not know how to produce it and how to use it", said Dave Freeman. We would be tempted to add, "and we do not know exactly how much of it we have".

In reality, there is some general consensus that coal resources are very large--probably in the range of a trillion (a thousand billion) tons. Moreover, there are still some virgin areas which have not been explored or explored only a little. But of the vast amount of resources, what percentage can be economically recovered? This is one of the critical questions and the one that, one way or another, was the most debated question during this Conference.

ONE ASSESSMENT OF WORLD COAL RESOURCES

As for the other energy resources dealt with in this book, one major paper was selected to review past assessments of world coal resources and adjust them to give a personal estimate. Two major points are made: that the classification of coal resources--which was questioned by some attendees--is important and that the gap between the amounts of resources in the ground and the economically recoverable reserves also is important. About the percentage of economically recoverable reserves one can say that the experts forecast a full range from optimistic to very pessimistic. Fettweis's analysis tended, in our opinion, toward the pessimistic--others would perhaps say the "realistic"--side of the estimates.

COAL RESOURCES ASSESSMENTS: PROBLEMS AND CONSTRAINTS

Although there is frequent up-dating of past national estimates of coal resources and, more important, of coal reserves, since these are closely related to production and industrial planning, few, if any, methods of assessment have been developed for coal resources. And this explains to some extent why fewer papers were retained for the coal session (this, to answer the introductory comments by M. Styrikovich) than, say, for the petroleum session.

The various papers, together with the lively discussions that followed, intend more to show the problems and constraints associated with coal resources than really discuss methods or estimates, because of the scarcity of such material. It seems to us that the new mining technologies and their possible role in increasing the amounts of recoverable coal reserves are of the highest importance to fill the gap between resources and economically recoverable coal reserves. These new technologies--open pit mining, hydraulic mining, underground gasification or liquifaction--were discussed. No real conclusion seems possible yet.

The achievements in the FRG with open pit mining of lignite reserves at Garsdorf are most impressive. In a few years time, achievements can be expected from Hambach. Of course overburden conditions are very favorable there. But if such methods could possibly be extended to operate under more severe geological conditions, more than 80% of US coal reserves (and probably also a high percentage of US coal resources) would be recoverable with such methods, assuming adequate reclamation could be achieved in the Rhine area as well. And the same would apply for many of the tar sand and oil shale resources in the USA and elsewhere.

Maybe the most important comment--or question--for the future role of coal was raised by W. Häfele. To develop nuclear energy a completely new way of thinking has been necessary, and we have had to tackle the technical problems with unprecedented financial and technological tools. Compared to this, everything related to coal seems extremely modest, shy, conservative. What would be the effect of attacking the coal problem in the same ways that we use to master the nuclear unknowns?

[The Coal Session was chaired by M. Styrikovich from the USSR.]

Styrikovich: Today coal presents a large problem, and I am a little bit sorry that in all the program we have only four presentations on coal. Of course, in today's energy balance the role of coal is not so big. But I think that in the problem of energy resources the question of coal is of special value, because the reserves of coal normally considered are much bigger than those for oil and gas. But my personal opinion is that if we go to economically recoverable probable resources of oil and gas, and the same for coal, the big difference is not so obvious. Under these conditions, I think that some talking about what economically recoverable coal resources really are is very necessary. For example, in the USSR, as well as in the USA and the Republic of China, there are large amounts of coal resources. In the USSR three big coal basins, the Lena, Tunguz, and Taymiz, represent about 30% of all probable coal resources of the world. But these three basins lie in almost unpopulated polar regions, and perhaps even in the future they will remain economically unrecoverable. The same can be true for a large percentage of all probable coal resources. I think that the problem of predominant economically recoverable coal resources must probably be reassessed a little in comparison with oil and gas.

CONTRIBUTIONS TO THE ASSESSMENT OF WORLD COAL RESOURCES OR COAL IS NOT SO ABUNDANT

Günter B. Fettweis

1. INTRODUCTION

The discussion of energy and mineral resources in the last few years has generally assumed relatively large useable coal resources of the world. According to Rolshoven (1972) they are "hardly exhaustible". In contrast to this, however, Hubbert in "Resources and Man" (1969) explicitly points out their limitation, and he simultaneously assumes the ultimate amount of mineable coal of the earth to be in the magnitude of 4.3 to $7.6 \cdot 10^{12}$ metric tons. Accordingly, coal could serve, counting from today, for almost another 400 to 500 years as a major source of energy for the world, and it may be exhausted entirely only in the second half of the coming millenium. According to Figure 1, a peak of world coal production of approximately six to nine times the present annual production is being assumed for the century between 2100 and 2200.

For Meadows (1972), at any rate, coal resources exhibit the longest lifetime of all nonrenewable resources discussed. Mesarovic and Pestel (1974) calculate that currently known useable resources can satisfy the entire energy demand of the world far beyond the year 2100. Accordingly, they want to base the intermediate-term solution to world energy problems on coal, bypassing nuclear energy, until in the course of the next 100 years it is possible to develop technology for the utilization of solar energy as a long-term solution.

The last pertinent report of the OECD initially states that because of mining conditions the mineable proportion of the world's discoverable coal resources of $13 \cdot 10^{12}$ metric tons--from which the amount already established by mapping and exploration is estimated to be about $7 \cdot 10^{12}$ metric tons--is lower than that of oil (1974). Subsequently the total recoverable reserves under the present technological and economic conditions of the world are presented at about $0.7 \cdot 10^{12}$ metric tons, of which approximately 60% is located in the OECD countries, enough for more than 100 years at present consumption levels. The OECD report--in agreement with other investigations--claims that the expansion of the coal supply is not resource limited. Additionally, it can be expected that the changed price situation may probably result in further additions to the recoverable resource levels indicated above.

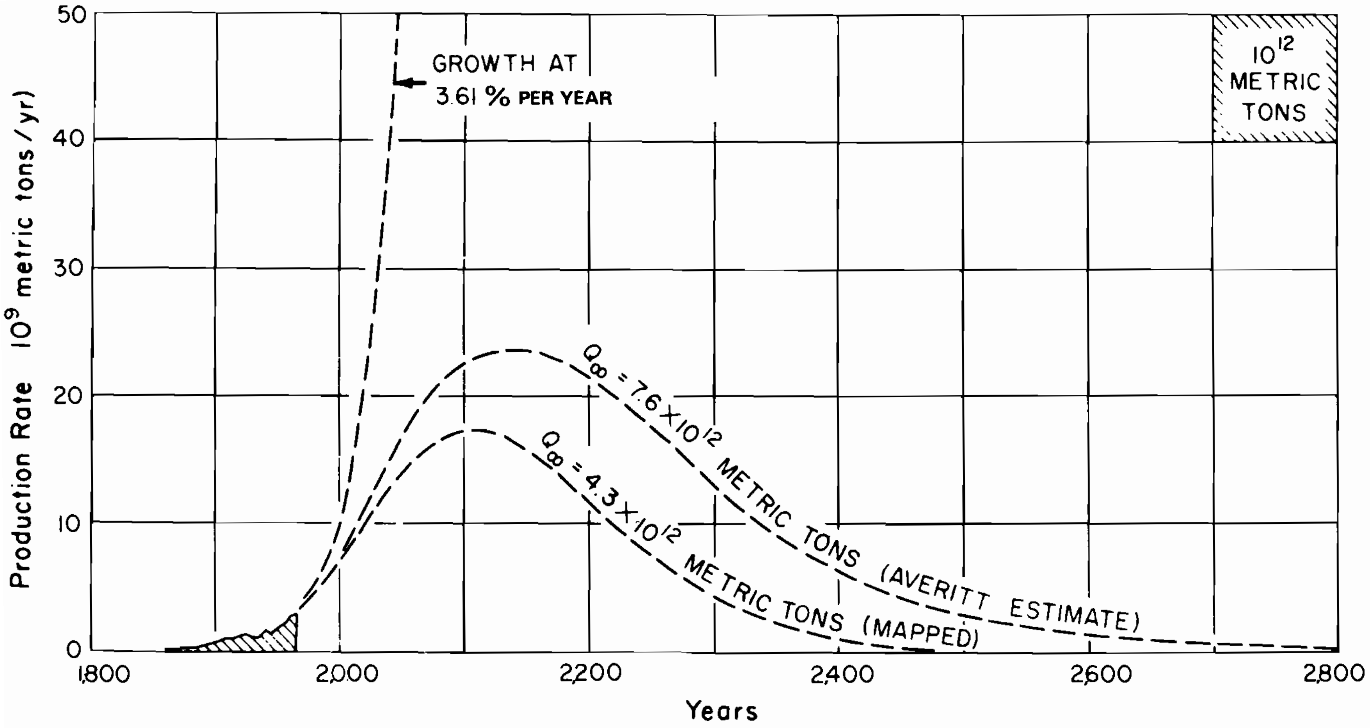

Figure 1. Complete cycles of world coal production for two values of Q∞ according to M. King Hubbert (1969).

The most recent estimate of coal resources is the "Survey of Energy Resources, 1974" of the Central Office of the World Energy Conference (1974). It indicates those coal reserves of the world, that are at present sufficiently known and recoverable under the present technical and economic conditions, to amount to $0.6 \cdot 10^{12}$ metric tons, and the total coal resources to be approximately $11 \cdot 10^{12}$ metric tons. By using the latter figure, the survey states a resources-to-demand ratio of the solid fuel resources, based on world use in 1972, of 3,686 years.

In different comparisons coal, therefore, appears frequently as that nonrenewable raw material for which a prospective depletion is least probable. In the current energy situation it frequently is looked at as the great reserve. In my opinion this picture needs to be corrected. Actually, the ratio of coal to inorganic raw materials is just the opposite of what is generally assumed from a comparison of the published figures of resources. In my opinion also, the optimistic statement of McKelvey and others, "that for millennia to come we can continue to develop the mineral supplies needed to maintain a high level of living for ... the world" (McKelvey, 1973), holds true for inorganic mineral raw materials. The "resource base" for that is indeed almost unlimited. The raw material in question has been essentially in existence since the formation of the earth.

Coal, on the other hand, is a product of relatively young life processes, geologically speaking. It is only present in sedimentary rocks and because of this--to my mind--restricted to an area of approximately 10%-15% of the earth's crust that is accessible to mining. Between the coal and the rock in which the coal is imbedded there is no steady transition in quality. The "resource base" is not indefinite but relatively well known and, with respect to the remaining contents of the earth's crust as well as to the relationship between geological and historical periods, it is in no sense exorbitantly large. Too, when burned, coal, which has passed through a process lasting millions of years, is again transformed into the gaseous phase from which it originated. A "recycling" is not possible. Coal can only be substituted for by other fossil fuels which probably exist only in smaller amounts or--at any rate only partly--by the disputed nuclear energy and "exotic", as yet unavailable, energy sources.[1]

If one considers the uneven distribution of coal resources in the earth and also the international political situation, one can see here that coal is not available everywhere in abundance today, nor will be in the future. The following expositions arrive also at this same result.

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[1] Because of differing geological conditions, in the evaluation of reserves one has to assume that petroleum reserves are not so small in comparison to coal reserves as has been heretofore assumed and as the current data seem to show.

I present my thesis as a mineral economist and mining engineer with a theoretical background and practical experience in related problems concerning the evaluation and extraction of small and large scale coal resources, especially in the Ruhr Valley and in Austria. I base my evaluation on the present condition and further development of technology. However, I will not touch upon the basic impossibility of predicting as yet unknown technology that could change the situation entirely. The question as to the probability of such developments is also ignored.

This kind of presentation is also influenced by the fact that it does not deal with resources of individual mines but with those of large provinces and the world. All coal reserves are listed in metric tons as well as under a simple addition of all types of coal, independent of their individual composition. This means that the difference between the various types of coal, from anthracite to lignite, could not be considered by means of a computational correction with respect to energy content and other pertinent properties. Furthermore, it was not possible to deal with the special problems of coking coal. It should, however, be pointed out that a computational correction from lignite to hard coal further reduces the indicated quantities. The acute shortage of coking coal on the market during 1974 should also supply an additional justification for the presented thesis. Additionally, consideration has been given only to problems pertaining to geology and mining, and not to those which result from the geographical position of deposits.

Independent of the subsequently presented criticism a relatively large range of errors is inherent in all statements of coal resources owing to causes which can be found in the method of evaluation and calculation. Even in favourable cases the range of errors amounts to 10% and occasionally to more than 10%. Accordingly, it makes little sense to state quantities of coal resources to more than three or four digits.

2. ON THE OCCURRENCE AND EXTRACTION OF COAL

Coal developed almost exclusively from peat and occurs in stratified deposits. The thickness of seams ranges from a film to seams of several tens of meters. By far, the greater portion of the seams is, however, less than three meters thick. Often an entire sequence of seams of different thickness is present. The extent of the seams reaches from smallest areas up to several thousand sq km.

Frequently the seams are deformed and torn apart by tectonic forces. Regardless of the transitions to be found one can distinguish two types of deposits: those that lie flat and which are less contorted, as for example the ones that occur frequently in the US or in the Republic of South Africa, and those which are folded and contorted to a larger extent, as for example those of the Ruhr Valley. Nevertheless, as a rule the flat lying deposits are also not at all regular. An example for these two types from the USSR is shown in Figure 2.

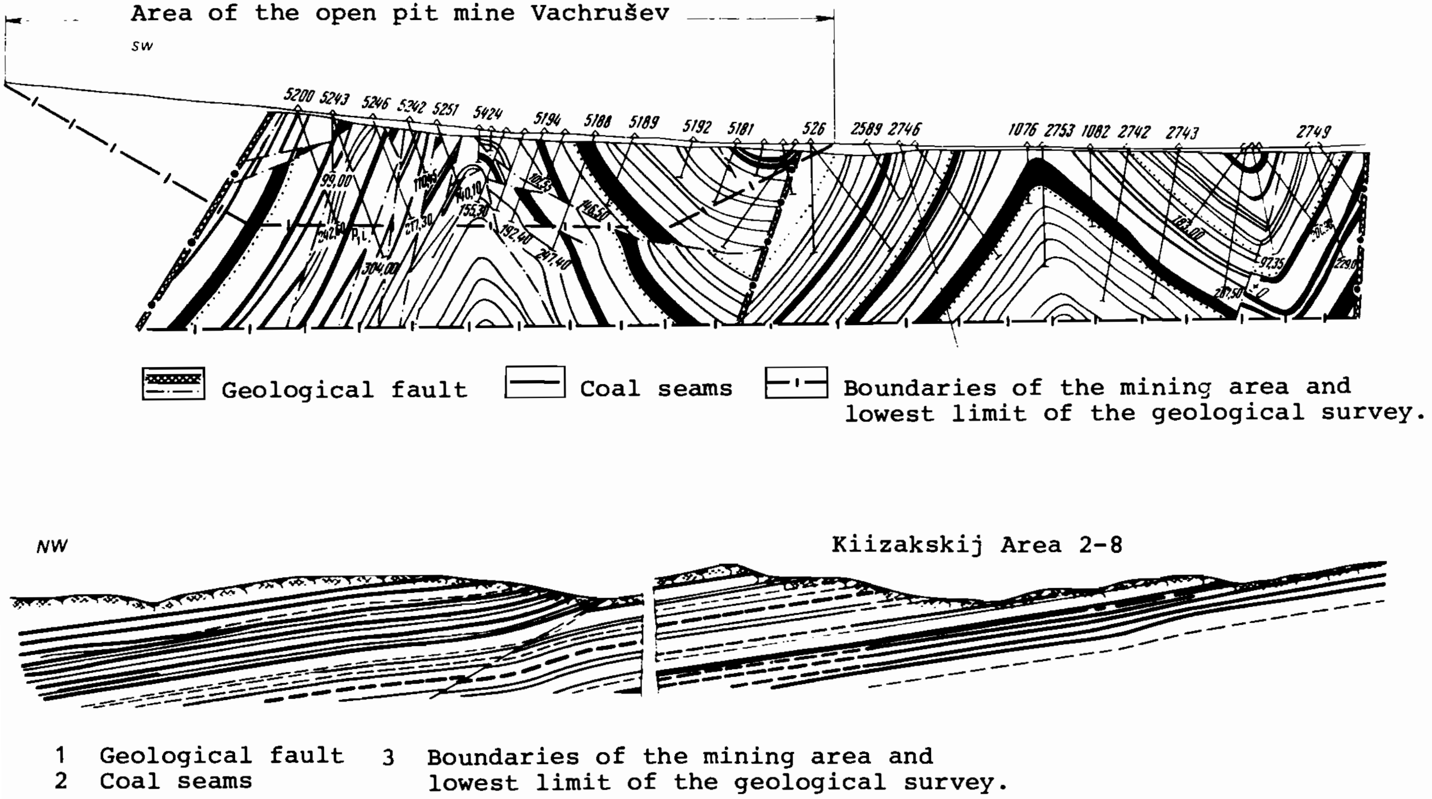


Figure 2. Geological cross sections of a) the coalfield and b) the southern part of the Kusnezkey coalfield. These are examples of the two principal types of coal deposits according to Kusnetzov (1973).

Owing to the type of occurrences that have been described it can be shown that coal deposits are essentially different from those of petroleum or natural gas. A coal deposit is extraordinarily manifold and, therefore, offers various possibilities for technical and economic utilization. One can select the best portions and leave those that are less promising untouched. In contrast, a petroleum or natural gas deposit, because of its mobility as a gas or liquid in a solid matrix, is essentially more "compact".

In the near future coal will be mined on a large scale only by means of direct extraction in open pit and underground mines; on a very small scale coal also will be extracted by auger mining. The feasibility of these methods and their degree of utilization both depend upon a multitude of factors in which one has to reckon with definite technical limits as far as the deposits are concerned. In this respect the thickness and the depth of the seams is of primary importance, along with the degree of their tectonic alteration and disturbance.

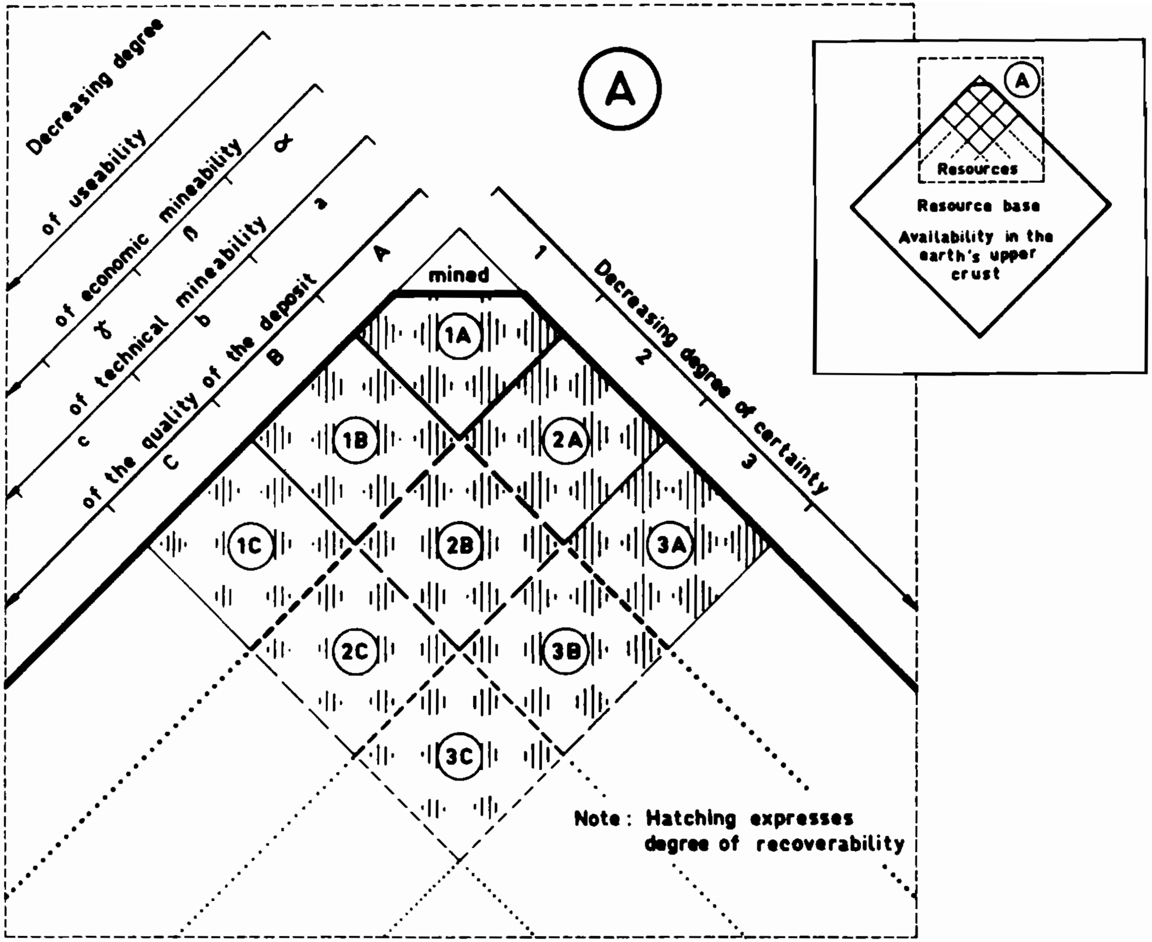
Until now the only known alternative to solid state extraction has been in situ gasification (see Fettweis, 1973). But this is not yet a technically mature method. If it can be developed, an open question so far, it will be restricted to especially favourable geological conditions. Its value is, in my opinion, not expected to be much greater than that of solar energy in producing large quantities of electricity.

The distribution of coal within the earth is relatively well known, regardless of the difficulties of its quantitative evaluation, because the geology of coal is relatively simple and relatively well known; here I stress the word "relatively". Too, there are great uncertainties in the estimates of the quantities. This is especially the case when inadmissibly large projections or extrapolations are made for unknown regions from some outcrops or a few widely spaced drill holes.

3. CRITERIA FOR THE CLASSIFICATION OF NONRENEWABLE RESOURCES

Figure 3 is an abstract, schematic attempt with an extension of other proposals (see Bourrelier et al., 1975; Brobst and Pratt, 1973; Department of Energy, 1973; McKelvey, 1973) to demonstrate the existing relationships for determining nonrenewable resources especially as they apply to coal. The resources are part of the crust availability and of the resource base, and they are accumulated in geological bodies, in our case, for example, seams. If one correlates the resources with a certain point in time they can be evaluated and described according to different criteria which partly overlap.

The first criterion is the degree of certainty depending on the degree of geological reconnaissance. It can range from great certainty to speculative assumption.



Note : Hatching expresses degree of recoverability

Figure 3. Abstracted scheme of mineral resources classification.

Secondly, an entire group of criteria, which are interrelated and by which the degree of possible useability can be characterized, has to be named. To this belongs the degree of economic mineability as well as purely technically judged mineability. Both types of mineability are determined partly by factors which are given as constants together with the resources, and partly by those which are not immediately connected with resources and do change for example, the technical and economic factors. Together with the resources only the factors of the quality of the deposits are fixed. For coal this includes partly the different material qualities of the seams as well as their depth, thickness, and frequency of disturbances.

From the mentioned criteria it can be stated with a permissible generalization that their highest degree always is situated at the boundary to the already mined quantities and that from thereon it diminishes. In this scheme this is expressed by means of an abstract subdivision into classes according to figures and letters. The boundaries between these classes are simultaneously less certain the further away they are from mined quantities, about which the greatest amount of knowledge exists.

An internationally uniform and acknowledged subdivision of the degree of certainty or subdivision of the possible useability of coal resources into various classes and a corresponding nomenclature does not exist. To be sure, the terms for the degrees of certainty have developed out of an original trisection of the resources into "visible", "probable" and "possible", but meanwhile a variety of deviations from these terms has occurred and a corresponding confusion has ensued. This has become more distinct in the case of the degree of useability. Considering the limited space available here it is not possible to expand on this any further. From now on we shall only mention classifications that are of importance to our specific considerations.

The criteria stated up to now pertain to large scale considerations and to a corresponding designation of the resources in place. They refer to the individual seams of a resource as a unit body. In contrast to this the degree of recoverability shown in Figure 3, but not yet discussed, expresses the portion which can actually be recovered. It results from the losses which must be left behind in the exploitation of the individual seams because of inevitable geomechanical, operational, and safety reasons, and occasionally because of the need to protect the ground surface; it also includes those losses that occur during beneficiation.

The amount of recovery depends on the extent to which reductions for the losses have been already considered in the computation of the resources in situ. In most cases this is not done. In the majority of countries coal resources are determined in a calculation in which--in a simplified version--the total area of seams considered is multiplied by an average thickness of the seams and by the actual specific gravity.

Accordingly, the result deals with a quantity in tons which are true units of the substance. In other places, as for example in the Federal Republic of Germany, the initially determined volume units are frequently only transformed according to a ratio of 1 m^3 = 1 metric ton instead of being transformed by a factor of 1.1 to 1.6 which indicates the actual higher specific gravity. This is done so that it is possible to calculate some losses from the beginning.

Also the degree of recoverability decreases generally with the decreasing quality of a deposit. Recent international literature frequently only shows an average of 50% (see Averitt, 1969; Central Office WEC, 1974). According to one of my evaluations the average value must, however, be smaller.

4. LIMITS OF TOTAL AMOUNTS, FIVE CONCEPTS

On every judgement concerning the evaluation of coal resource information it is basically important to know which viewpoint has defined the total quantities displayed. Thus the questions on the assumed limit for useability are in the foreground. Beyond this, the limit of certainty also plays a role. Do the resources only include those that are known for sure, or also those which are probably to be found there, or maybe even those which might possibly be found? Which might be considered as possible?

With respect to useability there are two principal starting points for the demarcation, and they are interconnected. The first defines a limit for seam depth and thickness and is therefore related to deposit quality. The second starting point is directly related to the question of the mineability and the interconnection results from considerations here that finally determine the definite limit of depth and thickness.

We shall return to the demarcation according to depth and thickness, that is the quality of the deposit, during the discussion of the evaluations undertaken up to now. It should be noted here that only because of a shortage of activities up to now that a very important figure of the quality--the intensity of geological disturbances--has not been considered.

The second starting point presents numerous differences in detail. These differences exist not only between countries but also between experts, whether they be geologists, mining engineers, or economists. These differences can best be displayed in a more general consideration which is not only concerned with coal.

The useable minerals, whether they are copperbearing minerals or coal, are known to be unevenly distributed within the earth's crust. This applies to the concentration per unit volume and the grade; in the same way this applies to the volumetric size of geological bodies with a certain average content and, therefore, also to the quantities. Both kinds of distribution seem to be log normal (see McKelvey, 1973), which, according to McKelvey, also means that of a large population of deposits a few contain most of the material. In general, as far as the economic useability of mineral deposits is concerned, it can be claimed that the grade of concentration and the tonnage are of special importance, as is the grade-tonnage ratio. Figure 4 is an attempt to illustrate these relationships schematically. Up to which limit in this curve can one speak of deposits and thus of resources?

The answers to this basic question can, with a permissible simplification, be subdivided into five main groups. The decisive criterion for this is whether and to what extent technical-economical considerations are utilized for the demarcation. P.T. Flawn labels the first group the "cost concept" (see Flawn, 1965; 1966); the group is primarily attributed to economists (see Flawn, 1964-1965). "Cost concept" says that the boundary in question is in any case shifted so far "that mineral resources are practically unlimited and are in fact defined by costs rather than by boundaries of a physical nature, and that through human ingenuity and new technology we can extract minerals from the sea and we can mine 'ordinary' rock" (Flawn, 1966). This means that a deposit will exist for every economic situation. Friedensburg's opinion belongs in this group (see my comments on Friedensburg in Fettweis, 1964) as does Bourrelier's and Callot's (1975). This opinion group therefore also views all statements about quantities as preliminary or as irrelevant.

In the second group we should all incorporate those answers to our questions that explicitly deny a connection between the considered total quantities and economic considerations. This group states the largest quantities and is frequently represented by geologists. I would like to call it the "mineralogic-geologic concept". Mainly the definitions of deposits as "accumulations of minerals" belong to it, as does, for example, Flawn (1966) who calls them this as the result of a purely geological consideration. In the German-language area the definition by Cissarz (1965) has become predominant as has that by Bentz and Martini (1968) which was derived from Cissarz. According to Cissarz, deposits are "geometrically limited geological bodies of changing mineralogical composition in which certain chemical elements have been essentially [more highly] concentrated by natural processes than would correspond to the total average of this element in the earth's [upper] crust". Occasionally, it is even postulated that the concentration should only exceed the average of the upper 16 km of the earth's crust (see Stammberger, 1958).

We will have to speak separately about the more recent Soviet demarcation which also has to be counted in this group. To this concept--besides other proposals--have to be added, above all, the reflections which D.A. Brobst and W.P. Pratt have only recently used as a premise in a comprehensive work of the US Geological Survey (1973). According to Brobst and Pratt,

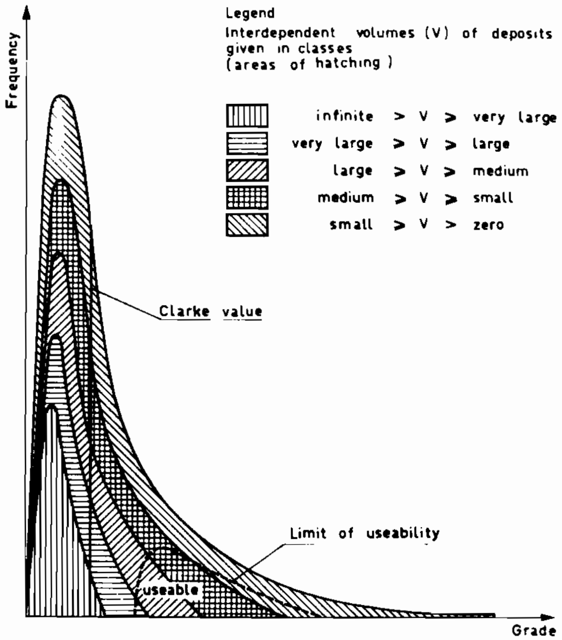


Figure 4. Scheme: lognormal distribution of mineral materials in the upper part of the earth's crust in grade and volume classes, and limit of useability.

resources include identified as well as all conditional, hypothetical and speculative "concentrations of elements in a particular location in or on the earth's crust (or, now, also in the ocean) in such a form that a useable mineral ... commodity can be extracted" and "eventually become available". Accordingly, only the basic technical possibility of extraction is the deciding factor, and this can reach very far if high costs are permitted. This is something that was pointed out by Hoover in 1909, something which may go as far as the "mining of ordinary rock" following the cost concept. Brobst and Pratt call this "geological availability". They state in this connection: "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". Furthermore, they emphasize explicitly that their interpretation distinguishes itself also from the one found in the very basic publication by McKelvey--which for this reason was reprinted in 1972 in connection with their own interpretation.

The interpretation of McKelvey belongs to the third group of answers to our question. It belongs to the classical method that for many decades has prevailed in the western states, independent of numerous variations in detail (see Petrascheck, 1961). For a long time the guidelines for the evaluation of resources in the socialist countries likewise could essentially be inserted into this group. I would like to call this group the "economic-geologic concept".

The agreements about the definition of resources and reserves between the US Bureau of Mines and the US Geological Survey for 1973 and 1974 (see Department of Energy, 1975; Classification of Mineral, 1974) also belong to this concept. They are based on the proposals by McKelvey. As a further development of the proposals by Blondel and Lasky (1956; Blondel, 1958) one explicitly distinguishes here between resources and reserves as shown in Figure 5. Here, a resource is "a concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such form that economic extraction of a commodity is currently or potentially feasible". Or "total resources are materials that have present or future value". The degree of certainty thereby ranges from measured up to speculative in undiscovered districts. In contrast to this "reserves are that portion of the identified resource from which a useable mineral and energetic commodity can be economically and legally extracted at the time of determination" (see Classification of Mineral, 1974) and this means "with existing technology and under present economic conditions".

This point of view corresponds basically to the original recommendations of the Gesellschaft Deutscher Metallhütten- und Bergleute (GDMB) in 1959 about the classification of mineral resources; these are presented in Figure 6. The "volume of the deposit" is, according to Figure 6, equal to the "resources" in the previously stated sense, and it comprises two groups:

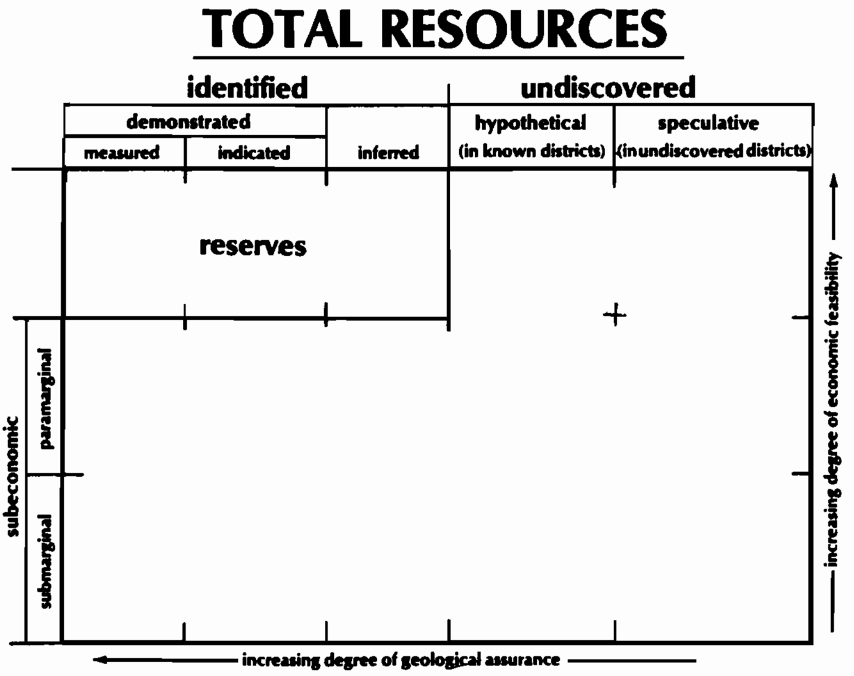


Figure 5. Joint US Geological Survey–Bureau of Mines classification system for coal resources and reserves 1974 (1975).

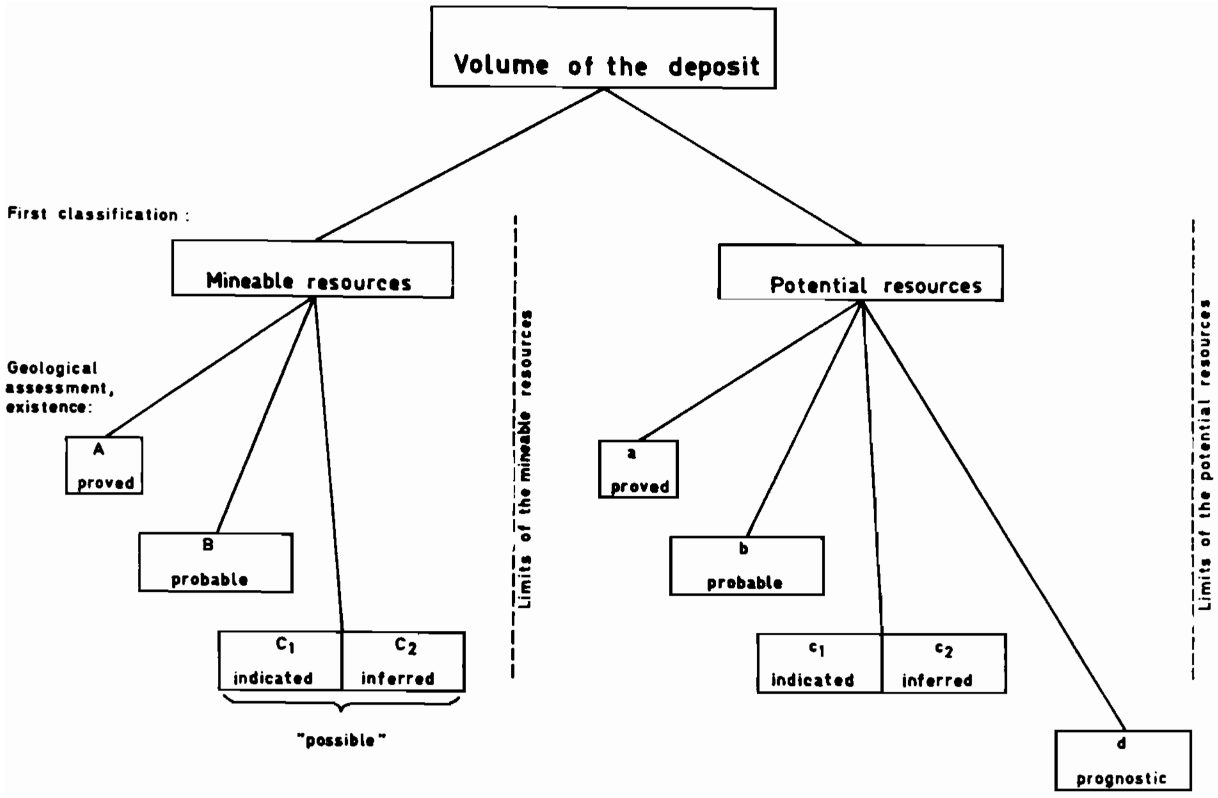


Figure 6. Classification scheme of solid mineral resources according to the directions of the Gesellschaft Deutscher Metallhütten- und Bergleute (GDMB), 1959 (see Eine Klassifikation, 1959).

"I. the [currently] useable resources (mining resources)"--which are viewed as equivalent to "reserves"--and "II. the potential resources", that is, those that cannot be utilized at present but which will be taken into consideration for utilization in the future. The degree of certainty ranges from certain to prognostic.

The subdivisions in the USSR until 1960 and in the German Democratic Republic until 1962 (see Stammberger, 1958; Ulrich, 1958) were very similar. According to these only such quantities as "useable mineral resources" (USSR) and "resources of solid mineral raw materials present in mineral deposits" (GDR) should be included; the latter in turn could be subdivided into two groups following the "qualification for a utilization in the national economical sense" (Stammberger, 1958; Ulrich, 1958). To the currently given requirements for recovery and processing the "balance resources" (= consequently mineable resources = reserves) correspond as a first group. The resources of the second group, which exceed those of the first group, that is, the "out of balance resources", had to be considered "as an object of a future industrial utilization". It has been pointed out by Stammberger in discussions related to this subject that resources are in any case a geological-economic category.

To be sure, the subsequently undertaken alterations of the classification principles in 1960 and 1962 retained these terms and their meaning, but they introduced an additional group (Figure 7), that is, the prognostic resources. It was stated that one is dealing here with "not yet proven resources"; but they are in fact resources "that have been found in isolated openings or which are scientifically predictable on the basis of general geological, geographical, and other information for large regions, formations, etc." (see Klassifikation der Lagerstättenvorräte, 1963). Together with the balance resources and the out of balance resources they form the total geological resources. As Stammberger has stated, therefore, they are "of dual nature in their character". They are very heterogeneous and contain not only quantities of a very low degree of knowledge with the criteria of the balance and out of balance resources, but also clearly non-feasible quantities, "for example with contents still below the lower limit for the calculations of the out of balance resources". The recent Soviet guidelines on resources and their Eastern European derivations are also to be incorporated into the second group, that is, into the geologic-mineralogic concept.

The third concept, that is, the geologic-economic concept, has the disadvantage (as did the Soviet concept with respect to out of balance resources) that it refers to an uncertain future. This also holds true if one speaks--as in the last

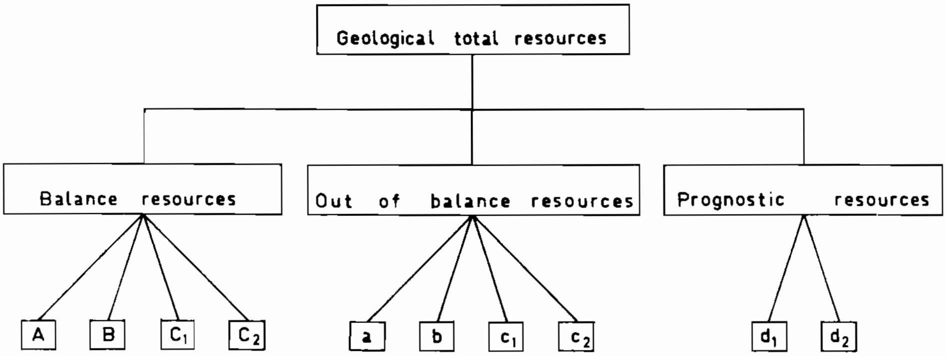


Figure 7. Classification scheme of solid mineral resources according to the directions of the USSR Geological Directorate, Moscow, 1960 (see Stammberger, 1966).

Survey of Energy Resources--in this respect of "the foreseeable future".[2]

The fourth group of answers to our question for the demarcation of resources in the earth's crust begins with a criticism of the group: "What is the foreseeable future"? or--as the youngest representative of this group asks in a paper of the Canadian Department of Energy, Mines and Resources--"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"? (see Department of Energy, 1975).

This Canadian paper proceeds to call unanswerable the question posed with respect to Figure 4, if no time limit is fixed. The paper continues along the lines of S.H. Schurr and B.C. Netschert et al., (1960), and proposes, as in Figure 8, a clear distinction between "resources" which when appropriately subdivided are roughly definable and quantifiable and a "resource base" that extends indefinitely beyond this. The definition of resources following McKelvey's definition (see Department of Energy, 1975; Flawn, 1965; McKelvey, 1973), cited under group four should, therefore, be supplemented by the phrase: "with a specified probability and within a specified future time span". With respect to time span it is stated that a period of about 25 years is the practical outer limit. The probability of economic exploitability in this time should in any case amount to more than 10%. The question whether

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[2] 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" (Central Office WEC, 1974).

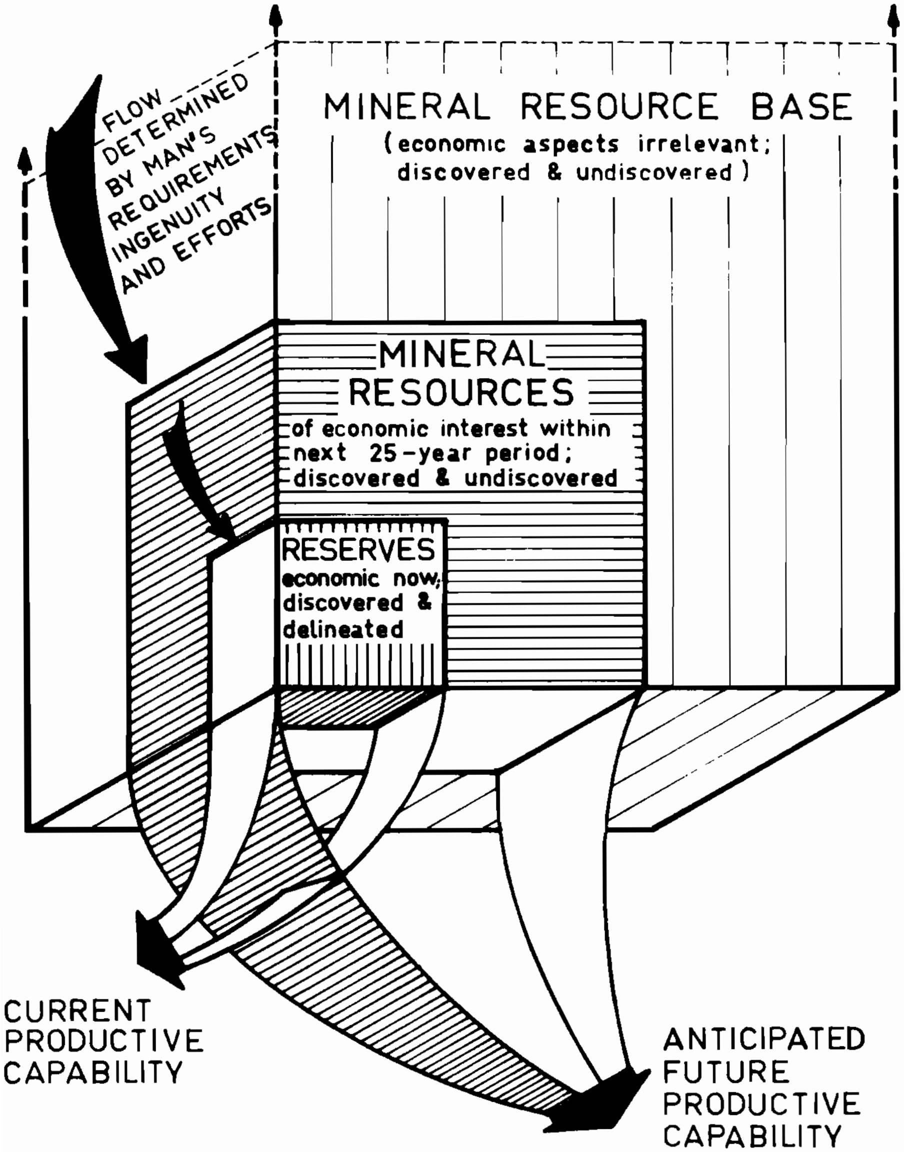
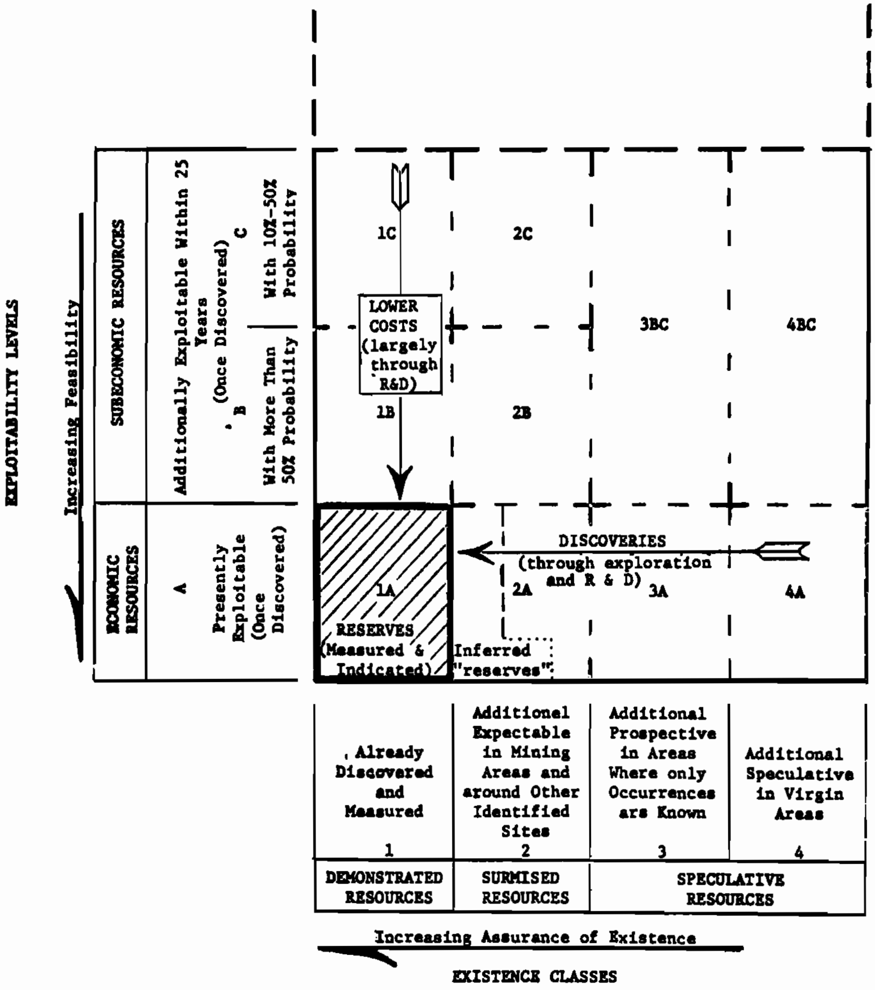


Figure 8. Scheme of mineral resource base, mineral resources and reserves, according to a proposal of the Department of Energy, Mines and Resources, Ottawa, Canada (1975).



Notes:

- Coal reserves (measured and indicated, that is category 1A) should be reported both as an in situ tonnage and a corresponding recoverable-net usable-tonnage. All other categories require only in situ tonnage estimates, although rough estimates of recovery factors may be added whenever possible.

  The accuracy of measurement for recoverable reserves needs to be greater than that for in situ reserves or resources, as determination of the recoverability factor requires additional information.

- For coal, class 3 is a major interest only for special cases, such as the Canadian Arctic Class 4 has little relevance for coal.

Figure 9. Classification scheme of coal resources and reserves of the Department of Energy, Mines and Resources, Ottawa, Canada (1975).

this is the case would have to be answered by a team of geologists, mining engineers, metallurgists and economists. The "resource base" may then refer to the total amount of a mineral in the earth's crust within a given geographic area as Schurr and Netschert et al. define it, or in a restricted and more practically useful sense as well.

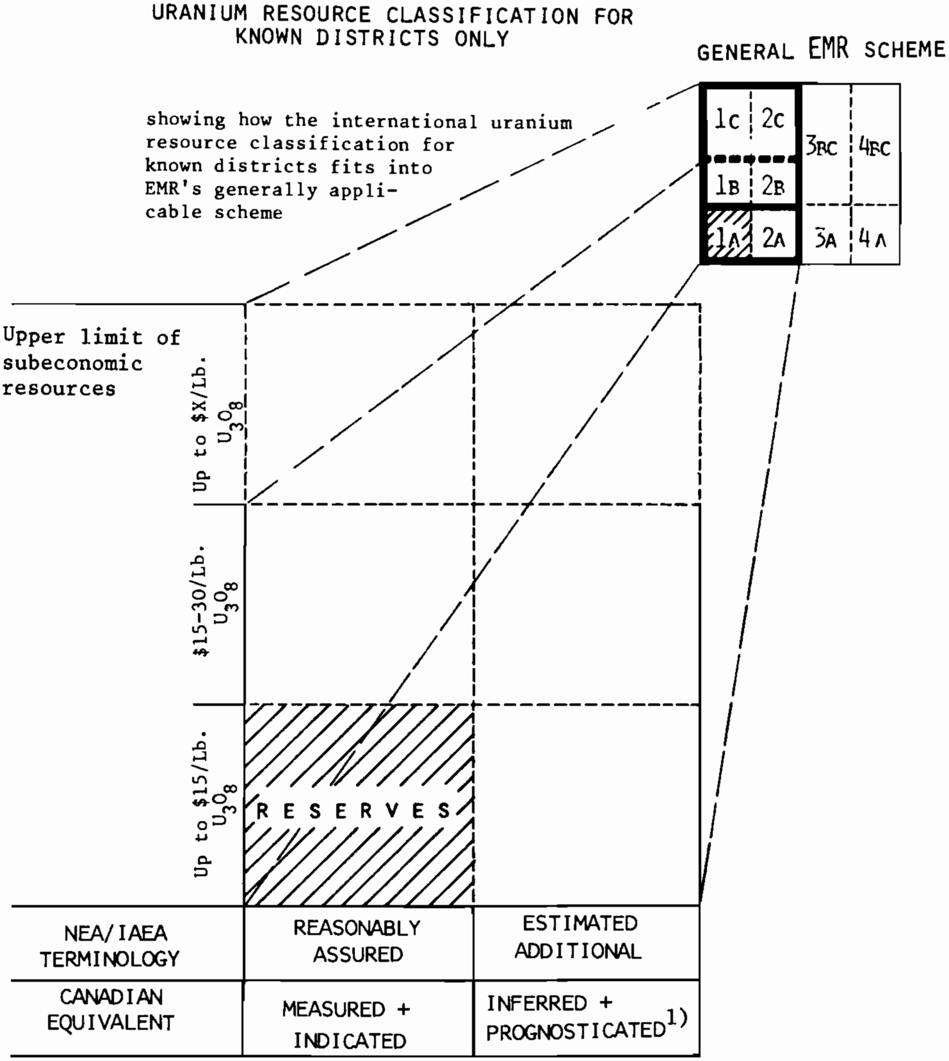
With respect to its practice-related orientation I would, therefore, like to call what I have outlined a "mining concept". The corresponding Canadian proposal for the subdivision of coal resources is reproduced in Figure 9.

As the Canadian considerations show, the particular method, that was developed in 1964 by the European Nuclear Energy Agency for the determination of uranium and thorium resources and which since then has been internationally acknowledged, corresponds to the proposals of the "mining concept". For the critical examinations of uranium and thorium resources the quantities are, as is well known, subdivided into groups that can be economically exploited at various prices and under the assumption of the currently foreseeable mining and processing technology. The price categories, therefore, can without difficulties be coordinated with the classes of the Canadian subdivision according to probability and time span (Department of Energy, 1975) as shown in Figure 10.

At the same time, a comparison of Figures 9 and 10 shows a weakness of the Canadian proposal, which, by the way, similarly holds also true for all related considerations. It concerns the problems that arise if one has to determine the degree of exploitability for speculative resources within a specified future time span and with a specified probability. For resources--according to sections 3 and 4 of Figure 10--that lie in areas where only occurrence is known, or that can only be surmised in virgin areas, data that would permit an evaluation of the exploitability inevitably are not available. The classification of uranium resources avoids this difficulty by the fact that resources of Sections 3 and 4 are not being evaluated at all.

Flawn calls the fifth group of answers to our question "the ore body" concept or the "coal bed concept" (see Flawn 1964-1965; 1965; 1966). It is based on a more static method of consideration and on the opinion that for the utilization, in any case, only absolutely finite volumes of geologic bodies that are physically, singularly distinguishable and that have a sufficiently high concentration are available. Thus, the available quantity is mostly equivalent to the currently well known and useable quantity, or it is a very small multiple of this. Following this concept the resources accordingly occupy only a very small part of the volume shown in Figure 4.

The range of the basic opinions also frequently can be found in the literature outside the cited sources. The "cost concept" is thereby frequently considered as appropriate



NOTE: The international classification, restricted to known districts, covers only the left half of general EMR scheme.
The "B" category of the general EMR scheme, which represents resources not now economically exploitable but judged to be exploitable within 25 years, is assumed to include resources that would now require a price exceeding $30/Lb. of U_3O_8 to be mineable.

1)"Prognosticated" covers estimated tonnages of deposits that are geologically prognosticated but not yet identified.

Figure 10. Comparison of the international uranium resource classification scheme of the Department of Energy, Mines and Resources, Ottawa, Canada (1975).

for the long term consideration of a national economist similar to a "public-policy point of view"; the "ore concept" or "coal bed concept", however, is attributed to the practical miner. It is also called the "commercial point of view" (see Stammberger, 1958; Ulrich, 1958).

According to Flawn (1964-1965), the truth lies between the extremes: "We may approach a world in which we can exploit ordinary rock, a world with different economies and a different technology; but we are not yet there (Flawn, 1965). I agree with this opinion. It appears to me that the presented "mining concept" is the one closest to reality.

5. COMPARISON OF THE WORLD COAL RESOURCES ESTIMATES 1913-1974

The relationships in the classification of coal resources as outlined up to now can be displayed and also simplified in the form of a subdivision as it is reproduced in Figure 11. The total quantities determined after one of the various concepts are thereby subdivided at several levels into at least two categories: the levels pertain to certainty, useability,

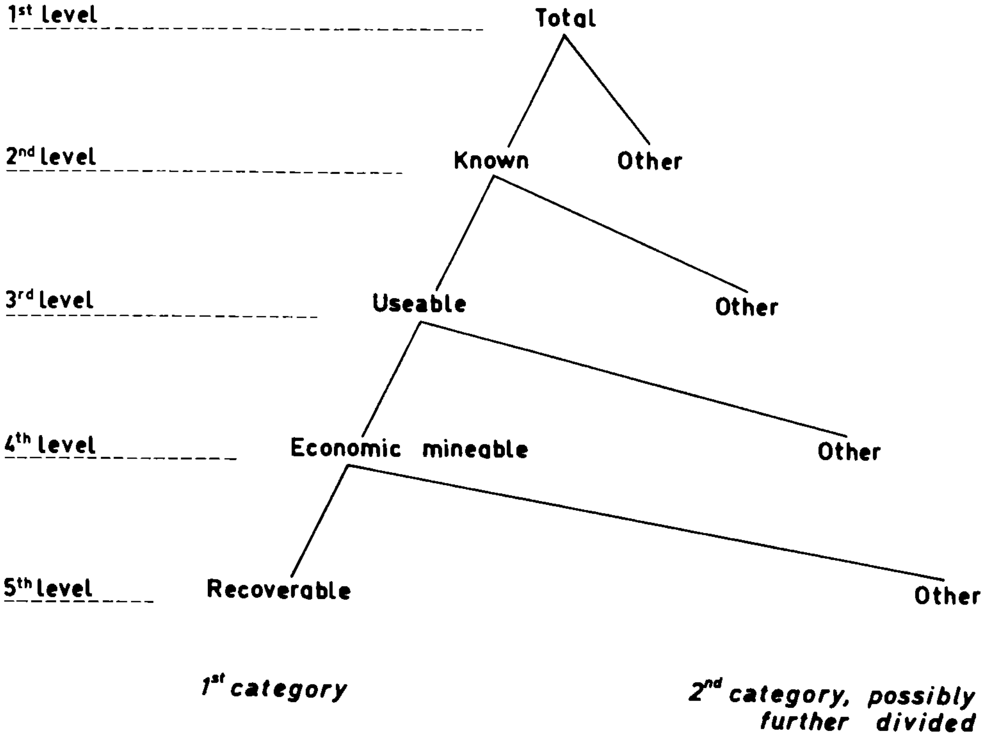


Figure 11. Classification levels of coal resources.

economic mineability, and recoverability. However, it is not necessary that at all times all levels contribute. In any case, according to this basic concept the past evaluations of world coal resources can be displayed.

The various statements to be found in the literature about the world coal resources all emanate from the same sources. These are

1) the evaluations for the 13th International Congress of Geologists of 1913 in Toronto (McInnes et al., 1913). The evaluations were based on a worldwise questionnaire issued for the first time to the central geological institutions, for which an individual systematology of the coal resources had been designed. An analysis shows that even the most recent statistics still use many of the data established at this time.

2) the "Statistical Yearbooks" of the World Power Conference numbers 1 to 4, and number 9 (see Brown, 1936; 1948; 1960). They contain a list of the most recent national data in which the questioned organizations were provided with guidelines concerning demarcation of the resources. The lists show primarily an increasing deviation from the basic data of 1913.

3) the two volumes of the World Power Conference "Survey of Energy Resources" of 1962 and 1968 (see Central Office, 1962; 1968). They rest on a separate worldwide questionnaire for which an individual form was developed.

4) the World Energy Conference "Survey of Energy Resources 1974" (Central Office, 1974). It is distinguished from the previous one by altered guidelines for classification and by more detailed information.

A comparison of the guidelines used in the various evaluations is given in Table 1.

If the guidelines for the evaluations of the year 1913 explicitly prefer to include only "coal of economic value", they probably have only referred to the raw materials quality of coal. Simultaneously, by assuming a depth limit of 1,800 m, a value is given which no doubt lies outside the economically interesting region (McInnes, 1913). Indeed, a technology that would permit the exploitation of coal seams under the geothermal and geomechanical conditions that prevail at such depth in coal bearing sedimentary basins was unknown in the past, is not known at present, and will not be known in the near future. Further, some experts in this field believe this to be impossible for the distant future.

Table 1. Comparison of the guidelines used for the determination of world coal resources 1913-1974.

1	2	3	4	5	6	7	8	9	10	11	12	13
Source and year of publication	Limitation of total amount	Limits in depth	Limits in thickness	Degree of Certainty				Degree of mineability			Degree of recoverability	
				Category 1		Category 2		Category 1		Category 2	Category 1	Category 2
				Name	Definition	Name	Definition	Name	Definition			
International Geological Congress 1913	Coal of economic value contained in seams within the limits in depth and thickness	Group I: < 4,000 ft Group II: 4,000-6,000 ft[1] Total: < 6,000 ft[1]	Group I: 1 ft Group II: 2 ft	Actual reserves	Calculations based on the knowledge of the actual thickness and extent of the seams	Probable and possible reserves	Approximate estimate only can be arrived	Of economic value		Of economic value	A large part will be very difficult to mine and generally the loss in mining will be great	
Yearbooks 1936 to 1960 of WPC	Total amounts as are of economic value within the limits in depth and thickness	Coals: 1,200 m Lignite and Brown Coals: 500 m	0.30 m	Proved reserves	With reliable data of actual thickness and extent of seams	Further reserves (proved + further = probable reserves)	Only approximate estimates can be given	Of economic value		Of economic value	No comment	
Surveys 1962 and 1968 of WPC	Aggregate of the measured reserves and the indicated and inferred reserves	Coals: 1,200 m Lignite and Brown Coals: 500 m	0.30 m	Measured reserves	With reliable data of thickness and extent of seams	Indicated and inferred reserves	Only approximate estimates can be given	Percentage economically recoverable	Proportion expressed as percentage of measured reserves that is considered to be of economic value	No comment	No comment (see 9 and 10)	No comment
Survey 1974 of WEC (definitions of the questionnaire)	Sum of known deposits and additional resources	No limitations	No limitations	Known deposits, total amount	Based on specific sample data, measurements of the deposits and detailed knowledge of the quality or grade of the deposits	Additional resources	Estimates based on the results of geological and exploratory information including resources in undiscovered deposits in known fuel bearing areas	Known reserves, quantity economically recoverable	The portion of the total amount of known reserves considered to be actually recoverable under current economic conditions and using current mining technology	No comment	Part which can be considered actually recoverable should be listed in "known reserves, quantity economically recoverable" (see 9 & 10)	Part remaining in the ground due to extraction requirements

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[1] For the German Empire the limit was 2,000 m

The guidelines used for the evaluations in the publications of the Yearbooks of 1936 to 1960 also provided a demarcation of the total quantities involved, stipulating that only coal of economic value should be included, but evidently in a broader sense. The difference for 1913 consists essentially in the fact that the depth limit for higher ranking coal has now been reduced to 1,200 m and that for lignite and brown coal to 500 m. For these ranges of depth, simultaneously, the minimum thickness of 0.3 m has been maintained (see Brown, 1936; 1948; 1960).

The guidelines for the evaluations of the years 1962 and 1968 brought an essential change. They abandoned the rule that the total quantities of the indicated coal resources should be of economic importance. Instead, what percentage of the "measured" reserves is considered to be of economic value was to be stated separately. For the indicated and inferred resources this question was not raised. This, however, also means that according to the definition the total quantities stated in the publications of 1962 and 1968 do not consider economic mineability. Instead, they display exclusively the limits of the quality of the deposits, as they have been determined by the limits of depth and thickness (see Central Office, 1962; 1968).

The definitions of the questionnaire--and it has to be stressed that we are dealing with the questionnaire--for the evaluation of the year 1974 distinguished themselves from those of the 1962 and 1968 Surveys by the fact that they have no longer asked for the percentage considered to be of economic value but rather for the quantities of the known reserves that can be considered to be actually recoverable under current economic conditions, using current mining technology. Also this question referred only to the known reserves and not to the additional resources. Another difference is that the limits for depth and thickness were left up to the judgement of each of the contributing states (see Central Office, 1974).

Thus, in the course of time, the restrictions for the total quantities have diminished. First the rule for indicating only coal of economic value was eliminated, and in the end even the limitation with respect to depth and thickness was abandoned.

In Table 2 and, collectively, in Table 3 the coal resources separated according to continents and greater regions and nations are shown as they are stated in the various Surveys. Accordingly, this presentation covers a time span of more than 60 years. For the year 1913 two numerical sequences have been stated. In order to allow a better comparison with evaluations to be carried out in the future not only the total quantities up to a depth of 1,800 m (for the Federal Republic of Germany, up to 2,000 m) are shown but also quantities up to a depth of 1,200 m. For this purpose the information published in detail by the various countries had to be interpreted with respect to the resources in Groups I and II in accordance with the questionnaire (see Table 1), something that had not been done in the official interpretation.

Table 2. Summary of the estimates of coal resources in 10^9 metric tons--measured recoverable reserves and total amount--by continents, regions and nations in the borders of 1974. See also Brown, 1936; 1948; 1960; Central Office, 1962; 1968; 1974; McInnes, 1913.

No.	Continent or Nation	Quantities in 10^9 metric tons	1913 IGC Toronto to 6,000 ft	1913 IGC Toronto to 4,000 ft	1936 WPC Yearbook to 1,200 m	1948 WPC Yearbook to 1,200 m	1960 WPC Yearbook to 1,200 m	1962 WPC Survey to 1,200 m	1968 WPC Survey to 1,200 m	1974 WEC Survey no limit in depth
1	USSR	Measured/Recoverable 1)	-	-	309	309	247	201	249	273/137
2		Total	234	234	1,200	1,200	1,213	5,979	5,528	5,714
3	CHINA	Measured/Recoverable 1)	19	19	-	-	-	-	-	300/80
4		Total	997	997	1,012	1,012	1,012	1,012	1,012	1,000
5	JAPAN	Measured/Recoverable 1)	-	-	6	6	6	6	6	9/1
6		Total	7	7	17	17	21	21	21	9
7	Rest of ASIA including European TURKEY	Measured/Recoverable 1)	-	-	5	5	44	1	17	32/16
8		Total	101	101	27	73	136	65	120	99
9	USA	Measured/Recoverable 1)	-	-	-	-	77	81	81	364/182
10		Total	3,839	3,234	2,913	2,967	1,673	1,506	1,506	2,924
11	CANADA	Measured/Recoverable 1)	415	415	422	56	43	54	55	9/6
12		Total	1,235	1,217	815	89	86	84	85	109
13	LATIN AMERICA	Measured/Recoverable 1)	2	2	2	2	1	1	4	9/3
14		Total	32	32	3	3	7	24	27	33
15	WESTERN, SOUTHERN and NORTHERN EUROPE 2)	Measured/Recoverable 1)	245	202	263 4)	270 4)	273	277	161	225/65
16		Total	497	225	563 4)	553 4)	505	502	185	482
17	EASTERN EUROPE 3)	Measured/Recoverable 1)	29	29	37 4)	20 4)	20 4)	80	55	94/61
18		Total	227	128	93 4)	104 4)	104 4)	195	123	126
19	AFRICA	Measured/Recoverable 1)	-	-	9	9	38	26	42	30/16
20		Total	58	58	222	207	72	77	86	59
21	OCEANIA	Measured/Recoverable 1)	4	4	32	9	51	42	52	75/24
22		Total	170	169	152	54	65	111	113	200
23	WORLD	Measured/Recoverable 1)	714 5)	671 5)	1085	686	800	769	722	1,420/591
24		Total	7,397	6,402	7,017	6,279	4,894	9,576	8,806	10,755

1) Recoverable reserves are given only for 1974.

2) Austria, Belgium, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, the United Kingdom, Yugoslavia.

3) Bulgaria, Czechoslovakia, the German Democratic Republic, Hungary, Poland, Rumania.

4) In the borders of 1937.

5) Without the USSR, Japan, the rest of Asia, the USA, Africa.

Table 3. Summary of the estimates of coal resources in 10^9 metric tons--measured recoverable reserves and total amount by main regions. See Brown, 1936; 1948; 1960; Central Office, 1962; 1968; 1974; McInnes, 1913.

No.	Region	No. of Table 2	Quantities in 10^9 metric tons	1913 IGC Toronto to 6,000 ft	1913 IGC Toronto to 4,000 ft	1936 WPC Yearbook to 1,200 m	1948 WPC Yearbook to 1,200 m	1960 WPC Yearbook to 1,200 m	1962 WPC Survey to 1,200 m	1968 WPC Survey to 1,200 m	1974 WEC Survey no limit in depth
1	USSR	1	Measured/Recoverable[1]	-	-	309	309	247	201	249	273/137
2		2	Total	234	234	1,200	1,200	1,213	5,979	5,528	5,714
3	USA	9	Measured/Recoverable[1]	-	-	-	-	77	81	81	364/182
4		10	Total	3,839	3,234	2,913	2,967	1,673	1,506	1,506	2,924
5	CANADA	11	Measured/Recoverable[1]	415	415	422	56	43	54	55	9/6
6		12	Total	1,235	1,217	815	89	86	84	85	109
7	EUROPE	15,17	Measured/Recoverable[1]	274	231	300	290	293	357	216	319/126
8		16,18	Total	724	353	656	657	609	697	308	608
9	CHINA	3	Measured/Recoverable[1]	19	19	-	-	-	-	-	300/80
10		4	Total	997	997	1,012	1,012	1,012	1,012	1,012	1,000
11	OTHER COUNTRIES	5,7,13, 19,21	Measured/Recoverable[1]	6	6	54	31	140	76	121	155/60
12		6,8,14, 20,22	Total	368	367	421	354	301	298	367	1,400
13	WORLD		Measured/Recoverable[1]	714[2]	671[2]	1,085	686	800	769	722	1,420/591
14			Total	7,397	6,402	7,017	6,279	4,894	9,576	8,806	10,755

[1] Recoverable reserves are given only for 1974.

[2] Without the USSR, Japan, the rest of Asia, the USA, Africa.

According to the evaluation and region, the resources are exhibited in two columns. The first column is uniformly designated as "measured/recoverable". From 1913 until 1968 it indicates the individual quantities contained in the sources that have been used for these years according to the definitions in Table 1 (category 1). In 1913 these were the "actual reserves", in 1936, 1948, and 1960 the "proved reserves" and in 1962 and 1968 the "measured reserves".

In 1962 and 1968, according to Table 1, the "percentage economically recoverable" of the measured reserves was requested. It becomes clear from the detailed statements of the Surveys of 1962 and 1968 that only a part of the questioned countries have supplied this information. Compared with the reported measured reserves it amounted to approximately 81% in 1962 and to approximately 86% in 1968. The other countries gave either no answer or no indication that the percentage is unknown. Possibly for this reason percentages given in the Surveys have not been utilized for an interpretation with respect to the "recoverable" quantities.

For the Survey of 1974 too, only some of the authorities who replied provided the requested quantities at the time, (that is, those considered economically recoverable) instead of the percentage. With respect to the detailed values of the "known reserves, total amount" reported at this time they amounted to approximately 79%, for which corresponding values were available. In contrast to earlier Surveys the interpreting institutions have, however, uniformly replaced the missing related information in each case by listing 50% of the reported "known reserves, total amount". This was done on the assumption that on the average one can count on a corresponding percentage for the part of known reserves which can be considered actually recoverable under current economic conditions using current mining technology. Accordingly, the Survey of 1974 is the only one that indicates corresponding quantities (Central Office, 1974). They are given in the second figure of the column "measured/recoverable", but only for this one year in question.

The second column "total" shown in Tables 2 and 3 for each region contains, furthermore, the reported total quantities for each of the regions concerned at the stated moment. The value in the Yearbook 1936 has been corrected according to the later rectification of the World Power Conference. Originally, the total resources of China were magnified 10 times by the accidental insertion of an extra zero.

The total quantities, according to Table 3, are graphically illustrated in Figure 12. From this it becomes evident that by far the largest quantity of coal resources is to be found in the regions of the USSR, the USA, Canada, Europe, and China. And thus it is situated in the northern hemisphere. Secondly, it becomes evident that the increase of information about the world resources since 1913 is only owing to the USSR. Comparing 1913 with 1974, the indicated total resources of the regions US and Canada have decreased while those of the rest of the world

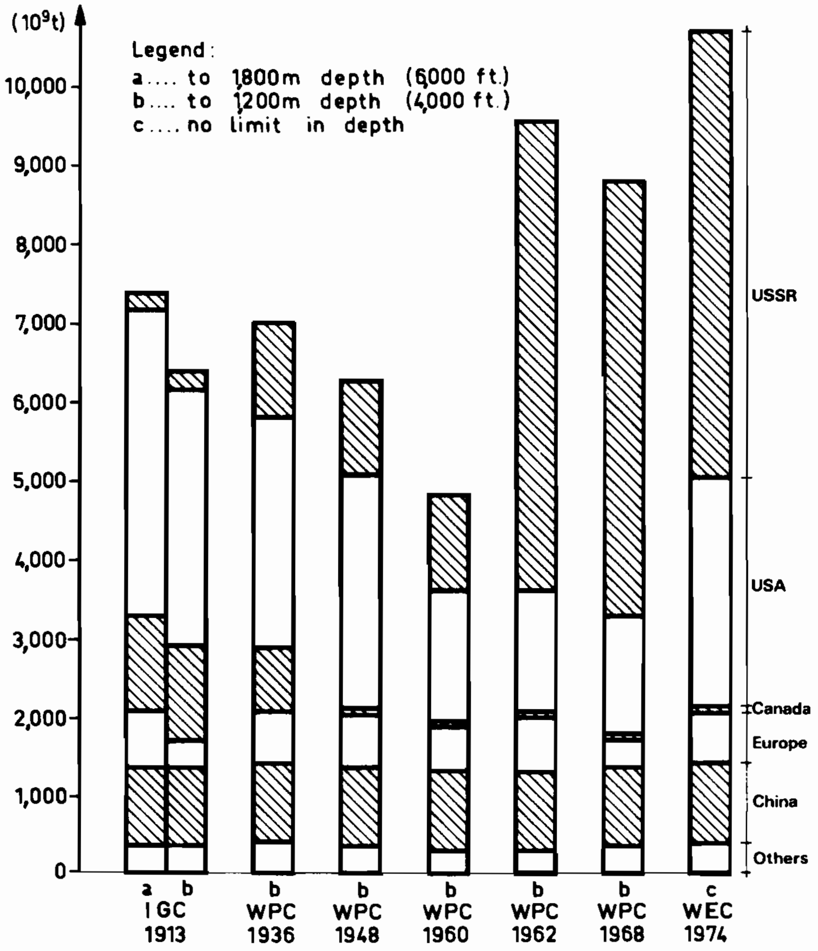


Figure 12. World coal resources, total amounts.

have changed relatively little. This holds true even if one considers for 1913 only for those known resources which had been determined up to a depth of 1,200 m.

The picture becomes even clearer if initially only the period 1913 to 1968 is considered. In this case, with the exception of the USSR, the resources of the various regions have remained either practically unchanged, as for China and for the rest of the world, or they have decreased, as for the US and Europe. For the total quantity without the USSR, a reduction by almost one-half becomes apparent. This reduction results mainly from the US and Canada.

The increase of the indicated resources which have been recorded between 1968 and 1974 can be attributed almost exclusively to an almost doubling of the resources of the regions of the US and Europe. An analysis of the details shows that for Europe, in this case, mainly the elimination of the depth limit was decisive. For example, in 1974 the depth limit for "known reserves" for France was 1,250 m, for the Netherlands 1,400 m, and for the FRG 1,500 m. An analysis of the figures from the United Kingdom and the FRG shows furthermore that the same holds also true in both countries for "additional resources". For the US and Canada the quantities of 1948 were again indicated for 1974 and they are, in any case, less than those of 1913.

The development of the "measured/recoverable" reserves becomes evident from Figure 13. The lower part states the quantities indicated according to the evaluation in Table 3. For 1974 both "measured" and "recoverable", which have been discussed, are named. For a better understanding, the sequence of the regions has been rearranged somewhat.

In 1913 "measured" reserves only were reported by Canada and Europe and, to a minor extent, also by China, Latin America, and Oceania; the latter two are contained under the heading "other countries". Data on the USSR exist only from 1936, on the US only from 1960. Figures for China resumed in 1974. It can be seen, therefore, that the increase of the entire "measured" quantities indicated from 1913 to 1974 are mainly caused by these "delayed reports" and only to a smaller extent by the increase of quantities for Europe and for the "other countries". The quantities for Canada, the country that played host to the 12th International Geological Congress of 1913, have decreased considerably.

The increase of the measured reserves ("known reserves, total amount") of the US in the years between the World Energy Conference of 1968 in Moscow and that of 1974 in Detroit, by a factor of 4.5, is no doubt remarkably large. The increase for Europe between 1968 and 1974 can, without question, to a large degree be traced back to the omission of the depth limit already mentioned.

The upper part of Figure 13 presents a supplementary comparison of the "economic reserves" from 1936 to 1974. With the exception of China, relatively new and complete data were available from all regions mainly for 1960 and after. However, it remains an open question whether the definition "of economic value" for 1936 to 1960 has been understood totally or partly as "economically recoverable", and whether it can be understood in that way, as it is clearly the case in the later Surveys. In order to obtain values for the years 1962 and 1968, the author has converted the figures given at that time as percentage of economic recoverability into terms of quantity. For those countries that have not given related information, the average of the other countries of their region has been utilized.

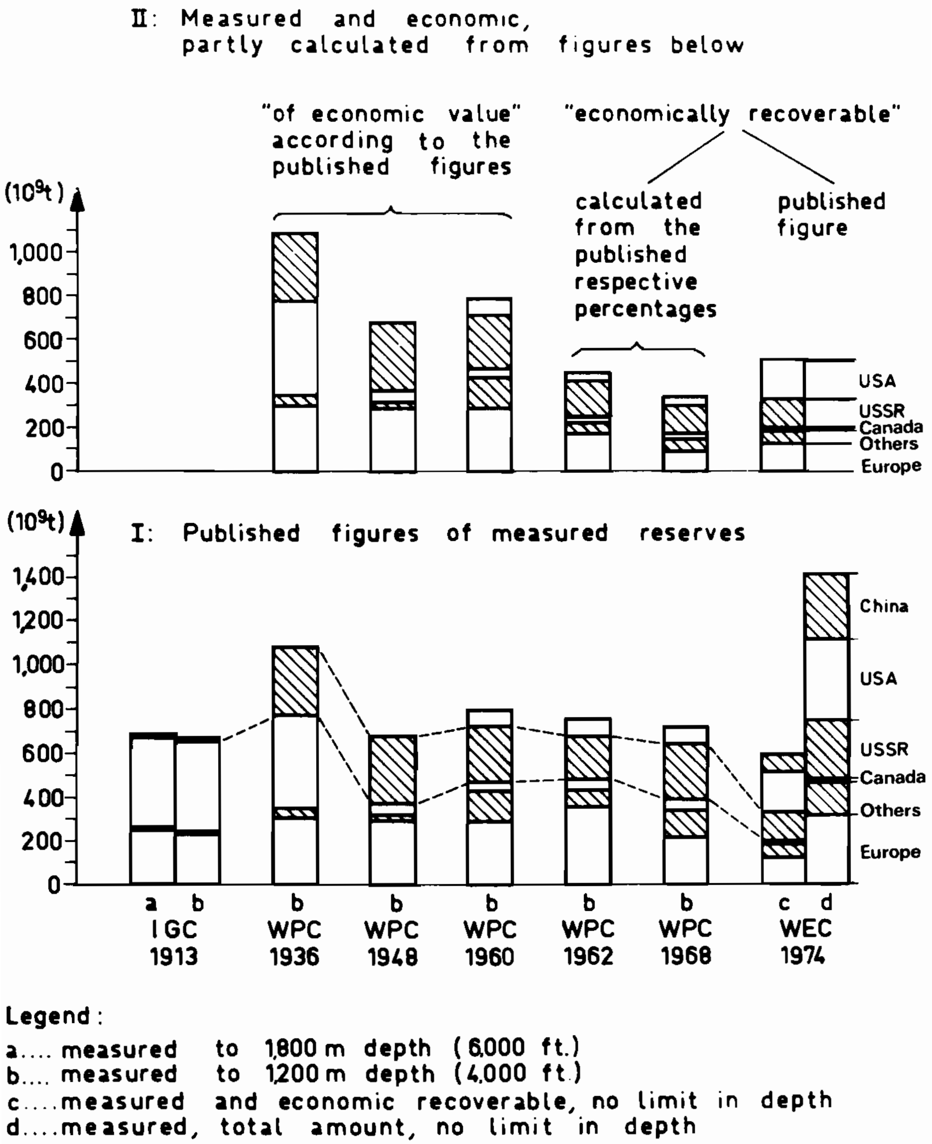


Figure 13. World coal reserves, measured and economic.

The data on the reserves, according to the upper part of Figure 13, are also shown in Table 4. Table 4 shows additionally the coal production of the various regions in the year of publication of the individual reserves, and also the life index (only the resources of the Survey of 1974 have been compared with the production of the year 1973) which has been calculated on this basis. In the life index, the partly recurrent and partly stagnant trend of the "measured reserves" is expressed more distinctly than in the illustration. Only the US is an exception because of the already stated large increase of the "measured reserves" in the Survey of 1974.

By summarizing, one will see at the beginning that the explanations for Figures 12 and 13 allow us to recognize an important condition which is mostly overlooked in the evaluation of data pertaining to resources. Only with respect to the "measured reserves" it is common to actually indicate separately a "recoverable" portion. The "degree of recoverability" employed refers mainly to technical reasons and also to the existing economic conditions. In contrast to this, as far as additional resources which have been estimated much more roughly are concerned no reductions are made, although this is urgently needed here. Indexes on the duration of the total resources must, therefore, lead to misleading values.

Further, a critical evaluation of the development of the indicated coal resources of the world since 1913 leads us to the conclusion that the first appearance is deceiving. If one subtracts the value for the USSR one realizes that 1974 shows less total quantity than 1913 or 1936. In many regions the quantity remained stagnant. At the same time, the data on the known resources of economic importance for the year 1974 represent the smallest quantities shown up to now in this connection in the Surveys.

Even if one includes the large quantities of the USSR the total resources that have been indicated according to Figure 12 have only increased by approximately 45% between 1913 and 1974, while world coal production has doubled. On the other hand, the data on the resources of almost all other important mineral raw materials have developed essentially more favourably. Thus, for example, total world iron ore resources have increased from $146 \cdot 10^9$ t, a figure which had been established for the entire world at the 11th International Congress of Geologists in Stockholm in 1910 (see Böker, 1911), to the present $782 \cdot 10^9$ t, following a corresponding UN Survey in

Table 4. World coal reserves, measured and economic, production in the year of their publication and life index. (See Brown, 1936; 1948; 1960; Central Office, 1962; 1968; 1974).

		Measured reserves of economic value			Economically recoverable reserves calculated from given percentages of measured reserves in		Economically recoverable reserves directly given in
		1936 WPC Yearbook	1948 WPC Yearbook	1960 WPC Yearbook	1962 WPC Survey	1968 WPC Survey	1974 WPC Survey
USA	Reserves 10^9t	-	-	77	52	58	60
	Production 10^6t	448	508	393	247	300	316
	Life Index years	-	-	196	211	194	190
USSR	Reserves 10^9t	309	309	247	410	300	329
	Production 10^6t	127	261	513	1,891	1,991	2,082
	Life index years	2,433	1.184	482	217	151	158
CANADA	Reserves 10^9t	422	56	43	451	341	511
	Production 10^6t	14	17	10	2,289	2,495	2,625
	Life index years	30,143	3,295	4,300	197	137	195
EUROPE	Reserves 10^9t	300	290	293	171	90	126
	Production 10^6t	60	841	1,062	1,118	1,087	1,080
	Life index years	95	345	276	153	83	117
OTHER COUNTRIES	Reserves 10^9t	54	31	140			
	Production 10^6t	134	146	216			
	Life index years	403	213	649			
TOTAL WITHOUT USA	Reserves 10^9t	1,085	686	723			
	Production 10^6t	1,035	1,265	1,801			
	Life index years	1,049	543	402			
TOTAL	Reserves 10^6t	1,085	686	800			
	Production 10^6t	1,483	2,773	2,194			
	Life index years	732	387	365			

Note: The production figures are given for the year of the publication of the Yearbook Surveys for 1973 production which is mentioned in the 1974 Survey.

Sources for production: Unternehmensverband Ruhrbergbau (1961), *Die Kohlenwirtschaft der Welt in Zahlen* (Verlag Glückauf, Essen).
Bischoff, J. and W. Gocht (1970), *Das Energiehandbuch* (Verlag Friedrich & Sohn, Braunschweig).
Reintges, H. et al. (1974), *Jahrbuch für Bergbau, Energie, Mineralöl und Chemie* (Verlag Gluckauf, Essen)

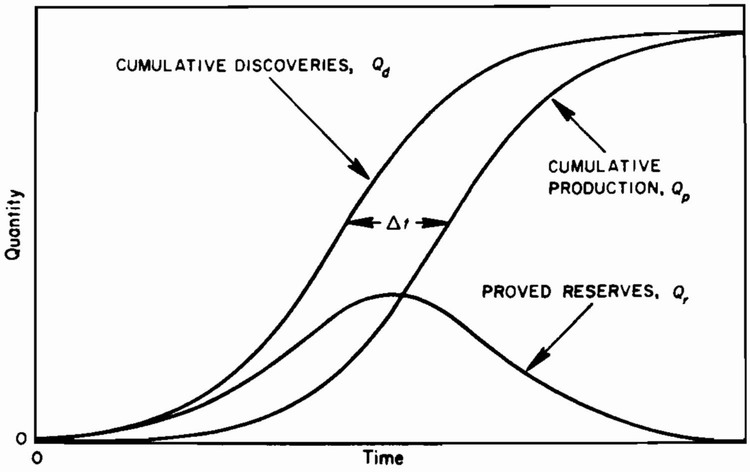
1970 (see Gocht, 1974). This means a multiplication by approximately five. In the same period the petroleum resources have increased by more than a multiple of 15 (see Central Office, 1974; Preussische Geologische, 1925).

In particular, a comparison of the development of the "reserves" in the sense of McKelvey and that of the American terminology shown in Figure 5, is of interest here. For the years since 1948 the related data for coal can be taken from Table 4. Compared with this, in the same period--as has been determined by Govett and Govett (1974)--the reserves of iron ore of the world have multiplied by 13, chromium by seven, bauxite and manganese have approximately quadrupled, and copper has increased by a multiple of three. Reserves of silver, lead, and zinc have also doubled within the 25 years considered. A decrease has occurred only for tin and tungsten, both of which are indeed considered worldwide to be becoming scarcer.

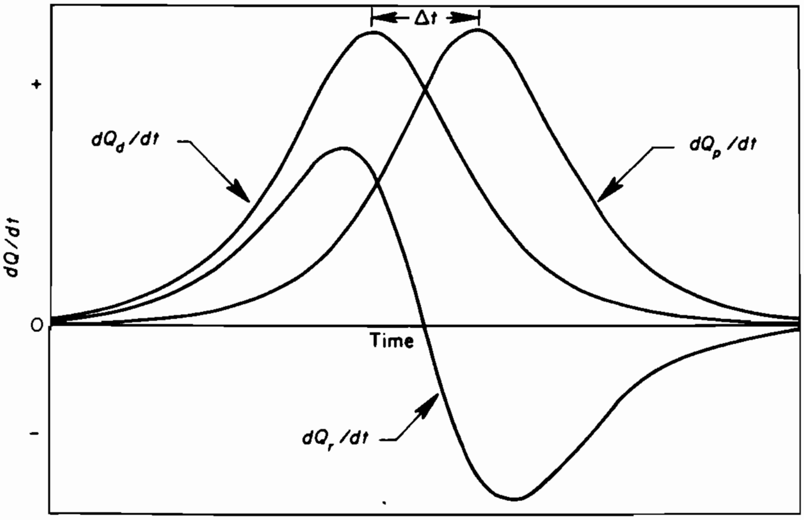
Now let us ask what influence past coal production has exerted on the development of the world coal resources and reserves. M. King Hubbert has reported on the basic relation between the discovery and exhaustion of a finite resource by using the development of a petroleum resource during a full cycle of production as shown in Figure 14. The area under the curves of the rate of discovery, dQ_d/dt, and of the rate of production, dQ_p/dt, must accordingly be equal to the quantity of the total resource. The known portion, Q_R, of a resource that is still available at any given time decreases if the rate of production is higher than the rate of discovery. The rate of discovery decreases when the greater part of the resource has already been discovered. The subsequently developing exhaustion of the resource leads, after a certain period, to a decline of production.

The decrease and the stagnation of coal resources indicated in Figures 12 and 13, except for the USSR, therefore, suggests the assumption that development is to be already found on the right side of Hubbert's curves. The assumption that in any case the major portion of the coal resources in the world is already known can, by the way, also be derived from geological considerations, especially on the basis of relatively simple coal geology, as well as in connection with the theory of the log normal distribution concerning the extent of coal deposits.

The partly found decrease of resources, however, is owing to past production only to a small degree. The coal production of the world to 1974 is estimated to be approximately $130 \cdot 10^9$ t (see Central Office, 1974). According to the assumed recovery factor--which I estimate to be lower than the one given primarily stated in the literature as an average magnitude of



Generalized form of curves of cumulative discoveries, cumulative production, and proved reserves for a petroleum component during a full cycle of production. Δt indicates the time lapse between discovery and production.



Relations between rate of production (dQ_p/dt), rate of proved discovery (dQ_d/dt) and rate of increase of proved reserves (dQ_r/dt) during a full cycle of petroleum production

Figure 14. Relations between reserves, rate of discovery and rate of production according to M. King Hubbert (1969).

50%--this corresponds to a consumption of the reserves in an amount from 260 to $400 \cdot 10^9$ t. It is estimated that about 75% to 80%, or 200 to $300 \cdot 10^9$ t fall within the period after 1913. In contrast to this, the decrease in resources down to a 1,200 m depth represents several $1{,}000 \cdot 10^9$ t. As shown in Figure 12, this took place from 1913 to 1968, and occurred primarily in the US and Canada. Nevertheless, the consumption of reserves reaches the magnitude of the resources indicated for Europe.

The picture changes slightly if one considers the "measured reserves" according to the lower part of Figure 13. They reach the same order of magnitude as the past consumption of reserves so that the latter is of greater importance here. The same holds true for the "recoverable" reserves in the upper part of Figure 13 and in Table 4. For a comparison, however, only the years after World War II, especially those since 1960, can be used because sufficient information exists for these periods only. The alterations of the related quantities, according to Table 4, are accompanied by an accumulative production between 1960 and 1973, in the amount of approximately $35 \cdot 10^9$ t, corresponding to a consumption of reserves of 70 to $100 \cdot 10^9$ t. In this case too, the reductions which have occasionally occurred do exceed the quantities produced.

The main reason for the presented alterations concerning the indicated resources and reserves is, therefore, not to be found in depletion through production but in a correction of earlier estimates. The noticeable reduction of the quantities given for Canada, with respect to "measured" as well as "total", has already been pointed out. Other characteristic examples exist in the case of the FRG, the UK, and the Republic of South Africa. The corresponding analyses can be rendered here only in the form of the result.

6. VIEWPOINTS ON THE ASSESSMENT OF COAL RESOURCES AND RESERVES

To consider coal resource and reserve assessment let us begin with a short presentation of the viewpoints themselves and their use with the subsequent discussion on the data of the great regions of the USSR, US, and China. Basically, I have set out from the viewpoint of the "mining concept". Accordingly, only economic and subeconomic quantities can be considered as resources. In the Canadian proposal already cited, the subeconomic quantities are those which are estimated with more than 10% probability to be, in principle, economically mineable within the next 25 years (see Department of Energy, 1975).

Too, the already indicated problem of the feasibility of speculative resources has to be solved here. This is also a problem for the Canadian proposal, because--depending on the region--in Canada seams with a minimum thickness between three and five feet and a maximum depth between 1,500 and 4,500 ft are supposed to be considered for inclusion in subeconomic coal resources. But how should this be done for quantities surmised in virgin areas about which no sufficient data exist? The

Canadian solutions evidently attempt to circumvent this question by acknowledging only a regionally-limited relevance or little relevance in regard to the pertinent quantities in Canada.

This problem can, in my opinion, generally only be solved if, for the incorporation of quantities in the category of resources and for the degree of certainty, the limits are defined as clearly and as quantifiably as possible, for example, as tried with respect to the degree of feasibility. Accordingly, only such quantities should be considered coal resources for which the number, thickness, and depth of seams can be predicted with the same accuracy as for "reserves". Correspondingly, we should be dealing here only with measured, indicated, and inferred deposits and not with hypothetical or speculative deposits as in Figure 5.

Estimates that go beyond this--and there are quite a number of them--should be included in the resource base. In this manner the coal resources do not remain open-ended in the direction of decreasing certainty. This postulation should not fail because of the fact that it will be essentially more difficult to fullfill for all categories other than coal deposits. Here, one should utilize fully the special property of coal deposits. Furthermore, with this an approximation for evaluating uranium and thorium resources can be obtained. This author proceeds accordingly.

As expressed previously, only direct extraction for coal mining comes into question in the near future. In my opinion, in situ gasification in the foreseeable future, that is, during the next 25 to 30 years, will eventually become a technically fully developed process for some geological conditions, that is, for deposits especially suited to its application. It will, therefore, in all probability, remain restricted to quantitatively unimportant cases. Even in the long run I do not, for technical reasons, think the prospects will be very good, especially because of the dependence on very special geological conditions. The technical possibilities for coal extraction depend on different factors. Of these, generally only depth and thickness are named in connection with the data on coal resources. The other structural characteristics of the deposits, and particularly the tectonic conditions are, however, at least of equal importance.

Methods for the direct extraction of coal are open pit mining and underground mining. Open pit mining, because of its accessibility, is technically less complicated and, therefore, cheaper. The limit between the two methods is mainly determined, on the one hand, by the thickness of the overburden D, and, on the other hand, by its own thickness K, as well as by the ratio of these two magnitudes D:K. Technical development has permitted greater mining depths. Depending on the other conditions depths today, already, reach a maximum D:K ratio of from 10:1 to 30:1. Nevertheless, underground mining still prevails worldwide as the method of coal mining.

For underground mining, depth is important mainly because as it increases, rock pressure, rock temperature, and, as experience shows, tectonical deformation and destruction of the deposits also increase. Therefore, the depth which can be controlled by the technology available today and in the foreseeable future is supposed to lie between 1,200 m and a maximum of 1,600 m. Whatever value can be reached finally, there can be no doubt that mining approaches a genuine technical limit with increasing depth.

Since the directions for evaluations from the 13th Geological Congress in 1913 (McInnes, 1913), a minimum seam thickness of 0.30 m has been considered as a further limit on the exploitability of coal. Considering that coal at that time could only be recovered manually in the stopes, this limit was, after all, determined by the dimensions of the human body. Furthermore, it could be reached only by manual labour with extreme exploitation of the adaptability of man to difficult conditions. Such labour becomes increasingly unthinkable not only for economic reasons, but also for social and humane reasons. Therefore, the future of coal mining belongs, without question, to machines even where this is not yet the case. Indeed, in the course of time, cases which have always been relatively unimportant, that is, those where seams of a thickness of a few tens of centimeters have been mined, have become even fewer. At the same time, the technically required measurements and the adaptability of machines which are less flexible in comparison to man have become increasingly important for the minimum thickness of coal seams that can be mined (Fettweis, 1962).

The minimum thickness of seams that can be recovered with the technology available today and in the foreseeable future amounts in the extreme case to 0.60 m. But even this is essentially only a theoretical value. Actually, in the world coal mining industry, seams with a thickness of less than 0.70 m and usually not under 1.00 m are hardly mined anymore. This is valid with respect to the adaptability of machines for underground mining as well as for open pit mining.

As already stated, owing to tectonic stresses the coal seams originally deposited in a flat form can be inclined and folded and, thus, partly tilted and extensively torn apart. Accordingly, quite different structural conditions exist in some circumstances even at the same depth and thickness. Attention should be paid to Figure 2. Mineability is primarily diminished by the fact that only larger tectonic separations can be shown in the illustrations, and also by the fact that they are accompanied and supplemented by an abundance of similar occurrences on a smaller scale. The thinner the seams are the more this takes effect. Related and basic evaluations of Ehrhardt exist for this situation in the Ruhr Valley (1967).

The disadvantage of tectonic disturbances--similar to that for thin seams--has grown even more, since coal recovery has been taken away from the human labour force and handed over to the more rigid mechanical devices which are not as adaptable. Accordingly, at the present level of underground mining technology, and for the foreseeable future, only those portions of seams still essentially undisturbed are exploitable. The same holds true, in principle, for open pit mining.

This situation is aggravated by another situation. Up to now the possibilities for mechanized recovery were mainly restricted to undisturbed portions of seams in almost exclusively flat positions. In contrast to this, it has only been possible in exceptional cases--owing to technical difficulties--to replace manual recovery in a steep bedding, that is, in folds and steep dipping seams, with fully developed mechanical methods. Accordingly, the recovery of steep dipping coal seams has become rare in many places of the world, as for example in American anthracite mining or in hard coal mining in the Ruhr Valley. Only the future will tell whether the expectations of the investigations of hydromechanical recovery, which have been successfully locally, will become true. Even these techniques will, in any case, require deposits that are as tectonically undisturbed as possible.

As the preceding discussions have shown, in the course of transition from manual to mechanical recovery a reduction of recoverable resources has occurred because of today's technology. Modern mechanized recovery techniques are indeed essentially less flexible than earlier techniques, something that has already been demonstrated by Armstrong and Dunham for the British coal mining industry (Armstrong, 1972; Dunham, 1974) and therefore today's techniques permit recovery of deposits only under especially favourable geological conditions.

To be sure, there is also a technical development which has at least partly compensated the losses caused by this. It can be found in the progress of the techniques of mineral beneficiation, which today allow us to process coal that is essentially more impure than a few decades ago, and to make it marketable.

In earlier resource evaluations only coal seams with an ash content of, for example, not more than 30% by weight have been inserted. This percentage today can be raised to at least 50%. In the Republic of South Africa currently even a very thick seam is being planned for recovery by open pit mining (Waterberg), the raw coal from which will probably contain only about 25% pure coal. To be sure, this seam must be considered an exceptional case because of its extremely high portion of non-combustible components. As a rule, the content of noncombustibles in the coal seams based on the dehydrated substance is below 50%.

In each case, for the evaluation of in situ resources, one must employ a recovery factor owing to mining and processing in order to obtain the actually useable coal quantities and to arrive at a realistic estimate of the existing possibilities.

Correspondingly, this does not only concern the "measured reserves" but also the additional resources. In this connection we can in no way agree with the frequent objection that resources which do exceed the reserves are generally too little known to ascribe a certain degree of recoverability to them. For the same reason one can, of course, demand that a relatively lower degree of recoverability should in any case be assumed in order to determine the recoverable amounts with a sufficient degree of certainty. Here, wrong conclusions that can otherwise be drawn from lifetime indices should be mentioned. Obviously, recoverable amounts can only be determined on the basis of amounts in situ.

Generally in the literature an average recovery grade of 50% is used. According to my considerations, considerations which, however, cannot be presented here in detail, this is too little, rather than too much for a worldwide average.

7. COAL RESOURCES OF THE FEDERAL REPUBLIC OF GERMANY, THE UNITED KINGDOM AND THE REPUBLIC OF SOUTH AFRICA

After these explications the development of the data on the resources for the three countries, the Federal Republic of Germany, the United Kingdom and the Republic of South Africa, should now be considered. The pertinent data, according to the sources and scheme of Tables 2 and 3, are listed in Table 5.

At first, two statements from the latest OECD report should be cited (1974) to characterize the rather confusing situation in the cases of the European states mentioned: "The coal resources of Europe of about $500 \cdot 10^9$ t have probably been the most thoroughly explored with the highest degree of proof" and "the greatest potential reserves of coal are in the Federal Republic of Germany, approximately $260 \cdot 10^9$ t (with the largest brown coal reserves in Europe), followed by about $170 \cdot 10^9$ t of coal in the United Kingdom" (OECD, 1974).

For the actual situation in the FRG one has to distinguish between hard coal and brown coal. Hard coal can only be recovered by underground mining, brown coal in open pit mining.

Hard coal lies in zones of existing mines, in zones which are not yet developed and, to a minor degree, in zones of closed mines. The technically mineable quantities in seams above 0.60 m and down to a depth of 1,500 m amount to approximately $25 \cdot 10^9$ t in situ according to the majority of estimates, among which are also my estimates (Fettweis, 1954a; 1954b; 1954c; 1955a; 1955b; 1962; 1964; Fettweis and Stangl, 1975). Approximately $18 \cdot 10^9$ t of these are situated at a depth down to 1,200 m. The portion of this amount which was economically mineable and recoverable under the technical and economic conditions of the past decade came to less than half. The relevant data range from 25% to about 40% (Fettweis, 1975; Palm, 1974; Reuther, 1975). It might be that the improved economic

Table 5. Estimates of resources in 10^9 metric tons--measured recoverable reserves and total quantities--for the Federal Republic of Germany, the United Kingdom and the Republic of South Africa (see Brown, 1936; 1948; 1960; Central Office, 1962; 1968; 1974; McInnes, 1913).

No.	Nation	Quantities in 10^9 metric tons	1913 IGC Toronto to 6,000 ft	1913 IGC Toronto to 4,000 ft	1936 WPC Yearbook to 1,200 m	1948 WPC Yearbook to 1,200 m	1960 WPC Yearbook to 1,200 m	1962 WPC Survey to 1,200 m	1968 WPC Survey to 1,200m	1974 WEC Survey no limit in depth
1	Federal Republic of Germany[1)]	Measured/ Recover-able[2)]	90	66	109	109	129	133	132	99/39
2		Total	251	96	336	336	286	293	132	286
3	United Kingdom	Measured/ Recover-able[2)]	141	135	129	130	128	127	12	99/4
4		Total	189	181	176	172	170	169	15	163
5	Republic of South Africa	Measured/ Recover-able[2)]	-	-	8	8	37	21	37	24/10
6		Total	56	56	205	205	70	63	72	44

[1)] Within the borders of the Federal Republic of Germany for 1913, 1960, and later; within the borders of 1937 for 1936 and 1948.

[2)] Recoverable reserves are given only for 1974.

situation of the coal mining industry will raise this value again to 50%. This may also be supposed for the depth above 1,200 m if one considers the foreseeable technical and economic development. For technical reasons one cannot expect a still higher value. Accordingly, the amounts actually recoverable at the present and foreseeable state of technology, amount to a maximum of $12.5 \cdot 10^9$ t to a depth of 1,500 m. Nevertheless, this is sufficient for more than 100 years at the present rate of production.

Until two years ago, $10 \cdot 10^9$ t of the total substance of brown coal, geologically assumed at approximately $60 \cdot 10^9$ t, was considered economically mineable and recoverable (Gärtner, 1974). The development of open pit technology, on the one hand, and the increase of the energy price, on the other, have recently led to estimates that in the future approximately $35 \cdot 10^9$ t can be considered economically mineable (Gärtner, 1975). This would correspond to $28 \cdot 10^9$ t of economically mineable and recoverable coal (equivalent to about $9 \cdot 10^9$ t of hard coal) considering a recovery factor for open pit mining of approximately 80%.

Accordingly, the total recoverable coal resources for the FRG are of a magnitude of approximately $40 \cdot 10^9$ t out of which more than two-thirds is brown coal. In any case, of these quantities a large portion is only inferred. This holds true for many reserve fields and for the greater depths involved with hard coal. Therefore, it is not impossible that after future explorations actual quantities will decrease, for instance because Ruhr Valley seams tend to become impure towards the north. Not enough is known about these seams at this time. I, therefore, estimate the resource values to be too high rather than too low.

As a comparison with Table 5 shows, the quantity of resources evaluated in this way has the same order of magnitude as the quantity that is shown there as "recoverable reserve". The data on the total amounts in Table 5--which are, depending on the moment considered, seven to nine times greater--are in this respect nonrealistic values of an assumed coal substance down to a 2,000 m depth, including nonfeasible quantities. They can finally be traced back to the related evaluations of the year 1913, which have been taken over each time and modified by more or less distinct additions.

For the United Kingdom the situation is similar. Armstrong reported this in detail in 1972. The greater total quantities occurring in the Surveys of the World Energy Conference until now obviously date back to the estimates of the Royal Commissions in the years of 1871 and 1905. In contradiction to the original intension, they have frequently been presented as certainly proved quantities.

The total resources of economically mineable coal which can be recovered by mines in use today as well as those possible in the future actually have been estimated (Armstrong, 1972) in the amount of 4 to $6 \cdot 10^9$ t. According to Dunham (1974) they amounted to just $3.5 \cdot 10^9$ t in 1974, which means a less than 30 year supply at the current rate of extraction. This can mainly be traced back to the fact that "the old method of hand working, by which thin seams and disturbed ground could be tackled, must now be regarded as socially unacceptable. Modern machine methods including mechanical prop-setting can only be used in areas where there is a low inclination of the strata, if any, and a minimum of faulting".

For the United Kingdom the total "resources of interest" are, according to the concept applied here, of the same order of magnitude as those indicated in the WEC Survey as known recoverable reserves. This is just about 2.5%, if one relates them to the total quantities indicated there.

The development in the Republic of South Africa is of interest because it is a less explored region. The reduction of resources since 1936 expressed in the data of Table 5 represents a sequence of steadily improved knowledge which was reported in a careful evaluation of the South African Coal Advisory Board in 1969. This report, which is still authoritative today, indicates only $16.5 \cdot 10^9$ metric tons as saleable reserves and saleable potential reserves. It is explicitly stated that another $8.2 \cdot 10^9$ t of resources in situ can be considered as economically extractable neither today nor in the foreseeable future. Besides, they would increase the total quantities only to approximately $20 \cdot 10^9$ t if one considers an extreme degree of recoverability of 50%. This represents approximately 10% of the earlier estimate of $205 \cdot 10^9$ t also mentioned in this report. To quote: "It now appears that the Republic of South Africa's reserves and resources of coal are not as extensive as is commonly accepted". The decline has occurred despite the discovery of large new resources in Transvaal, especially the Waterberg and the Soutpansberg fields.

According to Figure 3 the changes that have apparently occurred in the three countries are owing to a correction of the degree of certainty as well as of the degree of deposit useability. Above all, the basic concept has primarily changed. Reductions caused by a cautious evaluation of the certainty and mineability were greater than simultaneous increases owing to new discoveries and to improvements that have partly been made with respect to resources that can be extracted in open pit mines. The statements on resources of the large coal regions in the world are, last but not least, to be judged in the light of these experiences. This will be attempted subsequently.

8. ON THE RESOURCES OF THE USSR, THE USA AND CHINA

For the USSR one should first of all refer to its specific resource classification system and the changes that were made in it in 1960. It certainly was not accidental that the large increase in total quantities between 1960 and 1962 (as it is shown in Figure 12 and Table 2) coincides with the introduction of a category of prognostic resources. A corresponding number of new discoveries would indeed not be conceivable in such a short time.

Table 6 provides more information. In it, more detailed Soviet data on resources in the various categories from the year 1969 (UN, 1969) are compared with related data of the WEC Survey of 1974. All in all, the geological resources for 1969 are indicated at $8{,}669 \cdot 10^9$ t. Of this, however, only about $700 \cdot 10^9$ t are indicated as balance and out of balance resources. Correspondingly, $7{,}969 \cdot 10^9$ t fall to prognostic resources. As the comparison shows, the additional Soviet resources in the Survey, therefore, have to be, to the largest degree, prognostic resources within the meaning of the Soviet classification system. This classification, however, explicitly leaves unanswered the question as to the possible useability of prognostic resources. Accordingly, this applies also to that half of the world coal resources of the WEC Survey of 1974 which is made up of these Soviet resources.

Melnikov too mentions the total geological resources of the USSR as $8{,}669.5 \cdot 10^9$ t. According to his data, they refer to a depth down to 1,800 m, and they contain seams of hard coal with a minimum thickness of 0.3 m and of brown coal with a minimum thickness of 0.6 m (Melnikov, 1972).

According to further data provided by Melnikov, $4{,}392 \cdot 10^9$ t, that is, more than half of the prognostic resources of the USSR, fall in the two regions of Tungusski and Lena in the north of Siberia. Of these, however, less than 1% are known as balance resources of categories A, B, and C1, and only 0.7% belong to category C2, that is, those already with a slight degree of certainty. It can also be seen from Kusnetzov's (1973) detailed presentations of coal resources in the USSR that the two regions have been explored geologically only to a very small degree. For the most part geological maps on a scale of 1:1,000,000 are the only ones that exist. The situation is similar in regard to other deposits as, for example, those of Taimyr.

In my opinion it is probable that a further investigation of the Soviet deposits will likewise lead to a reduction of prognostic estimated quantities, as has happened in other parts of the world, from Canada and Europe to the Republic of South Africa. For this, not only the spaciously drawn limits of the quality of deposits, with a thickness of 0.3 m and a depth of 1,800 m, but also Soviet experiences arrived at in other places up to now are evident. As reported by Stammberger (1966) referring to a work by Mirlin (1964), in the course of time 4,000 deposits--that is, 30% of all those managed by geological funds of the USSR--had to be obliterated from the balance of resources owing to a lack of industrial relevance. Moreover, according to Strishkov et al. (1973), they have in the meantime already undertaken a correction of the total geological resources of coal from $8{,}669.5 \cdot 10^9$ t to $6{,}880 \cdot 10^9$ t. Finally,

Table 6. Various data of the USSR coal resources.

According to United Nations, Economic Commission for Europe, Coal Committee, Symposium Warsaw 1969 (UN, 1969)			According to the World Energy Conference Survey of Energy Resources 1974 (Central Office, 1974)	
		10^9 t	10^9 t	
1 a	Balance resources A, B, C 1	261.4	273.2	Known reserves, total amount
1 b	Balance resources C2	262.3	5,440.5	Additional resources
1 a + b	Balance resources	523.7		
2	Out of balance resources	177.2		
3	Prognostic resources	7,968.6		
1 + 2 + 3	Geologic total resources	8,669.5	5,731.7	Total resources

in 1972, Melnikov too specified that part of the total geological resources that can be considered conditionally accessible for recovery in connection with the statement of the total energy resources of the USSR as only $2,200 \cdot 10^9$ t (Melnikov, 1972a; 1972b).

Consequently, considerations concerning the prognostic resources of the USSR correspond to a concept that I introduced at the beginning as the "geologic-mineralogic concept". Within the meaning of the concept represented here, prognostic resources can, therefore, only be included in the "resource base". As "resource" one has to consider instead the sum of the balance and out of balance resources, amounting to approximately $700 \cdot 10^9$ t according to Table 6.

This also corresponds to the Soviet view discernible in the literature. Thus, for example, the coal resources of the USSR that can be open pit mined amount to $166 \cdot 10^9$ t, according to the detailed presentations by Kusnetzov, and they are to be found almost exclusively in the Asiatic part of the country (1973). On the other hand, it is stated that resources that can be open pit mined make up about 25% of the total resources of the USSR (UN, 1969). Furthermore, obviously, the data that have been used to establish a life span of about 1,000 years for the planned coal production of the country--the data of 1968 are increased 1.4 fold--are based only on the balance and out of balance resources (UN, 1969).

The resources that can be open pit mined will increase in the course of technical development. But it remains an open question whether the Soviet data have already taken into consideration the drastic reductions with regard to the resources for underground mining which, as a result of the technical development, have contributed to the reduction of resource quantities in the FRG and the UK.

According to the Soviet guidelines, resources are given in situ. If one takes as a basis an average degree of recovery of 50%--as done by the WEC Survey for "known reserves, total amount" reported by the USSR--one obtains recoverable resources of which can be compared with those of the FRG and the UK, which amount to about $350 \cdot 10^9$ t. This is, unquestionably, a very large quantity. Taken from the total quantities of the WEC Survey they, however, amount to only 6%.

In view of the detailed guidelines for the classification system one has, without question, to assign great accuracy to the indicated balance resources of categories A, B, and C1, and, therefore, also to the "known reserves" of the USSR in the 1974 WEC Survey as they are indicated under the heading "measured/recoverable" in Tables 2, 3, and 4. Their part of the total quantities of interest treated here amounts to about 40%.

The last WEC Survey, 1974, shows the coal resources of the US to be $2{,}924 \cdot 10^9$ t. This is in accordance with the "total estimated remaining coal resources of the United States, January 1, 1972"; this information was published by Averitt in US Geological Survey, Professional Paper 820, "United States Mineral Resources" (1973, with the deduction of the 1972 coal output. According to the introductory elaboration of Brobst and Pratt (1973) the basis of corresponding investigations is explicitly--as we have already come to see--the concept of "geological availability" which I have termed the "geologic-mineralogic concept". A closer analysis of the resource figures leads to the same result. On the other hand, the respective investigations are also owing to the same considerations which already were used by Averitt in his basic work in 1968 (Averitt, 1969) and which, according to Figure 5, also became part of the guidelines of the American classification system for coal resources and reserves in 1974 (USA Joint Geological Survey, 1974).

The indicated quantities are, therefore, made up of $1{,}433 \cdot 10^9$ t of identified resources and of $1{,}491 \cdot 10^9$ t hypothetical resources, the latter making up somewhat more than half the quantity. The hypothetical resources are estimated as an "approximate magnitude" and reach down to a depth of 1,800 m. The limit of thickness amounts to 14 inches for bituminous and anthracite coal and to 30 inches for subbituminous coal and lignite, according to the appropriate guidelines (Averitt, 1973; US Joint Geological Survey, 1975). In contrast, however, to the "identified resources" no subclassification system of the estimated quantities with respect to their thickness is given. For this reason the degree of feasibility is unknown, and one can read the already quoted guidelines with respect to hypothetical resources: "Exploration that confirms their existence and reveals quantity and quality will permit their classification as Reserves or Identified-Subeconomic resources" (US Joint Geological Survey, 1975).

In principle, the same contradiction that we have already pointed out in the Canadian classification comes to light. Strictly speaking, no spot can be assigned to the estimated quantities in the scheme of Figure 5. A closer investigation might specifically show that even in the long run they are at least partly uneconomic. This has to be assumed, for example, for all seams with a thickness under 28 inches. Within the meaning given here, the total hypothetical resources can, therefore, only be termed "resource base".

It is of interest that additional speculative amounts, according to Figure 5, are not considered to be probable. "The major geologic features of the United States are known well enough to justify the statement that, in all probability, no major coal fields remain to be discovered" (Averitt, 1973).

From the identified resources of $1,433 \cdot 10^9$ t, 43%, or, about $623 \cdot 10^9$ t, lies in seams that are thinner than 28 inches for anthracite and bituminous coal, thinner than five feet for lignite and subbituminous coal. According to the concept in question, these quantities also can only be included in the resource base.

Correspondingly, $810 \cdot 10^9$ t remain as resources in situ. Here too, it remains an open question as to what extent seams that cannot be mined with currently available or foreseeable methods are included, for example those in steep bedding or in disturbed zones. In any case, the mentioned quantity includes, up to about two-thirds, measured, indicated, and inferred seams of bituminous and anthracite coal with a thickness of 28 to 42 inches, respectively, and subbituminous coal with a thickness of 2.5 to 5 ft. Under the present conditions part of it lies, without question, far beyond the reach of technical and economic mineability.

From the stated resources in situ, using the degree of recovery customary in the US, 50%, one obtains recoverable resources amounting to $405 \cdot 10^9$ t. This amounts to scarcely 14% of the resources listed in the WEC Survey of 1974 (Central Office, 1974).

According to the 1974 WEC Survey, the "recoverable reserves" of the US were listed as $182 \cdot 10^9$ t. With respect to the resources that have been ascertained here, this amounts to about 44% and thus to about the same amount as for the USSR.

It is noteworthy that this quantity is heavily disputed. Armstrong reports that the economic mineable reserves were estimated to be only on the order of $45 \cdot 10^9$ t in 1970, compared with an amount of about $500 \cdot 10^9$ t, which can be mined in a purely physical way (Armstrong, 1972). According to McKelvey (1972), Chief of the US Geological Survey, a part of the continued growth of the nuclear power industry is said to be the result of the difficulty power companies are having acquiring low cost reserves of coal. In spite of the fact that coal in beds more than 14 inches thick totals to 10^{12} t, "estimates of the amount mineable at present prices have ranged from 20 to $200 \cdot 10^9$ tons"; but the "cost of recovery of coal in the various categories has yet to be determined" (McKelvey, 1973). Since then prices have increased substantially as a result of the energy crisis. At the same time costs climbed significantly too, for instance, because of increasing restrictions put forth by environmental agencies, especially for open pit mining.

Without doubt, China too has large coal resources at its disposal. However, the estimates that have become known so far can, obviously, only be viewed as relatively rough ones. Since 1913 the total quantities have been listed in most sources and in all tables of world coal resources as about $1{,}000 \cdot 10^9$ t. This number goes back to an old estimate, that of the German geographer von Richthofen who published a compilation on China in several volumes between 1877 and 1911 (Beyschlag, 1937; Harnisch and Gloria, 1973).

During the period between the two World Wars the Chinese Geological Survey presented, in opposition to von Richthofen, total resources of $238 \cdot 10^9$ t (Lehmann, 1953). This figure corresponds with the quantity mentioned by Bazenov et al., in 1959, $300 \cdot 10^9$ t; this latter quantity is accepted, as far as expansion and quality is concerned, to such a degree that at least a rough and tentative evaluation of the useability could be obtained. At the same time, too, Soviet authors specified proved reserves at $70 \cdot 10^9$ t; a year later, Chinese statistics specified proved reserves at $80 \cdot 10^9$ t (Harnisch and Gloria, 1973). These values, quoted by Harnisch and Gloria in 1973, have been taken over, without doubt erroneously, by the WEC Survey as "measured", and "recoverable". Correspondingly, they appear in Tables 2 and 3.

The $300 \cdot 10^9$ t have to be viewed, according to the concept that has been used here, as the measured resources in situ, about 50% of which, $150 \cdot 10^9$ t, are recoverable resources. All quantities which go beyond that currently can be classed only with the resource base. This, therefore, also concerns all those enormous quantities of $9{,}000 \cdot 10^9$ t down to a depth of 1,800 m that have been mentioned by Bazenov et al. as geologically possible.

9. ESTIMATE OF WORLD COAL RESOURCES

If one adds the estimated recoverable resources of the countries discussed, the Federal Republic of Germany, the UK, the Republic of South Africa, the USSR, the USA, and China, one obtains a total value of $966 \cdot 10^9$ t. This is about 9.5% of the total resources of these countries, as they indicated in the 1974 WEC Survey, amounting to $10{,}131 \cdot 10^9$ t.

The same percentage shall also be used for those countries which have not been discussed in any detail. They hold altogether resources of $508 \cdot 10^9$ t, according to the 1974 WEC Survey, which means only about 5% of the quantities indicated here; $159 \cdot 10^9$ t of this is to be found in Europe. We then obtain corrected world resources which are listed in Table 7 below.

Table 7. Estimate of the world coal resources, recoverable amount.

USSR	$350 \cdot 10^9$ t
USA	$405 \cdot 10^9$ t
Europe	$59 \cdot 10^9$ t
China	$150 \cdot 10^9$ t
Other countries	$61 \cdot 10^9$ t
World	$1{,}025 \cdot 10^9$ t

According to the reflections engaged in here, the resources of real interest amount, therefore, to $1{,}025 \cdot 10^9$ t. This, too, is a large quantity. It could guarantee the present world coal output for another 370 years. On the other hand, it lies below the data of the 1974 WEC Survey by one order of magnitude. If we start with Hubbert as shown in Figures 1 and 14, we would also obtain a possible development of output as shown in Figure 15.

Without doubt, the result of the work presented here can only be understood as an attempt at a rough approximation of reality. With regard to the foreseeable future, that is, the next three decades, I, however, believe these values to be more realistic than those of the 1974 WEC Survey whose values are higher by one order of magnitude. The 1974 WEC values should rather be classed with the range of availability in the earth's crust than with those available in the foreseeable future.

The smaller quantities that have been ascertained here permit us, above all, to express more clearly the problems of the uneven distribution of resources and thus they correct false conceptions. Armstrong (1972), the leading geologist of the National Coal Board, London, has rightly pointed out that a severe shortage of coal might occur locally much earlier

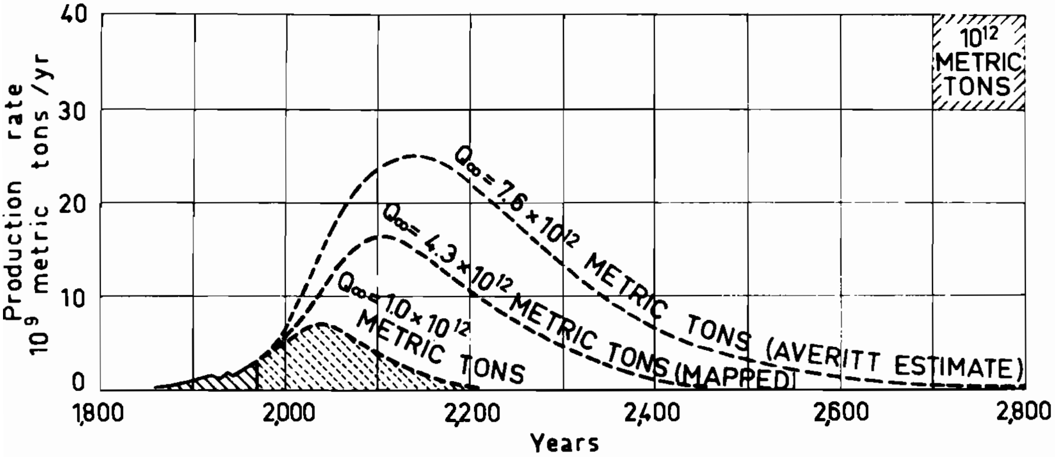


Figure 15. Comparison of cycles of world coal production according to M. King Hubbert (1969) for three values of world coal resources Q∞.

than the predicted moment of total depletion. According to his presentation, we are dealing here with a situation that in the UK, the oldest coal mining country of the world, is becoming noticeable even today. There, the mineable resources so far have only proved just sufficient to last beyond the end of the current century. In my opinion, a similar situation has to be expected for all of Europe at the beginning of the coming century.

In this connection it makes sense to agree with the statements by G.H.S. Govett and M.H. Govett. They indicate that it would be most unfortunate to believe that we have enough resources for a long period of time and then find that most of those resources are in fact nonexploitable quantities for which the existing extraction and processing techniques are inadequate (Govett and Govett, 1974).

The "recoverable reserves" mentioned in the 1974 WEC Survey, $591 \cdot 10^9$ t, are exceeded by the resources as we have come to understand them only by about 1.7 fold. To be sure, these reserves, too, have to be rated as possibly, if not even probably, lower, something which we cannot pursue here any further. In a calculus of analogy, where he had started out from figures for the US and the UK, Armstrong (1972) has, for example, rated the economically mineable hard coal reserves of the world to be, all in all, only $330 \cdot 10^9$ t at present.

At this point, it should also be mentioned that the 1974 WEC Survey, unfortunately, has increased the existing confusion concerning the demarcation of resources and reserves rather than reduced it. In particular, the WEC inquiries to ascertain resources in 1972 and the evaluation and description of those resources in the Survey for 1974 have, obviously, been carried out following different concepts. The inquiries of 1972, as can be seen in Table 1, continued, to a large degree, the concept of the surveys of 1962 and 1968; that is, they did not take economic value into account when total quantities and "measured" reserves (known deposits, total amount) were ascertained. Instead, economically recoverable reserves were treated as part of the total reserves; they were requested separately. The concept was, therefore, essentially "mineralogic-geologic" in the sense in which it was introduced in the beginning. Contrarywise, the evaluation and description of the total resources in the 1974 Survey were done with the help of terms used for the "economic-geologic concept", stated in footnote 2 above, which indicates that the resources observed are made up of those quantities that may be successfully exploited and used by man within the foreseeable future. The published figures of resources on the 1974 Survey therefore do not show what they say they show.

10. PROPOSALS FOR AN INTERNATIONAL CLASSIFICATION SYSTEM OF COAL DEPOSITS

What can be done so that in the future better figures than those now available can be obtained? In my opinion, this will only be possible if the desire to initiate an international working group on the problem of resource classification becomes a reality and if the results of the work of such a group find international recognition. I agree wholeheartedly with the desire of the Energy Project of the International Institute for Applied Systems Analysis to realize this.

Finally, on the basis of the analyses reported here, I shall attempt to present to the Conference some proposals for their work. Questions, however, that concern the classification of the rank of the coals have been excluded, as I pointed out at the beginning of this paper. The proposals are listed in the following 14 points:

1) One has to start with the basic interrelations concerning the distribution of nonrenewable mineral raw materials in the earth's crust, as shown in Figure 4. Reserves and resources are not accurate physical magnitudes; they show geological, technological, and economical aspects. In the long run, they can only be understood in terms of economies.

2) Coal deposits are distinguished from oil and uranium deposits by stratified beds of different thickness and different structural conditions which often lie close together in large numbers. These characteristics should be exploited fully regarding classification. We should strive for agreement on the guidelines for the classification system of other nonrenewable resources. But this should not be achieved at the expense of an optimum of possibilities for the classification of coal or its clarity.

3) One should attempt to combine the concepts, outlined at the beginning of this paper with respect to the limits of the total amount of nonrenewable resources, in such a way that each one finds its place. This is true, in any case, for the sequence from "coal bed concept" to the "geologic-mineralogic concept".

4) Likewise, one should, as far as possible, build upon the already developed coal classification systems in the most important coal mining countries of the East and the West. Only their further development and combination might have a chance to gain general recognition.

5) For the time being, resources and reserves of coal are calculated only partly with the help of the actual specific weight of the computed volumes. A different kind of computation fixes 1 m^3 at 1 t so that deductions for losses owing to mining and to processing can already be included. In the future one should consider uniformly the specific weight in order to reach the resources in situ. The deductions should then be undertaken separately.

6) In detail, a further development of the McKelvey diagram of the latest American classification (US Joint Geological Survey, 1975) as shown in Figure 16, is suggested. In this way, a division into the three parts of the total quantities considered should be arrived at. This is already the case for the balance resources, the out of balance resources, and the prognostic resources in the Soviet classification system and those of most other East European states (Klassifikation, 1959; Stammberger, 1962; 1966). Furthermore, the same holds true for Canada where the three groups are called reserves, resources, and resource base (Department of Energy, 1975), according to the basic proposals by Schurr and Netschert et al. (1960).

The reserves should be viewed as part of the resources, as has largely been done since Blondel and Lasky (1956). The resource base should, however, be placed separately next to it. From the sum of the resources and the resource base a new name should be coined that will not give rise to misunderstandings, for example: "Surmised total geological accumulations".

The reserves and other resources as well as the resources and the resource base have to be limited against one another in two directions, according to the degree of geological information and the degree of useability. The demarcation should be carried out, as far as possible, according to criteria that can be expressed quantitatively. The demarcation between the resource base and the earth's crust does not, however, have to have the same degree of exactitude. One should nevertheless also give guidelines for it with respect to a lowest depth and smallest seam thickness.

For industrial purposes only the extractable resources are of interest, that is, the resources in situ with the deduction

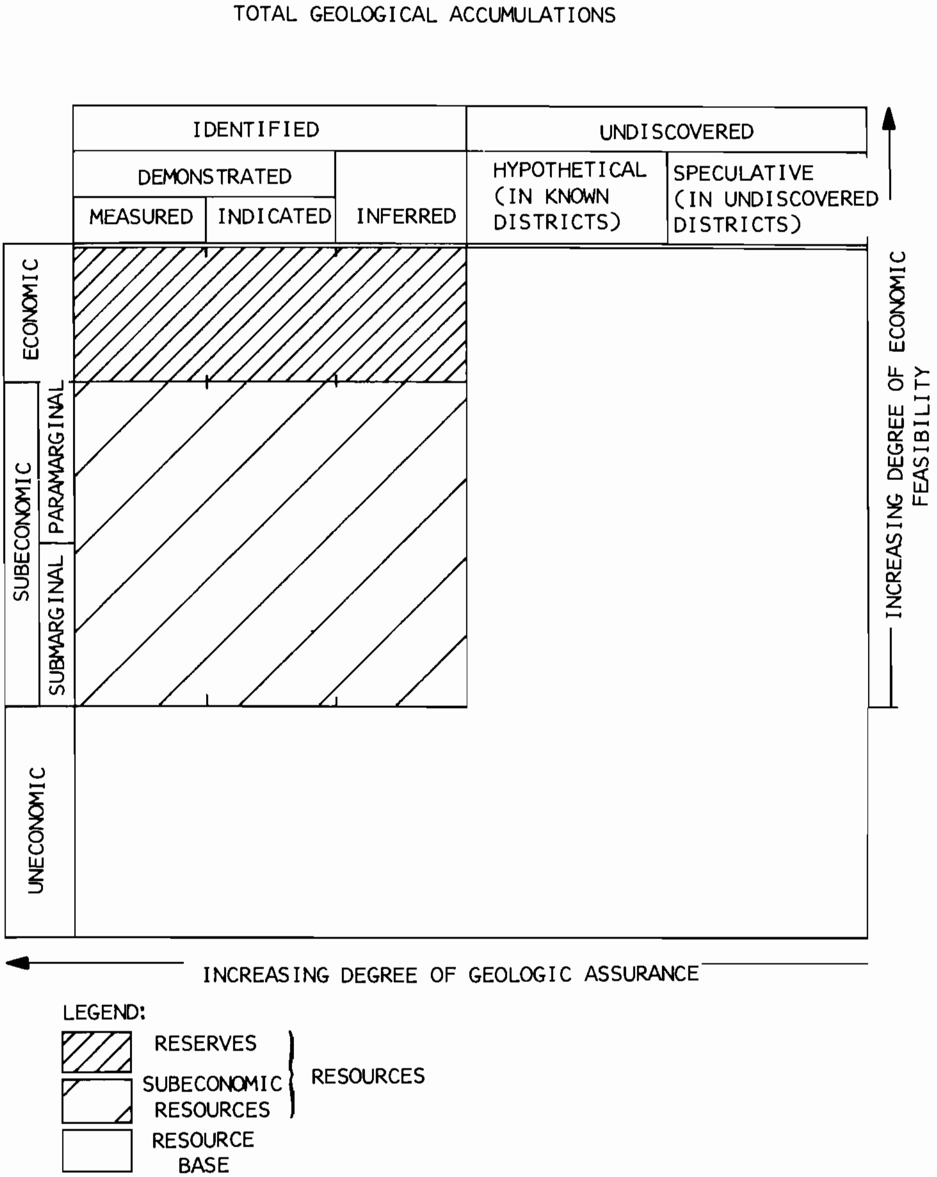


Figure 16. Proposal for an international classification scheme of coal resources and reserves.

of the losses owing to mining technology and processing. Correspondingly, reserves as well as resources have to be ascertained in two ways, "in situ" and "recoverable". Instead of "recoverable" the term "extractable" or "of interest" might perhaps be more propitious. In any case, numerical information always has to be provided with a supplement of this kind.

7) Reserves in situ should be viewed, as has been customarily done since Blondel and Lasky (1956), as that part of the resources in situ which are sufficiently well known, in order to allow an ascertainment of their economic mineability under present economic and technological conditions. In order to eliminate doubt, the ascertaining of economic mineability also can be determined more rigidly by means of data on minimum requirements for deposit quality, above all with respect to thickness and depth. For the depth limit, 1,200 m or 1,500 m comes into question.

The amount of geological information concerning the reserves must, in any case, be great enough so that, besides the extension of the coalbearing strata, the thickness, the basic structural conditions, and the depth of the seams can be predicted. Contrary to the Canadian conceptions and in agreement with those of the US this should comprise, besides the measured and indicated quantities, also those which are inferred (see Figures 5 and 9).

Within this meaning, the "reserves in situ" correspond thereby not only with the content of this concept in the Anglo-Saxon and the French language area but also with the "balance resources" of the USSR and with the "mining resources" (mineable resources) of the GDMB (see Figures 5, 6, 7, and 9). Under certain conditions, namely the restriction of sufficiently opened areas, they can, furthermore, be put in the same category as the "certainly and probably mineable" resources of the FRG's hard coal mining, which goes back to suggestions by Lehmann (1941). In any case, they satisfy the ideas of the "coal bed concept" as introduced at the beginning of this paper.

8) The resources in situ consist of the reserves in situ and the additional resources in situ. For those resources in situ that are not reserves in situ, the degree of mineability must also be determined quantitatively as far as possible. According to the McKelvey diagram, they should be termed subeconomic resources in situ. Following the Canadian proposal, they should comprise all those quantities that can be assumed, with a probability of more than 10%, to become economically mineable within 25 years. This period can, if need be, also be conceived differently. A further subdivision is also possible just as planned in the Canadian diagram as well as in that of the Americans (paramarginal, submarginal).

Concerning the quality of the deposits, it is even more advisable to set limits for the subeconomic resources in situ than for the reserves in situ, that is, limits within which the subeconomic resources in situ can be contained, as for example down to a depth of 1,200 m or 1,500 m.

The subeconomic resources in situ must, in any case, be known well enough so that one can judge the useability from the quality of the deposits. Otherwise, the demarcation, according to the degrees of certainty and useability would show an inconsistency, which is to be avoided. Correspondingly, the demarcation for the degree of certainty also has to be placed in the same way as that for the reserves in situ, that is, at the identified quantities including the inferred ones, according to the American classification system.

The subeconomic resources in situ combine, therefore, the American and the Canadian conceptions. With that they also correspond to the out of balance resources of the USSR and the potential resources of the GDMB, with the deduction of the prognostic resources which have been mentioned there. (See Figures 5, 6, 7, and 9.) To a degree, they are also identical with the "certainly and probably limited mineable coal resources", according to Lehmann (1941). They are the likely reserves of tomorrow.

The addition of the subeconomic resources and the reserves to the total resources and their demarcation from the resource base, in any case, attempts a practical development of the classic "geologic-economic concept" and the "mining concept". Beyond that it provides a parallel for the guidelines concerning the ascertainment of coal resources with those for the calculation of uranium (see Figure 10).

9) One should extensively use the possibility of placing the resources in situ in categories of various thickness and depth. This classification is of special importance for the marginal zones of technical mineability. Therefore, a placing in categories of 0.2 m or 0.3 m can, for example, be useful in the lower range of thickness.

Beyond that a classification according to the inclination and the tectonic strain on seams should also be introduced generally. If one, in addition, considers the raw material quality of the coal, one can obtain in this way a gradation of the quality of the deposits which is more independent of current technical and economic developments. The possibility of storing and evaluating data with the help of computers eliminates the difficulties which were formerly connected with such a far reaching subclassification system.

10) The conversion of resources and reserves in situ into recoverable amounts should be accomplished with the help of a "degree of recoverability". The level of this "degree of recoverability" ought to be estimated according to the foreseeable technical conditions for mining and processing.

Hence, one has to proceed with the estimate of the degree--as with the ascertainment of total efficiency--by steps. After the deduction of the losses owing to mining, one has to calculate the foreseeable output of the processing plants for the remaining quantity. Correspondingly, one has to start also from the quality of the examined coal with respect to its share of noncombustibles.

One has to proceed carefully with the calculation. General empirical values have to be used if an ascertainment is not possible otherwise. In cases of doubt, the lower value has to be chosen.

It is perhaps better to replace the term "recoverability" with "extractability" in order to avoid misunderstandings. Correspondingly, it should read: "extractable reserves", "extractable subeconomic resources", and "extractable resources". For these, other terms could also be agreed upon, as for example: "saleable resources", "industrial resources", or "resources of interest".

11) As guidelines to ascertain the "resource base", one should use, for the present, the limits for thickness and depth from the suggestions of the 12th International Geologic Congress of 1913 that have been changed somewhat by Melnikov. This means a depth of 1,800 m and a minimum thickness of 0.3 m for hard coal seams and 0.6 m for brown coal and lignite seams (Melnikov, 1972).

In principle, the resource base is also made up of two parts. The first comprises those sufficiently known quantities which are neither economic nor subeconomic, but uneconomic. These are, above all, seams that lie too low or that are too thin to be classed with the resources. Here one can do without the data concerning their quantity.

The second part corresponds to the undiscovered deposits, that is, the hypothetical and speculative resources of the American classification (see Figure 5), the resources of the categories 3 and 4, the resource base of the Canadian system (see Figure 9), and the prognostic resources of the USSR (see Figure 7). This part deals with surmised quantities which are too little known geologically to allow their classing with economic, subeconomic, and uneconomic categories. In view of the individual characteristics of geological bodies this also, as a rule, is not possible even with the help of experiences drawn from other deposits. This holds true, in any case, for the present level of knowledge inasmuch as sufficient information is demanded; sufficient information is something one has to insist upon for meaningful considerations with respect to the yield. To be sure, this can also be an interesting field for future research.

Accordingly, a subdivision of the resource base into categories of various qualities of deposits is as little possible as an estimate of its degree of extractability. Whatever part of the resource base can actually be used, according to the present and foreseeable technical and economic conditions remains, therefore, unknown until the results of further research on the conditions of its deposits come to light.

For the quantities of the resource base, the comparison which Brobst and Pratt have used with regard to their ideas concerning the geological availability and, with that, the "geologic-mineralogic concept" is fully applicable: "They are birds in the bush".

12) The classing of deposits with the groups of the reserves, resources, and the resource base should be carried out by a team of experts, made up of as many affected professions as possible. This applies, in any case, to geologists, mining engineers, and mineral economists. Only in this way can an authoritative evaluation that follows the newest developments be guaranteed.

13) We can only follow the technical and economic development if the deposit evaluation is repeated at regular intervals. For all data on resources and reserves, be they in situ or extractable we have, in any case, to list the year of ascertainment separately. The older the data, the less their reliability.

14) For short-termed and middle-termed considerations of energy supply only the extractable reserves should be used. Long-termed considerations can be made on the basis of extractable resources. The resource base is, in my opinion, too uncertain a magnitude for all those considerations that are more to the point. Its estimate should, however, give rise to further geological exploration and technological research in mining, processing technology, and utilization. In this way it seems likely that additional resources and reserves will be found.

As far as the work of an international working group on the problems of resource classification is concerned I finally suggest contacting institutions dealing with the same problems. This, in any case, includes the World Energy Conference. Without the efforts of this institution, as far as our problems are concerned, the discussion we have engaged in here could not have taken place. Further, I should like to mention the project group for coal technology of the International Energy Agency in London. At present, they are working on the elaboration of an International Coal Resource System (ICRS). Suggestions that have been given to them indicate mainly that the American guidelines are to be used. Last, but not least, I also recommend creating a team, composed of representatives of all the professions concerned, responsible for establishing an international resource classification system.[3]

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[3] Since this presentation I have extended my proposals in the direction of an international scheme in my book, Weltkohlenvorräte, Eine Analyse (Glückauf Verlag, Essen, 1976).

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DISCUSSION

Kaufman: If we accept the hypothesis that the frequency distribution of deposit size is log normal, then the uncertainty about numbers and sizes of a well explored versus a frontier area lies in uncertainty about the parameter of the log normal distribution. That is, in a well explored area we know which log normal distribution is appropriate; in a frontier area we do not.

By expressing our degree of certainty or uncertainty in terms of probabilities assigned to the parameters of a log normal distribution, do we not obviate the need for complicated verbal categories that qualitatively reflect this more precise statement of degree of knowledge? Furthermore, given a characterization of number of deposits and of their size distribution in terms of explicit probabilities we can calculate any economic resource quantity we desire.

Let $\tilde{x}$ be log normal with density:

$$F_2(x|\mu\sigma^2) \equiv \frac{1}{\sqrt{2\pi}\;\sigma}\, e^{-\frac{1}{2\sigma^2}(\log x - \mu)^2}\, \frac{1}{x} \quad .$$

For well explored areas, (μ,σ^2) can be calculated or estimated accurately enough to be considered known (see Figure 1).

Assess in probability terms the behavior of $(\mu,\sigma)^2$. that is, assign a predictive distribution to $(\mu,\sigma)^2$. Then, for example, let us concentrate on the median e^{μ} (see Figure 2). For practical reporting, one can report the median, the mode, or some other measure of central tendency of the predictive distribution together with an explicit measure of the uncertainty about parameters.

Fettweis: I agree you speak about the log normal frequency distribution of deposits and what that means for exploration. But I dealt with another problem in this connection. I discussed the mineability of mineral accumulations in the earth's crust as a function of their grade and size and the question as to what part of these accumulations can be regarded as resources. I used the schematic figure of the hypothesis, that grade and size are log normally distributed, therefore, only to demonstrate better the different answers to this question you can find in the papers of different authors. And the five basic concepts behind these answers that I could show you, of course, are only explainable verbally. Perhaps one reason for the misunderstanding is the differences between petroleum and the mineral kingdom. Grade, in the mining sense, is no problem for petroleum.

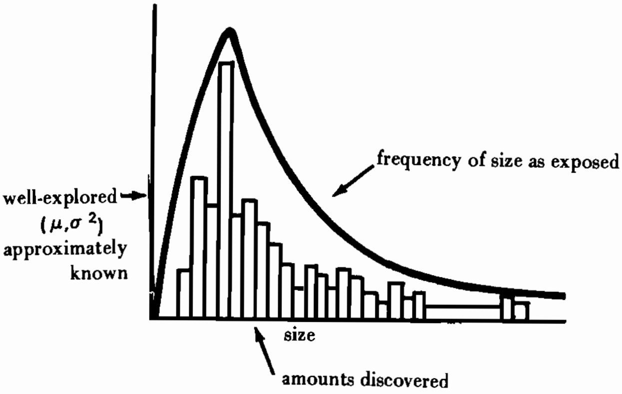

Figure 1.

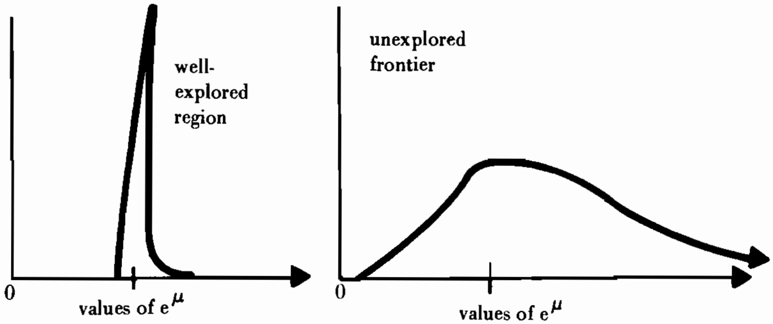

Figure 2.

But please let me add that in our case, when different professions, such as geologists, mining engineers, petroleum engineers, economists, system analysts, and others, are speaking together such a verbal language has its advantages too. It is a fact that not everybody speaks the language of the system analysts. With regard to good results for the discussions I would acknowledge this fact and take it into consideration.

Clarke: In support of Fettweis, the way in which different national authorities actually reconsider their coal reserves is both on an absolute scale of spacing between sample points in some nations and in terms of intuitive limits for estimate error in others. It is only after a technical audit of samples of the manner in which the new data have been used in arriving at the estimates (of inferred, undiscovered, etc. tonnages) that equivalence in terms of probability can be ascertained. The proposed IEA world coal resource assessment follows similar principles to those given by Fettweis in his Figure 3. In this the economic feasibility is supported by a matrix of four subaxes. However, in this field, a "time-window" combination of trends in demand recast for an ever changing present, matched against the accessibility, producibility, and intrinsic value of the coal deposits, in spite of being able to take account of probabilistic "uncertainty" of estimate, is still useful to have for a higher level classificatory language to illuminate simple and fundamental issues. The proposed IEA clearing house will perform a technical audit of samples, give conversion factors for resource and reserve estimates from one nation's terms into all others and vice versa. Figures will be quoted under the categories locally used. This is the reason we support the retention of descriptive terms on the McKelvey axis. (The data base is available for more sophisticated probabilistic estimates such as required by Kaufman.)

Fiala: I wonder whether there is not an alternative to a purely geological approach for inferring undiscovered resources: fossil fuel is produced via photosynthesis and we heard from King Hubbert that the solar energy influx of a couple of weeks equals all energy stored in fossil fuels. What, therefore, is the reason for the fact that such an insignificant percentage of the total solar energy influx over millions of years was stored in fossil fuels? What are the actual limiting factors? Is it minerals (fertilizer)? Could it be possible that a "biological approach" could provide some information about how large the deposits of fossil fuels altogether would have to be? As we know the preconditions under which photosynthesis takes place, it should be possible to obtain via such a biological approach information about undiscovered fossil resources.

Fettweis: It would be better if this question could be answered by a geologist or a geochemist instead of a mining man. But, in any case, I can say that there are considerations on this question by the kind of scientists I mentioned, for instance, on the mass of organic carbon in the sedimentary basins of the world depending on the conditions and the speed of the biologic evolution on the earth's surface and in the oceans, of course, and of the geological evolution of the earth's crust. Up to now, these considerations could not give new figures to the estimates of total coal resources of the world. A very recent estimate by a Soviet geochemist of an order of magnitude of $40 \cdot 10^{12}$t of coal in the earth's crust has been published with special explanations (UNESCO Kurier, February 1975).

Bowie: I consider it important to assess what is likely to be utilized over the next 20 to 30 years; hence, I would like to add my support to the Canadian system. As I said earlier today, it would seem that the resources required for the more distant future--say 2075--are not so important at the present time.

Fettweis: I fully agree.

Roy: I support the question and comments of Kaufman. The boundaries on the USGS-USBM (McKelvey) diagram have a probability basin. Why then go to verbal description of the categories?

Fettweis: I would like to leave this question to the gentlemen of the USGS-USBM because the McKelvey diagram, and its description, is their proposal. But I would say that the boundaries do not have a probability base in the normal sense. In any case, my proposal has been to extend the McKelvey diagram in such a form that it can also collect ideas and principles of other classification systems, for instance, like those of the German-speaking countries and of the USSR.

Styrikovich: In this report, as well as in others, you have a quantity in tons of coal, and this is not so simple. In tons of what coal? In our country, we use the quantity of coal resources in so-called reference fuel. It is almost equal to the so-called hard coal equivalent--seven million kilocalories per ton. In several papers we have tons only, without meaning. Is it hard coal with 7000 kilocalories per kilogram or lignite with, say, only 2000? It is important always to be as precise as possible.

COAL RESOURCE ASSESSMENT IN THE UNITED STATES

K. J. Englund, M. D. Carter, R. L. Miller, and G. H. Wood, Jr.

INTRODUCTION

The methodology of coal resource assessment is of growing concern to the US Geological Survey in its efforts to provide meaningful and timely resource estimates. Coal, because of its abundance, can be a vital factor in attempts to achieve national self sufficiency in energy. On the basis of current estimates, coal resources in the United States appear to be adequate for foreseeable demands. However, there is an urgency to develop more sophisticated assessment models in view of 1) environmental restrictions associated with the mining and consumption of coal; 2) economic consideration for the mining of deeper, thinner, or lower quality coal beds; and 3) increased worldwide demands for coal.

In order to delineate and appraise in greater detail the characteristics of domestic coal resources, the US Geological Survey has expanded all sectors of its coal research program in the past year by some 300%, including a) field investigations in high yield areas, b) exploration by drilling and geophysical prospecting, c) compositional and geochemical studies of coal, and d) planning for the assimilation of the large volume of data derived from these coal research programs into a computerized National Coal Data System.

CONCEPT OF COAL RESOURCE ASSESSMENT

Estimating coal resources from a quantitative standpoint is a relatively simple and manageable mathematical problem, more so than for many other resources, for example, oil and gas. The assessment of coal resources is also facilitated by extensive knowledge concerning the geologic occurrence of coal. An example is the progressive metamorphism or coalification of organic matter from peat to anthracite which allows the tracing of the origin of coal from modern swamp environments to ancient deposits. With an understanding of the occurrence of coal and with the aid of geologic mapping and drilling, the extent and thickness of coal beds can be delineated with considerable accuracy. The tons of resources can then be determined by multiplying the area by the thickness and by the specific gravity of the coal.

When parameters are included that concern the economic, engineering, environmental, and legal aspects of coal mining and consumption, the calculation of coal resources becomes a more complex procedure. These parameters may include sulfur and ash content, trace-element concentrations, depth of over-burden, proximity to other mineable coal beds, reliability of data, slope angle of the land surface, recoverability factor, and many others. When an increased number of variables is used, the manual compilation and calculation of coal resources is a time-consuming procedure that has increasingly tenuous results. For these reasons, a comprehensive effort is being made in the US Geological Survey to develop an effective assessment model that will process all pertinent data for prompt and reliable results.

In addition to the selection and use of various critical parameters, a coal resource assessment model should incorporate uniform definitions and criteria for the analysis and dissemination of its results and products. For this purpose, the US Geological Survey and the Bureau of Mines, agencies that collaborate closely on resource and reserve assessments in the United States, have standardized the terminology used in their assessments. A few of the commonly used terms are as follows (see Figure 1):

> Resources--Concentrations of coal in such forms that economic extraction is, or may become, feasible.
>
> Identified resources--Specific bodies of coal whose location, quality, and quantity are known from geologic evidence or engineering measurements.
>
> Undiscovered resources--Unspecified bodies of coal surmised to exist on the basis of geologic knowledge and theory.
>
> Reserve--That part of the identified coal resource that can be economically and legally mined.
>
> Measured--Tonnage is computed from dimensions revealed in outcrops, prospects, mine workings, and drill holes. The points of observation and measurement are so closely spaced and the thickness and extent of coals are so well defined that the tonnage is judged to be accurate within 20% of true tonnage. Although the spacing of the points of observation necessary to demonstrate continuity of the coal differs from region to region according to the character of the coal bed, the points of observation are no more than .5 mile (0.8 km) apart. Measured coal extends as a .25 mile (0.4 km)-wide belt from the outcrop, or points of observation or measurement.
>
> Indicated--Tonnage is computed partly from specified measurements and partly from projection of visible data for a reasonable distance on the basis of geologic evidence. Indicated coal extends as a .5 mile (0.8 km)-wide belt that is more than .25 mile (0.4 km) from the outcrop, or points of observation or measurement.
>
> Inferred--Quantitative estimates are based largely on broad knowledge of the geologic character of the bed or region, and few measurements of bed thickness are available. The estimates are based primarily on an assumed continuation from demonstrated coal for which there is geologic evidence. Inferred coal extends as a 2.25 mile (3.6 km)-wide belt that is more than .75 mile (1.2 km) from the outcrop, or points of observation or measurement.

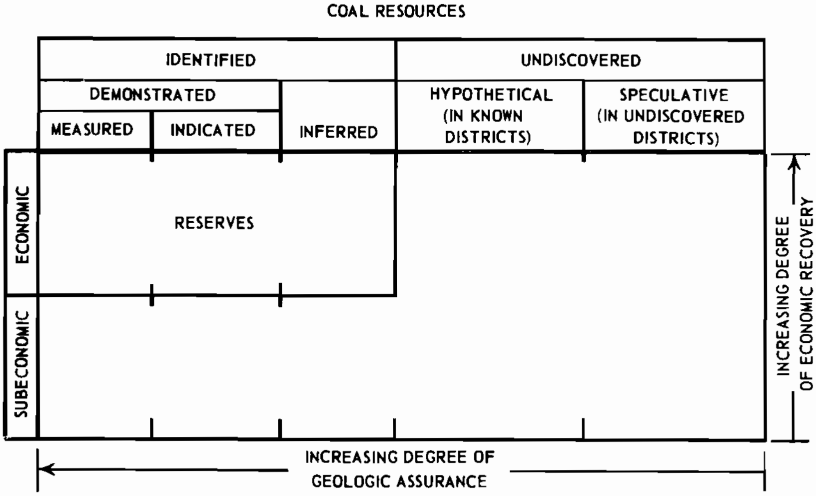

Figure 1. Conceptual diagram for the classification of mineral resources. From McKelvey (1972).

The measured, indicated, and inferred coal are reliability-of-data categories which are determined by the density and proximity of data as shown diagrammatically in Figure 2.

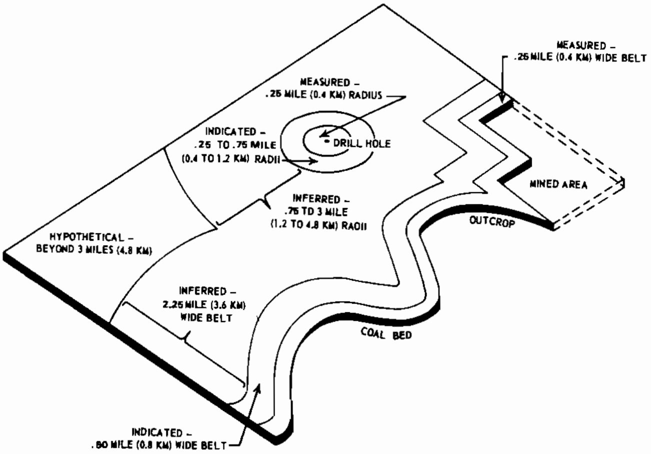

Figure 2. Coal resource categories based on density and proximity of data.

CONVENTIONAL COAL RESOURCE ASSESSMENT

The conventional coal resource assessment used in current tabulation in the United States is essentially a manual method that involves several steps from the initial compilation of coal-related data to the retrieval of total resource estimates in specific categories as outlined in Figure 3. This procedure has minimal flexibility and is limited to the parameters indicated in Figure 3. The conventional coal resource assessment (see Figure 4) prepared in cooperation with the Bureau of Mines indicates that the coal resources of the United States exceed 3 trillion short tons (2.9×10^{12} metric tons), identified resources total 1.5 trillion short tons (1.4×10^{12} metric tons), and reserves are estimated at slightly more than 200 billion short tons (0.2×10^{12} metric tons). This procedure has functioned satisfactorily for the compilation of routine resource information concerning the quantity of resources in reliability or thickness categories for county, state, or national totals. However, it cannot readily provide the answers needed for specific economic or environmentally related questions such as 1) the availability of low-sulfur coal, 2) the slope-angle distribution of strippable coal resources, and 3) the location of coal having concentrations of toxic or beneficial trace elements. The answers to these questions require time-consuming manual extrapolation and manipulation of data, and because of the previous lack of detailed information within the system, the results have been necessarily generalized and varied.

NATIONAL COAL DATA SYSTEM

To meet the needs of a modern coal resource assessment program, the US Geological Survey is entering all machine-processable coal-related information into a computer-based National Coal Data System. Phase I of this system will replace the hand-calculator tabulation of total coal resources and, although limited in scope to the parameters of the manual system, it can provide data more quickly and also facilitate the updating of resource figures. In Phase I, the existing national coal resource inventory is being computerized, chemical data are aggregated into the same areal units as resource figures, and new statistics on production and loss in mining will be entered as they become available. The total resource estimate will consist of original and remaining coal resource tonnages by county, state, and coal field and will show the degree of reliability of data, thickness of coal bed and overburden, rank, formation, and the general chemical character of the coal. In summary, Phase I will store, retrieve, perform simple arithmetic functions and tabulate all resource data. This inventory will be modified as new resource, production, and chemical data become available, and will gradually be replaced by Phase II as the coal resources are restudied and re-estimated in specific geographic areas.

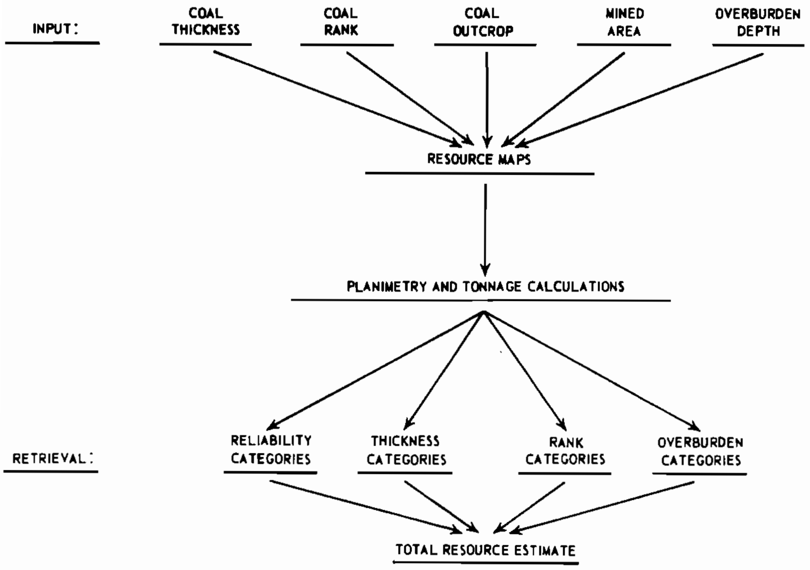

Figure 3. Conventional coal resource assessment.

(X10^9 METRIC TONS)

	IDENTIFIED			UNDISCOVERED	
	DEMONSTRATED		INFERRED	HYPOTHETICAL (IN KNOWN DISTRICTS)	SPECULATIVE (IN UNDISCOVERED DISTRICTS)
	MEASURED	INDICATED			
ECONOMIC	50	147	NONE	1,482	NONE
SUBECONOMIC	63	238	935		

INCREASING DEGREE OF ECONOMIC RECOVERY

INCREASING DEGREE OF GEOLOGIC ASSURANCE

Figure 4. Total coal resources in the United States.

In contrast to the areal aspect of Phase I, Phase II of the National Coal Data System, particularly in the input stage, is based on a data point system. Implementation of Phase II consists of entering several hundred different criteria into the system for each field observation or drill-hole record. Input data, as shown in Figure 5, are grouped into seven broad categories:

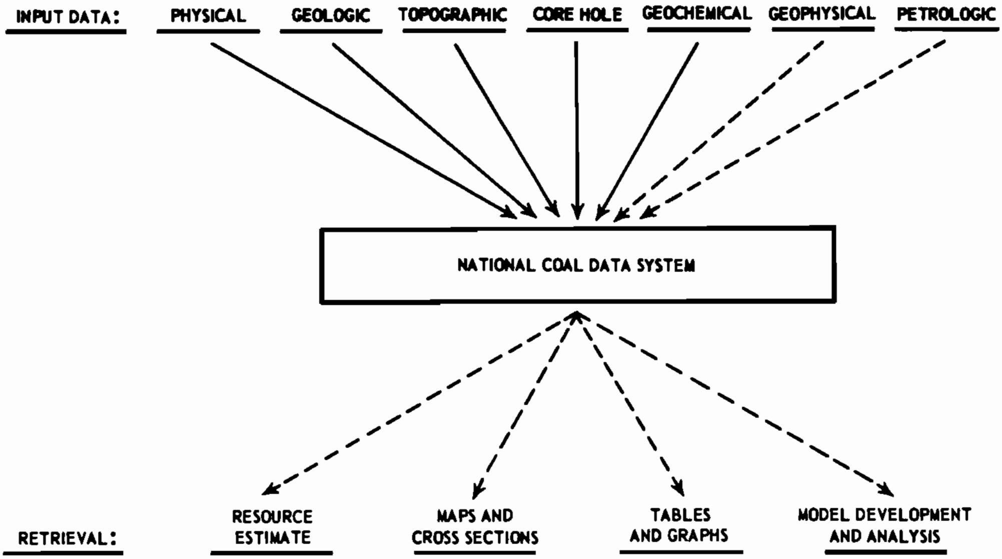

Figure 5. National coal data system.

Physical data--The first group of input items includes the thickness, location, identification, elevation, and specific gravity of the coal bed, engineering properties of the coal and overburden, and the extent and type of mining, if any, at the data point.

Geologic data--Many field observations that can be made at the data point comprise the geologic data group. Some of these items are the 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 hydrologic observations.

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

Core-hold data--The items entered for core-hole records are similar to those entered for geologic data, but they are generally more numerous because several beds usually are penetrated by each drill hole.

Geochemical data--The results of sampling and chemical analyses of coal beds are listed under geochemical data, including proximate and ultimate analyses, and major, minor, and trace elements.

Geophysical and petrologic data--The entry of data into the system from geophysical and petrologic studies of coal beds will be developed in the near future.

In Phase II of the National Coal Data System, four broad categories are being considered for the retrieval of data, including: a) resource estimates, b) maps and cross sections, c) tables and graphs, and d) model development and analysis (see Figure 5). In the first category, the system will be used primarily to calculate coal quantity and quality in any area, coal bed, or sequence of coal beds, in relation to the sulfur, ash, trace-element, and heat content; distribution and reliability of data; and overburden thickness. The second category involves the conversion of basic computerized data into maps and cross sections with the use of digital plotters. This procedure will derive and plot 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 analyze, retrieve, and report computerized data in tabular or graphic format. Digital plotters will probably be used in the fourth category to construct and derive models that show the location of coal resources having specific quantity or quality parameters.

In summary, for the orderly storage, analysis, and retrieval of a vastly increasing volume of coal-related data, the US Geological Survey is implementing a computerized coal resource assessment system. Successful design and utilization of this system will enable research geologists, engineers, and economists to supply the coal resource information needed by government and industry.

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SOME QUESTIONS CONCERNING BROWN COAL EXPLORATION RESEARCH

W. Haetscher

INTRODUCTION

The most important step in brown coal mining is the research on the deposits preceding actual mining operations. Research on the qualities (parameters) of the coal deposit is required to establish the facts for a substantive evaluation of the feasibility of mining the coal, the operation of the projected plant and further processing requirements. A great many different geological specialities are required to carry out this work. Some methods and objectives of this research as carried out in the GDR are shown in Table 1.

The geological research, that is, the transition from unknown reserves to proven reserves worth mining, can be divided into three steps:

1) search for coal deposits,
2) preliminary exploration,
3) exact exploration.

One of these steps will permit classification of the coal deposits (see the proposal in Table 2). The criteria for economically recoverable reserves are that seams must have a thickness of more than 2 m and a maximum ratio of surface larger than the thickness of seam of not more than 10:1. Following the findings of the geological research, brown coal reserves will enter the raw materials balance of the national economy.

EARLIER METHODS OF BROWN COAL RESEARCH

Until 1945, dry or wet drilling was sufficient to establish the quality of the coal, given the simple geological conditions of the reserves and the relatively low technology of brown coal processing. With the economic development of the GDR, increased consumption of coal from more complicated coal deposits and the more sophisticated utilization of brown coal (for example, for larger power stations, cokeries, higher quality briquetting plants, low temperature carbonization, etc.) increased the requirements for geological research and knowledge of coal qualities. New and better methods for brown coal research had to be developed, for example, to establish hydrological and physical qualities of the soil. As a result, brown coal became increasingly subject to "petrography" and chemical quality analysis. Today we have new concepts of brown coal

Table 1. Object, method and aim for geological exploration of brown coal fields in the GDR (see Suess and Hille).

Reconnoitering District	Object	Reconnoitering Parameter	Reconnoitering Aims	The Results
geology generally	whole(total) stock place	kind of stone (petrographic character), richness, spread tectonics, stratification	geological structure supply field (surface layer: coal thickness)	planning (project) coal pit
brown coal petrology	brown coal layer	macropetrographic technology gratification, chemical problems	coal quality kind of coal	power stations, coke works, pressure degazing
hydro-geology	gritsand sand	grain distribution, porosity, water permeable	ground water guidance quantity	draining, system of water distribution
	ground water	ground water table, chemical problems, abundance	water quality, drinking and use water	ground water utilization outfall
ground physics	adhesion stones	grain structure, density, reaction to water, density	ground mechanical reactions of stones (petrographic character)	reliability slope situation
stone-soil reconnoitering	sand gritsand (argillaceous) earth quartzite	chemical problems, physical technology qualification	usability for stone-earth raw material	building material industry, pottery
ground geology	surface layer	vegetable utilizable minerals	qualification for restoration	ground restoration, agriculture and forest economy

Table 2. Proposal for exploration stages and storage classes (see Suess and Hille).

preliminary exploration	store	exploration stage coal fields parameter after Table 1	economic importance
search for deposits	prognosis	outcome geological information forecast	prognosis of richness in coal
assessment	-	in some details explored	large-scale planning ahead, coal industry
		in main conditions explored	project mining investment
thorough development	-	all important peculiarities of the resting place are well-known	annual planning, mining

research, the so-called complex reconnoitering, using various geological parameters to examine the qualities of the coal deposits. However, drilling remains the most important method for brown coal exploration.

PETROLOGICAL AND RAW MATERIAL CHARACTERISTICS OF BROWN COAL IN THE GDR

Brown coal reserves in the GDR fuel balance now amount to nearly 20×10^9 tonnes. Because of the lack of "hard coal", more than 90% of the GDR's primary energy is produced from brown coal. Brown coal is used for purposes that traditionally used "hard coal", for example, the metallurgical industry, heavy chemistry, railroad transportation. The main problem with substitution was that the various qualities of brown coal had to fulfill several different industrial requirements. Thus, to provide for the efficient utilization of brown coal, we had to classify its qualities (see Bilkenroth and Rammler, 1955). The classifications of coal currently mined in the GDR are given in Table 3.

The GDR's annual output of 250×10^6 tons of brown coal is divided between electric power generation (45%) and briquetting (55%). Briquettes are used to meet the heat requirements of different sectors of the economy. The classification of the deposits is an important step in the classification of the relationship between the quality of the raw material and the quality of the end product, the briquettes.

Table 3. Five classes of brown coal quality in the GDR.

Class	Quality Classification (class characteristics)	Store Part
coke coal	little ash and sulphur	~ 25%
briquette coal	little ash, more sulphur unsuitable for carbonization at low temperature	~ 36%
carbonization at low temperature coal	high coal tar, ash more than briquette coal	~ 15%
boiler coal	high ash, more than certain calorific value	~ 18%
salt coal	Na_2O ~ 2% to 3%	~ 6%

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METHODOLOGY OF EVALUATION OF THE MINERAL RESERVES IN THE CZECHOSLOVAK PART OF THE UPPER SILESIAN BASIN

Miloslav Dopita and Jiří Franěk

1. GENERAL METHODOLOGICAL COMMENTS

The discovery and evaluation of mineral raw material deposits is the defined aim of mining geology. The term "mineral raw material deposits" is a historic variable, altered by changes in mining and the technical conditions of extraction, industrial uses of mineral raw materials, the economic and political situation of the state, the development of world prices, and so on.

The first pre-requisite of any consideration regarding the economic exploitation of a deposit is knowledge of the extent, quality and ease of extraction within the geological sequence in which the deposit lies. For this, a method of calculation which can be performed on the basis of geological research, geological propsecting or survey can be used for the determination of reserves. Reserves of mineral raw materials are not calculated on a large scale under normal conditions. They are usually divided into smaller units, for which a separate calculation is made. Division of a deposit into smaller units, subject to a definite method of calculation, depends first on the character of a deposit, knowledge of its extent, nature and method of exploration or extraction, as well as on the purpose of calculation. The approximately 25 extraction methods nowadays known for coal deposits often use compound methods of calculation according to the method of exploration employed. In Czechoslovakia, for example, the deposit investigation stage very often uses the combined polygonal method of calculation with elements typical for the method of extraction and geological panels. Mineral reserves are classified according to

a) degree of knowledge, and
b) national economic importance.

The degree of knowledge about a mineral deposit is expressed by the categories of reserves. In the CMEA countries (countries belonging to the Council for Mutual Economic Assistance) proved reserves and various degrees of knowledge are separated into the following four classifications: A, B, C_1, C_2. Until 1955 category A included two subgroups A_1 and A_2. Also, other investigated deposits sometimes include so-called inferred or prognostic reserves, which are designated by category D.

Category A represents the best proved mineral reserves with the fully-known condition of the deposits, including the shape and geological structure, parameters of the quality, and technological factors, which determine the methods of mining and processing for the raw material.

Category B includes reserves verified to such extent that the main special features of the geological construction are known, as well as the industrial grades, form and composition of the body of the deposit. Inside the deposit there are sections which do not comply with the criteria of workability. The category also specifies the quality and technological as well as mining and technical parameters.

Category C_1 represents reserves measured to such an extent that they are known, in general, to exist under certain conditions, with natural and technological grades and types of industrial raw materials, quality and technological features as well as mining and technical influences affecting conditions of mining and processing.

Category C_2 includes reserves in which the geological conditions of deposits, their shape and composition are given only on the basis of geological and geophysical investigation and according to analogy with sections already investigated.

Category D represents reserves which are only hypothetical--inferred or prognostic. This is a separate group which includes reserves not yet investigated, and which are inferred on the basis of the regularity of the origin and location of the mineral raw materials in the area investigated.

Actual mineral raw material deposits can be divided into three groups according to the complexity of their structure, quality and technological variability:

1) simple and constant,
2) complex and variable,
3) very complicated with an extremely irregular distribution of useful and nonuseful components.

Complexity of structure, variability and extent of the deposits affect appreciation of the economic value of geological exploration. Thus, for example, for the second group investigation is made only for category B, for the third group, for category C_1. A higher degree of knowledge about the deposits belonging to the second and third group can be gained only by mining, development and extraction work. The third group also includes deposits explored in the past.

According to their national economic importance geological reserves are classified as *marginal* and *submarginal* reserves. Marginal reserves are understood as proven geological reserves confirming to the specifications (so-called conditions) set down for these reserves for their extraction and processing. Marginal reserves are suitable for economic utilization. Submarginal reserves are proven geological reserves, the exploitation of which is at present economically inconvenient. However, they may be exploited in the future.

The terms, according to which the reserves can be classified as marginal or submarginal, are contained in the so-called conditions. The manner in which these conditions are set down in Czechoslovakia is officially fixed. General conditions are provided for all deposits or groups of deposits of a certain kind of mineral material in the prospecting and exploratory period. These last-mentioned conditions are based on general national-economic standards in Czechoslovakia and have long-term validity. For a detailed exploration, especially of exploited deposits, so-called special conditions are fixed, reflecting specific technical, economic and other features of the analyzed deposit.

Experience has shown that for the planning and designing of mining activities, as well as for the balancing of mineral reserves, geological reserves cannot be employed as a reliable basis because in practice only part of these reserves are workable. This is the reason the concepts of recoverable reserves and workable reserves are used. In Czechoslovakia, recoverable reserves represent geological reserves of the $A + B + C_1$ categories minus permanently bound reserves (in protection pillars) and minus reserves which are supposedly unworkable for geological, safety, mining operational or economic reasons (in the system of evidence and balancing of reserves applied in Czechoslovakia for this group of reserves the term "reduction of reserves" is used). In exceptional, or technically favorable cases, it is possible to also include in the group of recoverable reserves part of the reserves of category C_2 (depending on the type of deposit). Workable reserves (identical with so-called industrial reserves according to the terminology of the Council of Economic Cooperation) represent recoverable reserves further reduced by the losses of mineral substance owing to extraction conditions, for example, losses caused by the development of face panels and losses during the extraction process proper. The general layout of the system of classification of mineral reserves applied in Czechoslovakia is shown in Figure 1.

2. METHODOLOGY AND RESOURCE VALUATION IN THE OSTRAVA-KARVINÁ

2.1 Geologic and Mining Characteristics of Ostrava-Karviná

The Ostrava-Karviná coalfield that is, the Czechoslovakian part of Upper Carboniferous coal bearing sediments--is an integral part of the large filling area of Devonian and especially carboniferous coal-bearing sediments which extend over an area of about 1,200 square kilometers in Czechoslovakian territory and spread out to Poland, there covering an area of approximately 5,300 square kilometers. For their genetic classification, these coal-bearing deposits belong to a group of stabilized--that is, post-Carboniferous--unfolded, fore-deep basins.

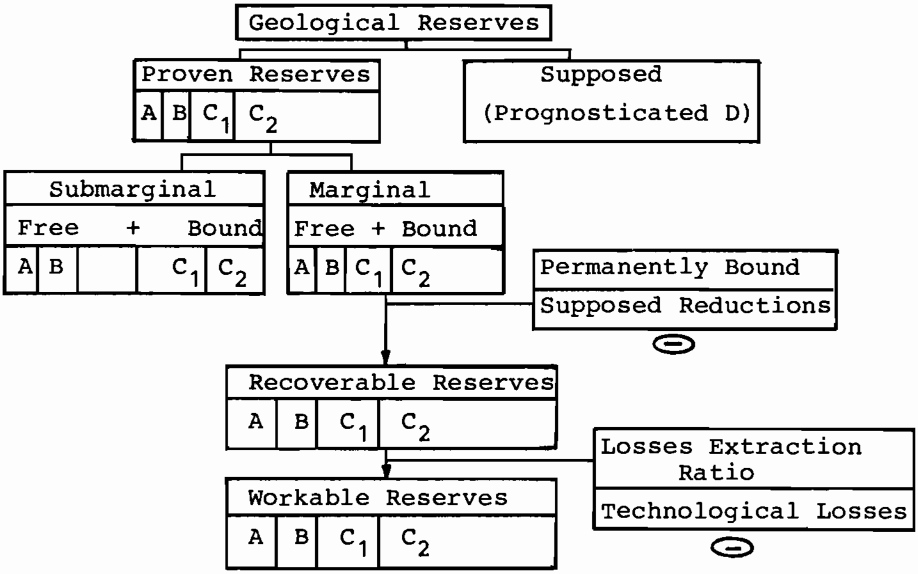


Figure 1.

The Upper Carboniferous coal-bearing strata in the Ostrava-Karviná coalfield are overlain mainly by tertiary and quartenary sediments. Formation of the Carboniferous relief was determined by the intensive erosion and denudation processes in the Mesozoic and, partially, in the Cenozoic Eras and completed by the Lower Tortonian transgression which resulted in a relatively marked relief.

The main washouts, along with some lateral and diagonal washouts, in the massif of the Carboniferous sediments are filled by coarse and medium grained Lower Miocene basal clastics over the major part of the coal basin. These clastics are called "detritus", and they extend to a thickness of about 280 meters.

The clastic contains mineralized water with sodium bicarbonate or sodium chloride contents from 15 to 100 gramms per liter. The mineralized water is gasified by methane and carbon dioxide, and exposed to pressures of 10 to 50 atmospheres. The zone of basal Miocene clastics, covering an area of at least 150 square kilometers and bearing of about 3.5 milliard cubic meters of gasified water, belongs to the most dangerous water-bearing horizon with respect to coal working in the Ostrava-Karviná coal basin.

The detailed regional stratigraphic classification of the Ostrava-Karviná region is based on reference faunal and lithologic horizons and complies with the needs of the coal mining area. The paralic development of sediments of the Ostrava Formation is characterized by the abundance of fine-grained rock and a considerable number of workable coal seams in contrast with the Karviná Formation which is marked, especially in the lower part of its stratigraphic sequence, by coarser-grained rocks and thicker coal seams.

The Karviná cyclothem is more variable in nature than the Ostrava cyclothem and this resulted in the development of Karviná coal seams, which are characterized by irregular splittings and rejoinings. These changes are concentrated in short distance areas by frequent wedge outs, especially in the Saddle coal seams and slates, predominantly in the Suchá and Doubrava coal seams.

The tectonic picture of the Ostrava-Karviná coalfield is characterized by medium intensity tectonics in its western part, which pass to tectonics of low intensity in the eastern part.

The Karviná Formation is characterized by the most favorable features according to the coal content which reaches about 4.8% in this area and even 7.3% in the Lower Suchá region. The Ostrava Formation has a considerably lower coal content of 2.3% and a very low coal content of 1.5% in the Hrušov area. Coal bearing beds of the Upper Carboniferous have in their vertical sequence a definite section of minimum amounts of coal or no coal at all. The sequences, to a great extent, correspond with the sedimentation portions of marine or brackish sediments. Other non-productive sections appear also in so-called red beds especially in the Karviná Formation, where either no coal seams occur or they are replaced by the structureless high ash and low rank coals.

Overall thickness of the Upper Carboniferous in the Ostrava-Karviná coalfield exceeds 3,800 m, out of which about 1,000 m are located in the Karviná Formation. In the coal bearing Carboniferous there are about 255 coal seams with larger and smaller workable sections out of which 168 seams are confined to the Ostrava Formation and 87 seams to the Karviná area. The average thickness of the seams in existing collieries is about 124 centimeters, however, in the Ostrava Formation seams average only 73 centimeters thick, whereas in the Karviná region they average 176 cm. In the Ostrava area seams 60 cm thick are worked. Thinner seams are mined rarely. Consequently, in the Karviná Formation coal seams of 80 cm thickness are considered the lower limit of workability, although in favorable conditions seams of under 70 cm thick are worked locally too.

Owing to the considerable variety of coal quality degrees and to frequently occurring extraordinary maceral structures in the coal substance, in the Ostrava-Karviná coalfield commercial ranks are distributed according to the international three-code classification of hard coals (that is, commercial ranks from I to VII).

Geological reserves of the Czechoslovakian part of the Upper Silesian coal basin have approximately 16 milliard tons of coal. Economically workable coal reserves are estimated in productive collieries to amount to over 3 milliard tons of coal extending to depths up to 1,200 m.

In the Ostrava-Karviná coalfield there are 16 national coal mining enterprises which produce from 23 to 24 million tons of coal annually. Four of these were developed after the year 1948. The Ostrava-Karviná coalfield is the only producer of coking coal in Czechoslovakia. The total exploited area covers about 300 square kilometers and includes about 400 square kilometers of newly explored mining fields, prepared as reserves. Recently, attention has been given to the southern part of the coalfield, the Carboniferous which here is situated deep under the Carpathian sheet formation.

The average seam thickness of coal seams extracted in 1972 was 156 centimeters composed of approximately 200 cm in the Karviná region and 100 cm in the Ostrava Formation. The average bulk density (specific weight) of coal was 1.355 tons per cubic meter and the average ash content of the raw material approximated 31%.

The average depth at which coal was extracted in 1972 was 543 meters under the surface, that is 289 meters below Adriatic Sea level. The annual increase of working depth amounts to eight meters, and almost the whole coal product is obtained from seams from zero to 22 degrees dip range. Collieries Hlubina and Ostrava produce coal from depths of over 1,000 meters.

All collieries in the Ostrava-Karviná coalfield are classified as gaseous mines with gas outbursts mainly in the south and the southwestern parts of the coalfield. The total daily exhalation of methane varies in individual mines between 10,000 and 300,000 cubic meters per 24 hours, the average exhalation quantity being 10 cubic meters per ton of raw coal per 24 hours.

2.2 System of Evaluation of Coal Reserves

According to mining and geological characteristics, the Ostrava-Karviná coalfield appears to be a relatively old coal district. The experience obtained from the evaluation of geological reserves of productive mines and, above all, from the comparison between reserves estimated by exploratory drilling from the surface and actual data proved by mine operations on several newly constructed collieries has shown, on the one hand, that there are marked differences between geologically-calculated workable reserves and the actual reserves assessed by mining methods. On the other hand, they demonstrated the low degree of recognizability for coal deposits of the Ostrava-Karviná type when estimated from exploratory drilling from the surface.

Practice has shown that geological and workable reserves have to be considered as basically different concepts. Geological reserves generally take account of the most basic natural features such as seam thickness, coal quality, depth of the position. They provide therefore a very general picture of the coal deposit and cannot be employed immediately for prospective planning, future mining activity planning or immediate mine management. It is necessary to keep in view that our conception of geological reserves includes all marginal and submarginal reserves calculated within certain natural or artificial boundaries regardless of the actual possibilities of mining equipment and technology and regardless of economic limits.

In our opinion the only useful basis for short- and for long-term planning for the assessment of economic efficiency and for reviewing and checking the extraction ratio of reserves is workable reserves. On analyzing the causes of the differences between the geological and workable reserves more closely it is obvious that their origins lie with natural, technical and operational, safety and economic factors. Among the natural factors the foremost include:

- determination of the conformability of seams for seam thickness, structure, square extent;
- tectonic faulting of the deposit, fractures of the middle and minor extent, conditioning in a decisive manner not only the development of the deposit but also the coal extraction itself;
- conformability of adjacent rocks (problem of methane ignitions during ripping operations);
- conformability of chemical and technological properties, especially the occurrence of anomalous coal types (oxidized highly metamorphosed coals).

The technical and operational factors came to the foreground above all recently as mechanized supports have been more generally applied. As regards the extraction ratio of reserves, modern mechanization of mine operations appears as a rather negative factor because its adaptability to varying geological conditions is much lower, in comparison, than human beings.

The mechanized face supports require, for instance, a relatively constant seam thickness, regular shapes for extracted panels and a certain minimum size for the panels limited by economic efficiency. The application of mechanized face equipment in thin seams under 60 to 70 cm is a world problem because until now no efficient equipment has been developed for this thickness range. In addition the extraction of coal reserves from these seams is a question connected with the requirements for improving work conditions and for the humanization of the work environment in general.

For the influence of safety aspects on the extraction ratio of geological reserves let us mention abandoned coal reserves in the vicinity of mine fire zones and abandoned mine workings flooded as a protection against water inrushes from water bearing strata in extremely gassy seams and in zones with dense concentrations of abandoned mine workings.

Economic influences, which substantially reflect the effects of all factors, cause the leaving behind of coal reserves especially in distant and inaccessible zones of mining fields and panels, the extraction from which would require much higher costs in comparison to extraction costs for other similar local geological and mining technical conditions.

Because the greater part of the above-mentioned causes is practically unrecognizable during the exploratory and survey period, it is generally necessary to correct values for the geological reserves into the values for the workable reserves by means of expert appreciation based on long-term experiences with the deposit.

Thus all these mentioned circumstances lead to a marked volumetric difference between the geological reserves and the workable reserves. In the Ostrava-Karviná coalfield the volume of workable coal reserves is approximately 40% of the volume of the geological reserves. Misunderstanding the nature of these correlations caused, in the past, inadequate evaluations of the life of existing and newly designed mine levels, misrepresentations of new investment requirements and false concepts of the coal potential of Ostrava-Karviná coal field in general.

In concluding, let us remark on the proper evidence of and the balancing of coal reserves. Modern methods of management for mining activity, as well as a systems approach to mining problems, required new methods for the evidence of and balancing of coal reserves. Since 1970, computing equipment has been applied in the Ostrava-Karviná coalfield in order to facilitate the work of mine geologists and to obtain a complex picture of the structure of the geological and workable reserves. At present, the following configurations have been elaborated for the evaluation of the reserves and for annual balances concerning each individual colliery, groups of mines and the total coalfield in, for example, category D:

1) reserves according to categories and types of reserves on horizontal and level planes,

2) reserves according to seams,

3) reserves according to the nature of liability (types of barrier pillar),

4) reserves according to thickness groups, dip and ash content,

5) reserves according to stratigraphic horizons,

6) reserves according to average thickness and mine levels.

Furthermore, detailed analyses of workable reserves are made with respect to the requirements of the middle-term plan and the long-term plan, whereby for the characteristics of individual panels the following factors are taken into account: degree of geological recognizance, situation of the panel--its face in the mine field, planned period for extraction, orientation of the face extraction, method of seam extraction (by one or more benches), seam thickness, petrographic nature and workability of the seam (plowability, cuttability), geomechanical parameters of the hanging wall and footwall, quartz content in the roof rock (with regard to the risk of methane ignition during ripping), degree of tectonic faulting, dip of the seam, length and width of panels, method of roof control, depth under the surface, self-ignition risk, etc.

Such a complete and detailed analysis of the importance of information (degree of data reliability, differences between productive, developed and designed mine levels) is employed for the planning and designing of mine operations, for the elaboration of a technical innovation program, for the solution of safety and work environment problems, for the protection of the surface relief and, in general, as a starting basis for all present and future mining activities in the Ostrava-Karviná coalfield.

3. CONCLUSION

In our paper we have tried to inform you generally about the systematic evidence of coal reserves in Czechoslovakia, the principles from which apply equally to all mineral materials, and also about the applied method of evaluation of coal reserves and the experience obtained by the appreciation of reserves of the coal deposit of Ostrava-Karviná type.

We assume it necessary to underline that, for use by the national economy as well as for the technical-economic considerations, the only adequate and reliable basis for estimates of mineral resources is represented by workable reserves. Accordingly, geological reserves can be used only as a basis for the determination of workable reserves. The estimates of geological coal reserves themselves can be employed solely as a means of appreciation of the total coal content of the geological formations, measures, bed units or seam units and in relation to the orientation of exploration and research.

THE BROWN COAL RESOURCES OF THE RHINELAND: GEOLOGY, MINING AND UTILIZATION

P. Kausch, H. Kothen, and H. Nehring

GEOLOGICAL OUTLINE

The Rhenish brown coal reserves contain about 55,000 million tons of coal and extend over an area of 2,500 sq km between Cologne and Aachen (see Figure 1). The brown coal reserves are located in a basin-shaped area of tectonic subsidence which opens towards the northeast to the North Sea, its longitudinal axis running from southeast to northwest (Quitzow and Hager, 1966). Owing to tectonic actions the basin broke into three main longitudinal blocks, namely the blocks of Rur, Erft, and Cologne (see Figure 2).

These major faults are accompanied by numerous minor faults striking in parallel and partially breaking the main blocks into small faulted blocks. Owing to these tectonic patterns the coal seams are locally found close to the surface and down to some 500 meters, as in the center of the basin near Bergheim. The Rhenish brown coal is from the Upper Oligocene and Miocene ages, though the main part of the deposit formed during the Miocene age. The Rhenish lignite reserves are divided into the following three seam groups (Quitzow and Hager, 1966):

1) The Lower Seam Group--In the Eastern part of the Cologne Block, the existence of up to five thin coal layers was proved by drillings. These layers are very thin and partly impure and therefore have not been mined as yet.

2) The Main Seam Group--The main seam group unites approximately in the center of the basin near Bergheim and forms one seam of a thickness of up to 100 m. This seam subdivides into three major and, in some zones, even more seams.

3) The Upper Seam Group--Near Eschweiler the Upper Seam Group unites and forms one compact seam of a maximum thickness of 35 m. Towards north and east it subdivides into three partial seams of varying thickness.

The intercalations are made up of sand and clay. The sequence of the strata of the tertiary overburden is made up of thick sand and gravel layers with repeatedly intercalated clay strata. The quaternary strata above the tertiary consist mainly of sand and gravel. In some zones, these sediments are capped by a loess cover of varying thickness which sometimes exceeds 10 m.

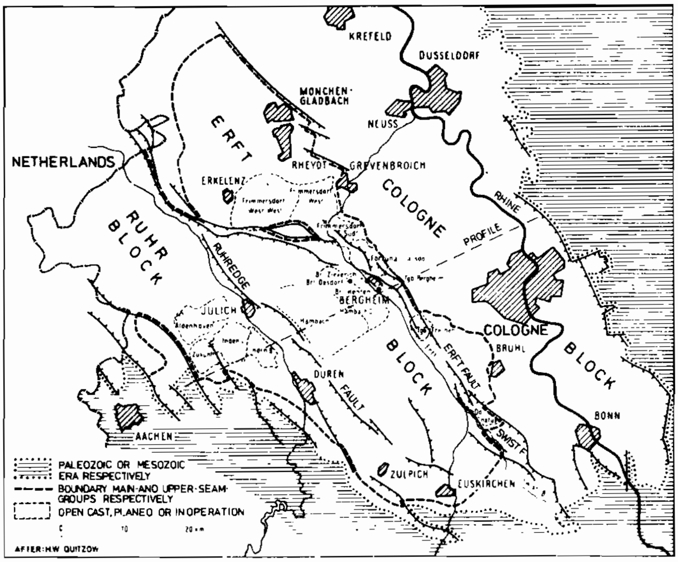


Figure 1. Map of the lower Rhine Valley.

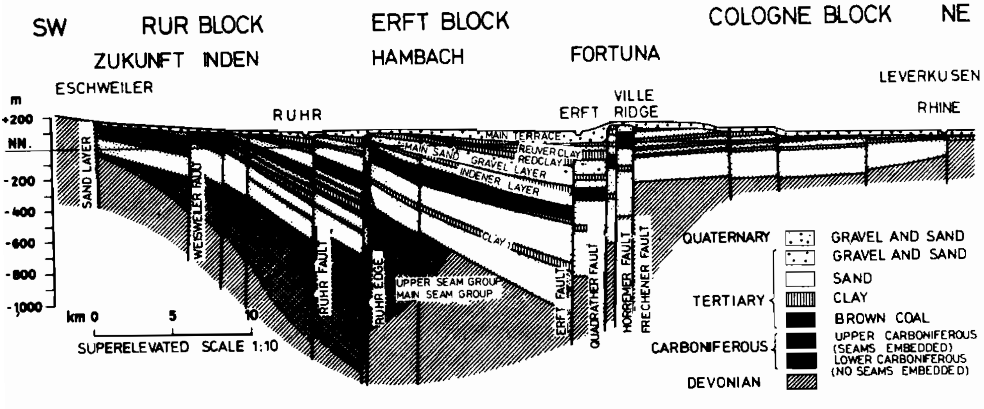


Figure 2. Geological profile of the lower Rhine Valley.

During the peat-forming period rivers ran through the moorland. They deposited clastic sediments which resulted in furrowed intercalations. In part the seams are impure owing to inundations, especially near the coast. Furthermore, tectonic movements during the moor formation and erosions led to variations of seam thickness.

THE GEOLOGICAL PROJECTION

The necessary geological projections cover the entire Lower Rhine Valley. Within the borders of the currently operated and the planned opencast fields the investigations are most intensive, the representations most accurate. In other, currently unclaimed, zones of the valley we have mainly prospective drillings which are often just drilled into the seams but do not penetrate them.

The preparation of geological maps for the brown coal industry in particular serves four different purposes:

1) For drawing up mining plans and for mass calculation, the brown coal seams, the intercalations as well as all major strata of the overburden, must be represented in the form of contour lines. Also, any and all strata are to be represented in geological sections. Thickness contours of the coal, the intercalations, and the overburden are required in order to construct contours of equal roof-rock-to-coal ratios (m:m). Apart from that, the quality of the coal, the calorific value as well as ash and water contents, bulk density, briquetting and slagging characteristics are analyzed and represented.

2) Of equal importance is the preparation of geologic data to plan the dewatering measures prior to mining. These measures can only be optimized if the geologic data are reliable and detailed.

3) For the planning of satisfactory and stable final slopes, geomechanical investigations are a prerequisite; such investigations are carried out on the basis of the geological projection.

4) Finally, the bedding conditions must be accurately clarified and represented in view of the assessment of mining damages, the protection of buildings and of the relocation and construction projects.

Drillings are the basis for the geological representation of a mining field. The density of the bore hole locations for every partial section is adjusted to the complexity of the geological conditions (see Figure 3).

For a large mining field with irregularly complicated geologic conditions it would be uneconomical to choose a regular spacing between drilling locations. The bore holes are arranged

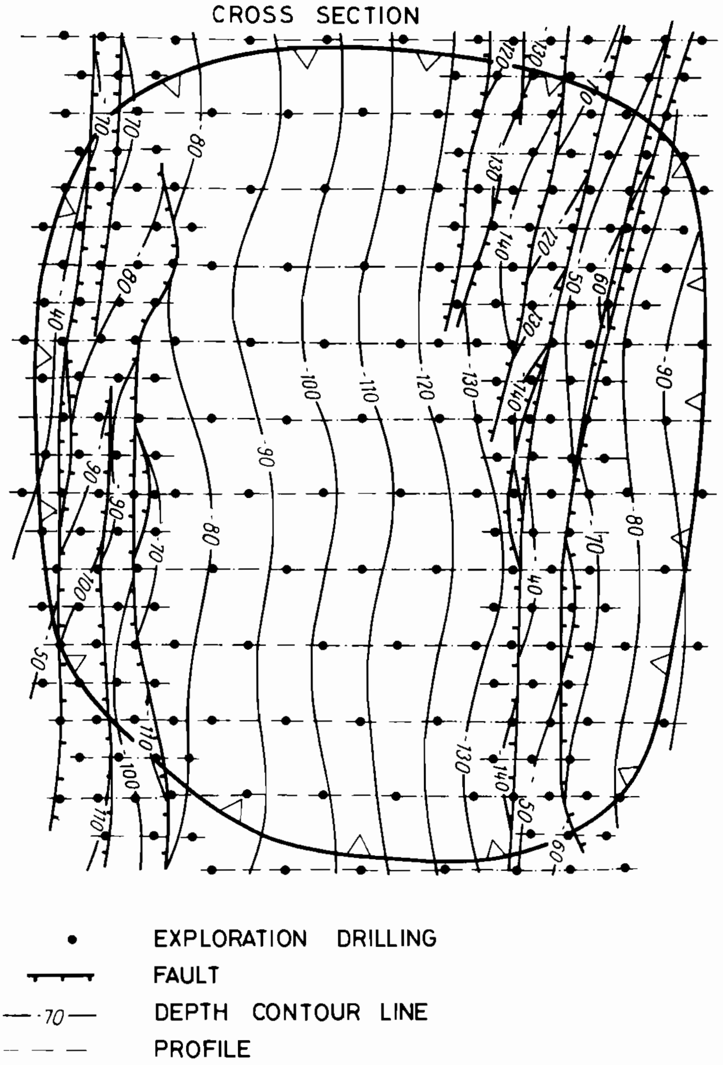


Figure 3. Adjustment of drilling density to the varying complexities of the geological conditions.

in profile lines running in the main direction of dip of the deposit and, if possible, transversing the faults at a right angle. A compromise has to be found when the tectonic conditions are basically inconsistent with this concept.

The distances between the profile lines are between 140 m and 800 m in both the currently operated and the planned mining fields of Rheinische Braunkohlenwerke AG, always depending on the complexity of the geologic conditions. On the profile lines, the bore holes are arranged at intervals of 50 m to 400 m, also depending on the local geologic conditions.

According to these criteria the drill hole density varies in both active operating and planned opencast areas between 5 and 90 drillings per sq km. For the other zones there is a density ratio of 0.5 to 3 drillings per sq km. The network of drillings must be made increasingly dense, until the deposit projection is sufficiently accurate. Rheinbraun's currently operated and planned opencast fields are generally blocked out until the uncertainty of coal volume statements is less than 3%.

DRILLING METHODS, GEO-PHYSICAL LOGGING, AND CORRELATION OF THE GEO-PHYSICAL MEASUREMENTS

To date more than 20,000 drillings have been made in the brown coal district of the Lower Rhine Valley. Depending on the purposes of the various bore holes, several drilling methods have been applied, such as dry drilling, rotary drilling with and without core recovery, water injection drilling--usually for piezometer wells--and air lift drilling for pump wells.

Because of the costs involved, dry drillings are made only where the seam is not deeper than approximately 150 m, while at greater depths the rotary method is applied, although it gives rather inaccurate and incomplete results. As a rule of thumb, there are six to ten rotary flush drillings for every rotary-core drilling, which in particular is used to investigate coal quality. For geo-mechanical purposes, however, the cohesive strata of the overburden in the range of the final slope bodies also are surveyed by means of core drillings.

Because, in rotary drilling, the survey and delimitation of strata give inaccurate results, such boreholes are geophysically surveyed, just as some of the piezometer and pump wells. For exploration drillings, particularly, two logging methods are applied, that is, resistivity and gamma-ray logging.

By means of resistivity logging the different electric resistances of the seams and the wall rock strata are measured and recorded in diagrams; for gamma-ray logging the natural ratioactivity of the individual strata is recorded and also represented in diagrams (see Figure 4).

Generally, a combination of these two measuring methods enables a relatively accurate description and delimitation of the occurring strata. Apart from that the geo-physical loggings are used to correlate the strata, for they are the only possible way to get a relatively accurate identification and correlation of strata of the same age, when the tectonic conditions are difficult. Apart from the mentioned logging methods other systems are applied in individual cases, for example, formation density, microlog, continuous deviation survey and caliper surveying. The evaluation of the described investigations, together with our knowledge of the development of the Lower Rhine Valley, draws the picture of the lignite deposit.

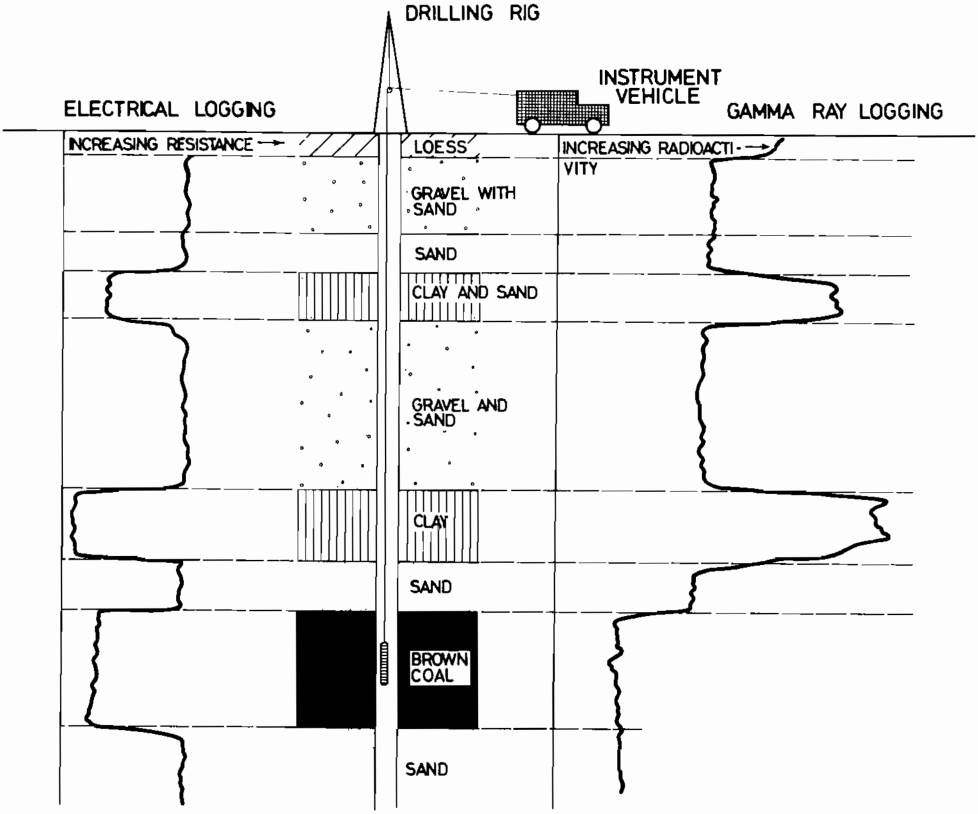


Figure 4. Schematic representation of geophysical logging.

QUALITY OF THE BROWN COAL

Important quality parameters for the characterization of the brown coal are water and ash contents, calorific value, and bulk density, quite apart from the briquetting, coking, and gasifying properties, the sulphur content or the composition of the ashes. Basic investigations in the light of numerous analyses show that the relation between depth and the parameters of the water content, the calorific value, and the bulk density is so obvious that we can make forecasts as to the probable development of these quantities depending on the depth. Furthermore, the relation between the water and ash content, and between the ash content and bulk densities were established.

For the Lower Rhine Valley we have collected the results of more than 13,000 analyses on both water and ash content of raw coal from core drillings. The predominant part of the occurring brown coal contains between 1.5% and 5% ash. In terms of the ash contents the minability of the lignite depends on where its use as fuel in power stations starts to be uneconomical. As this limiting value is currently a mean ash content of about 12%, we can use coal with maximum ash contents of up to 20%.

The water content of the raw brown coal varies between 63% and 45%. Water content depends on the coal's depth, and it decreases at about 3% per 100 m to a depth of 600 m. Within the coal bed the water content of the individual coal lithotypes (bright/dark stratification) differ considerably; there seems to be no tendency from the top wall to the bottom wall. While the mean calorific value of the water-free and ash-free coal (H_u waf) of 6,100 kcal/kg increases slightly with age, the values for raw coal (H_u raw) vary between 1,600 and 2,900 kcal/kg depending upon respective depth. The average increase of calorific value of raw coal amounts to 200 to 250 kcal/kg per 100 m of depth. Within the coal body the calorific value of raw coal shows hardly any tendency from the top wall to the bottom wall owing to the overwhelming influence of the water contents.

The bulk density of the coal depends on depth and ash content and it is therefore for the Rhenish brown coal between 1.15 and 1.22 t/m^3. The sulphur contents of the raw coal in the Lower Rhine Valley are usually between 0.2% and 0.3%, sometimes higher.

THE LIGNITE RESERVES IN THE LOWER RHINE VALLEY

Calculation of mass on the basis of deposit projection resulted in a total coal volume of approximately 55,000 million tons. This calculation considered only seams of more than three meter thickness and seams of the upper and main seam groups. Because of the uncertainties of the deposit projection in partial areas and because of the mining losses to be expected, the coal volume, calculated in m^3, is equated here with the weight unit, expressed in tons. This operation incorporates a deduction of 15% and more.

Very important for evaluation of economic minability is the linear ratio of roof rock and intercalations to coal (m/m). Dividing Rhenish brown coal resources to this ratio, the majority is to be found between a ratio of 2:1 to 10:1.

In the currently operated and projected opencast fields about 10,000 million tons of brown coal are available. Experience, hitherto made with existing open pits, has proved that there is no limiting depth for open pit mining. This means that mining Rhenish brown coal even to a depth of 600 m is technically feasible. The only limiting factors are market situation of the brown coal in comparison to competitive energies and the environmental problems in a densely populated area such as the Rhenish brown coal district.

According to the present status of opencast mining technique development and to the prevailing energy prices, about 35,000 million tons brown coal (corresponding to 11,000 million tons of hard coal) from the above mentioned 55,000 million tons reserve in the Rhineland can be considered economically mineable.

DEVELOPMENT OF OPENCAST MINING TECHNOLOGY

Today brown coal can be offered at a low heating price and--because of important reserves available--will be a considerable long-range contribution to the fuel supply of the Federal Republic of Germany. It is a low cost, safe energy raw material. This development had its origin in the early 1950's when the coal reserves near the surface, which could be mined in shoal open pits, were almost exhausted, and the transition to the deep opencast mines was initiated. The resource (see Figure 5) shows a detail profile of the Garsdorf brown coal seam--required new technical developments covering the open pit machinery, the drainage of the loose sediments as well as the reclamation and the use of brown coal, in the course of the successful realization of the new techniques large quantities of the said resource have been transferred to being economically mineable. The success of this concept is to be seen in the synchronized development of the mining technique and the utilization of coal.

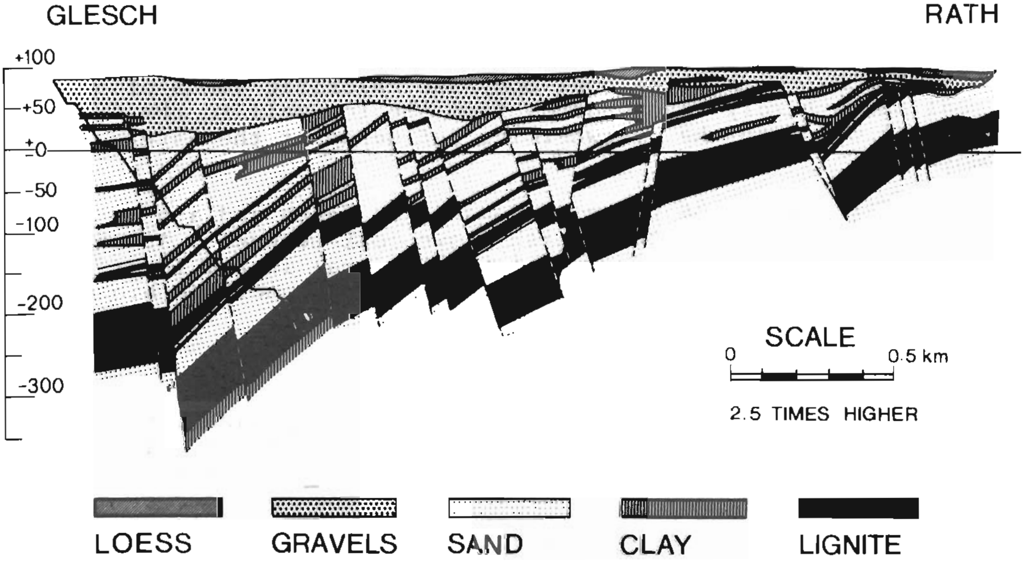
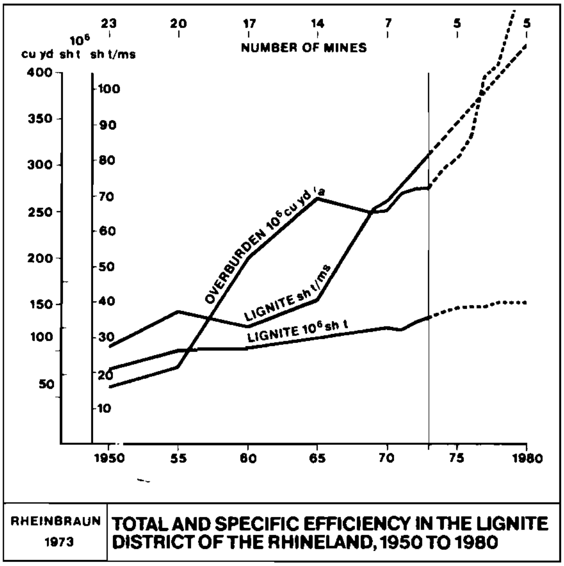


Figure 5. Geological profile/opencast mine Garsdorf.

The following remarks shall characterize some details of the above mentioned development. In the course of its realization the production increased from about 60 million tons in the year of 1950 to 110 million tons in 1974. At the same time the overburden to be removed, because of the greater mining depth, increased overproportionally from 45 million m^3 in 1950 to about 226 million m^3 in 1974 (see Figure 6). The ratio of overburden to coal, which has a strong influence on the profitability of a brown coal opencast mine, grew from 0.75:1.00 to more than 2:1. The Hambach opencast mine, whose opening will be in 1978/1979, has coal reserves of 4,500 million tons, and will reach depths of approximately 500 m and an overburden to coal ratio of more than 6:1.



RHEINBRAUN 1973

TOTAL AND SPECIFIC EFFICIENCY IN THE LIGNITE DISTRICT OF THE RHINELAND, 1950 TO 1980

Figure 6.

The Rhenish brown coal industry operates economically, having taken advantage of cost degression as far as possible by means of installing large-size operating units with powerful machinery (see Figure 7). This, however, required concentrating on operating a few large mines, controlling ground water levels and slope stability in loose sediments, and finally, economically solving the environmental problems that an opencast mine involves.

Very difficult environmental conditions are connected with resettlement problems in this densely populated area, which has about 410 persons per square kilometer, and with reclamation problems in connection with the very fertile loess soil, which is being cultivated intensively in agriculture. Realizing a large output in the whole mining operations, these problems could be solved economically and satisfactorily for all parties concerned.

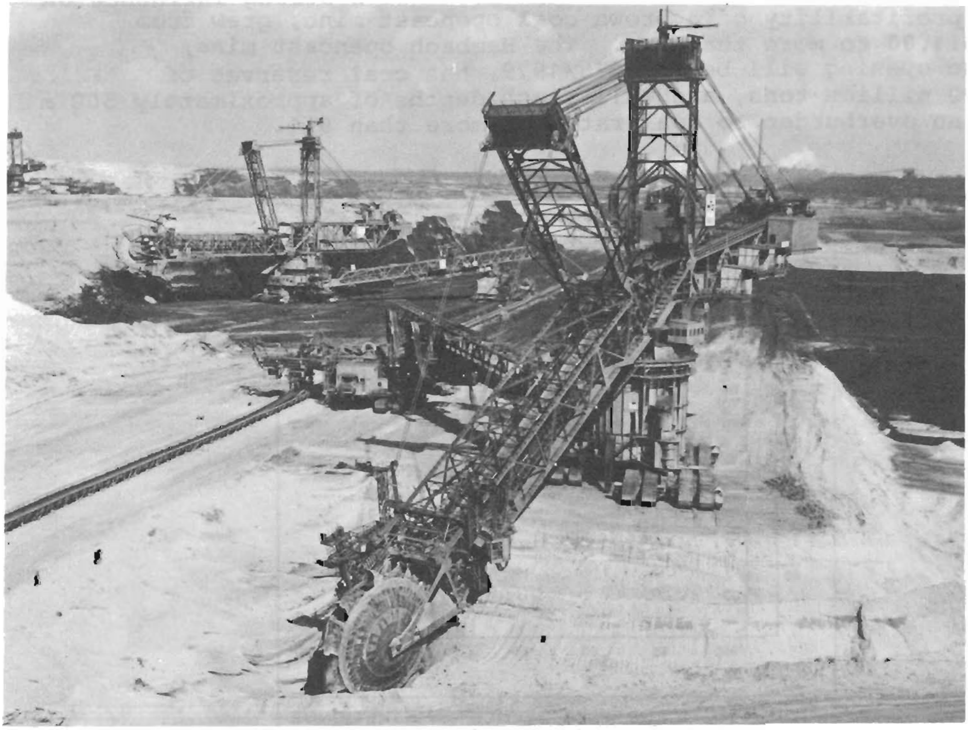


Figure 7. Opencast mine Fortuna-Garsdorf.

The deposit requires opencast mines with extended areas, in which the overburden is excavated on several levels with continuously working excavation devices. Transportation systems with a very high capacity transport the overburden across the opencast bordering slopes to the dumps in the exploited part of the mine.

Up to now bucket wheel excavators with a daily capacity of as much as 100,000 m^3 of solid soil have been used. Additional new devices of twice this capacity are being built at the moment. Excavators of a capacity of 240,000 m^3 per day are already ordered. Enlarging the output of the bucket wheel excavators entails a corresponding development of the stackers for the overburden disposal. The rated capacity of the new stackers will be 240,000 m^3 per day.

The characteristics of the deposits involve extensive mass removal operations in the opencast mines, which results in a cost share of almost 40% of the total costs. Therefore, the selection of the technically most efficient and economically optimal transportation systems is of upmost importance. Transpörtation by conveyer belts (see Figure 8) fills these requirements, and this technique offers the possibility of further automatization and rationalization. This development has been realized to a large extent. The newly designed conveyor belt units will have twice the capacity of the now installed systems. The belts are constructed for an hourly throughput rate of 37,000 tons.

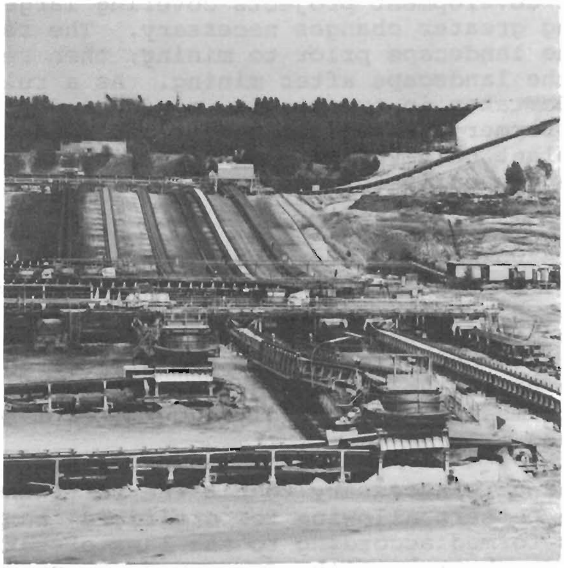


Figure 8. Conveyer belt gathering point--Fortuna-Garsdorf opencast mine.

DEWATERING AND RECLAMATION

Let us complete the above short review of the mining technology development with a review of dewatering and reclamation, the successful development of which has been necessary for the realization of deep opencast mines.

Since brown coal seams occur in geological formations within several ground water levels, it is necessary to keep the deep opencast mines completely free from ground water and to carefully protect them against flowing water. To lower the ground water level, individual wells and a series of wells were dug. Some of them are deeper than the basement of the coal seam. In the brown coal mines of the Rhineland approximately 1,300 million m^3 of water are lifted annually, corresponding to about 12 m^3 of water per ton of usable coal. This water is pumped to the Rhine River.

In the past 20 years over 20,000 million tons of water have been pumped. The area in which the ground water table was lowered is about 2,130 km^2. Because of the lowering of the ground water, the inhabitants and industry and agriculture were confronted with a number of problems. Consequently appropriate measures were undertaken to arrange for a compensating supply of water.

Opencast brown coal mines need a large operational area. Apart from the resettling of villages, the building of roads and the relocation of small rivers, it was of prime importance to plan for future development projects covering larger areas, thus already making greater changes necessary. The resettlement measures change the landscape prior to mining; then reclamation measures restore the landscape after mining. As a rule, reclamation is undertaken in two stages, mining and biological reclamation. The former creates the conditions needed for the latter, that is, plant cultivation, town planning, etc. Biological reclamation calls for the creation of agricultural areas and forests.

Coal mining is followed directly by dumping overburden into the pit (see Figure 9) thus building the raw spoil bank. On top of this bank the loess or forest gravel is spread immediately and reclamation is carried out. The amount of overburden masses determines the surface character of the reclaimed areas. A surplus causes the piling up of high dumps, and a deficit leaves pits. Problems will undoubtedly occur when landscape planning is involved.

Careful planning is necessary to fit the remaining waters into the landscape pattern allowing for artificial banks so that a new landscape is formed according to the laws of nature (see Figure 10). The banks will be developed in accordance with the lake's future use, that is, for fish or water birds, as a water reservoir, or for recreational purposes. In any case, the banks will be shaped and the borders planted with reeds, shrubbery or trees.

UTILIZATION OF BROWN COAL

In the past, brown coal was first of all used for making briquettes. Then, with the development of the new mining technique, it began to be increasingly utilized for electric power generation. Today, 85% of the brown coal is used to feed the brown-coal-based power stations of more than 10,000 megawatts. The future utilization of brown coal will be in coal conversion.

Figure 9. Building up the raw spoil bank, followed directly by reclamation.

Figure 10. Reclaimed forest and lake area.

For the future, when the nuclear power stations have increased their share in the electric power generation, we plan to reduce the load of the brown coal power stations, and replace obsolete brown coal stations with nuclear stations as soon as reinvestment becomes necessary. The coal thus made available can be used for coal gasification, substitute natural gas, and synthetic gas.

The focus on the future use of coal for gasification is to be seen in the production of synthetic gas for the chemical industry (for methanol, ammonia, or Fischer-Tropsch synthesis), in the production of reducing gases for the iron and steel industry (that is, for direct reduction of iron ores), and as an auxiliary fuel for the blast furnace. The main use will be for the production of methane as a substitute for natural gas.

Intensive research is being undertaken to develop gasification processes as well as to produce brown coal coke as a sinter fuel for the iron and steel industry, as a reducing agent for the electrometallurgical industry for the production of ferro-alloys, and in the electro-chemical industry for the production of phosphorous and carbide. To show the variety of possibilities for using brown coal we can mention the production of a soil improver that consists of brown coal and some other ingredients.

This brief survey should present the Rhenish brown coal resources and their assessment. We have looked at the influence which may be obtained by the development of a suitable mining and reclamation technique and at the conversion of coal from economically minable reserves. This adjustment to the technical and economical conditions to produce marketable, low cost products guarantees a maximum utilization of the natural resource, brown coal.

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CLASSIFICATION OF FRENCH COAL RESERVES

N. Bonneau

Whereas in the 1950's the aim of the annual inventory of reserves was to define the total amount of resources in existence, it now appears increasingly necessary to be concerned with the "management of the reserves", that is to specify, among the physical total of the resources, those which can be exploited by means of today's techniques and to chose among them those most likely to bring about a productivity gradient and acceptable economic results.

In 1953, the Geological Department of the Charbonnages de France, taking as sole criterion the greater or lesser probability of physical existence, classified the reserves in three big groups (certain, probable and possible) and defined "as a remainder" those reserves which could only be considered for exploitation at a certain moment of time (for example, Pillar recovery).

As the years passed, definitions based solely on the criterion of existence appeared inadequate owing to the fact that a resource should not only exist physically but also be able to produce adequate economic results: we had a confused feeling that a criterion of quality should be taken into account in the sphere of upgrading as well as in that of obtaining technical results and authorizing investments. As early as 1964 the Nord Pas de Calais coal basin had complemented and remodelled the definitions given in 1953 by the Charbonnages de France by putting emphasis on the factor of workableness.

At the end of 1969, the Centre Midi coal basin also took up the definitions given by the Nord and appreciably refined the Charbonnages de France classification. In June 1970, the Lorraine coal basin brought out a new method of evaluating its reserves by classifying them in four categories, and by establishing the criterion of value alongside that of mere existence. Finally, in 1971, it seemed necessary to take this evolution into account and to define a new method of classifying reserves: a single system for the whole of the Charbonnages.

METHOD OF CLASSIFYING RESERVES APPLIED FROM 1 JANUARY 1972

This new classification has been set up with regard to two sorts of criteria, one of existence (categories: A, B, C) and the other of interest (two classes: 1 and 2), and combining these factors leads to six categories of reserves.

First Criterion

The first criterion corresponds to the degree of certitude we have concerning the existence of the coal seam, and accordingly we characterize three sorts of reserves.

Category A Reserves

These consist of sure reserves whose exploration is advanced enough to leave no doubt as to their existence. In the favourable case of barely-faulted coal seams with regular composition and slope, this exploration can be limited to guarantees concerning the continuity and composition of the seam. These guarantees are obtained by boreholes or by rock galleries which cross the veins. The guarantees are valid only within a limited distance from the exploration in the vein and from the mine workings, and only if the density of the boreholes or of the vein crossing is considered adequate.

Category B Reserves

These consist of two types:

1) levels being worked and levels immediately below with reserves that are still to be explored but about which a favourable judgement can be made: near to zones being worked (larger or smaller according to the regularity of the seams), prolongation of the veins established by means of cross-cut or boreholes, etc. Doubts could remain about the existence and evolution of disturbances, even large ones.

2) deep levels with resources whose existence and regularity of structure have been adequately established by boreholes and which present a favourable outlook.

Category C Reserves

Reserves evaluated in zones where the structural prolongation of the coal seam and vein is logically possible, but has not been proved, or at least inadequately proved.

Second Criterion

The second criterion corresponds to the degree of interest that we can attribute to the reserves, from a technical as well as from an economic standpoint, and in the perspective of the moment; it leads to the determination of two kinds of reserves represented by classes 1 and 2 below:

Class 1 Reserves

These consist of reserves that are interesting from the point of view of economic results, and that might well achieve the necessary progress in rate of yield in the future.[1] To classify a layer in this section, one must take into account among other things:

- the structure of the layer and the quality of its walls;
- the possibilities of mechanization known at the time of classification;
- the headings and installations which must be carried out in order to work the layer, taking into account the reserves which it contains;
- the possible upgrading of the products and the possibilities of sale.

Class 2 Reserves

These reserves are dependent on techniques that can be used in the mine with fair technical success, but the reserves are considered too mediocre from an economic point of view (either their yield is inadequate with respect to their upgrading, or their products are too difficult to sell, or else their investment costs are too high, etc.). It must be taken for granted that we cannot consider here reserves not dependent on techniques that can be used in the mine with reasonable success.

REMARKS

Because of the degree of uncertainty of the reserves in Category C, a distinction between c_1 and c_2 cannot always be justified; it is left to the individual judgement of the coal basins. Among the reserves, only prepared panels or those capable of development without heavy investment should be classified. On the other hand, reserves in panels not capable of development (because they are too deep or too far outlying) should be indicated with their global tonnage but not divided among the different categories.

The technically workable resources of a coal seam should be expressed as a total by the formula $a_1 + a_2 + b_1 + b_2 + c_1 + c_2$.

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[1] The opening of a thick layer which must be accounted for in the calculation of the class 1 reserves can be smaller than the total average opening; for example, a thick layer which, if worked to a total extent, is no longer interesting economically, can become so when worked in part with better adapted and more thorough mechanization.

The reserves that can be planned are expressed by the sum total $a_1 + b_1$; however, in certain coal seams the b_1 reserves can be allocated a reducing factor, to take into account the degree of uncertainty attached to their evaluation. Table 1 shows French coal reserves on 1 January 1974.

Table 1. Technically workable reserves (without Pillar recovery) (in thousands of tons).

Coal Basins	$a = a_1^a + a_2$	$b = b_1^b + b_2$	$c = c_1^c + c_2$	Total	$a_1 + b_1$
<u>NORD PAS de CALAIS</u>					
- coal seams developed or capable of development	31,290	53,133	43,401	127,824	66,967
- coal seams not capable of development				332,323	
<u>LORRAINE</u>					
- coal seams developed or capable of development	161,319	339,219	-	500,538	331,038
- coal seams not capable of development				300,844	
<u>CENTRE MIDI</u>	46,940	42,336	22,048	111,325	62,856
<u>TOTAL FOR FRANCE</u>					
- coal seams developed or capable of development	239,549	434,688	65,449	739,687	460,861
- coal seams not capable of development				633,167	
TOTAL				1,372,854	

DISCUSSION

Dunham: There is serious doubt about the usefulness of global figures such as the $3 \cdot 10^{12}$ or $1.5 \cdot 10^{12}$ short tons quoted by Englund. Our experience in the UK is that only a small proportion of the gross resource can be recovered. When hand mining methods predominated, extraction was very flexible, and seams could be followed more or less wherever they went. But now, with highly sophisticated, mechanized deep mining, extremely simple geological conditions are essential. The fact that, according to British National Coal Board figures, we have a resource amounting to $163 \cdot 10^9$ tons does us little good; the important point is that only $3.5 \cdot 10^9$ are known to be extractable by present methods; and even taking into account new areas, it seems unlikely that more than 10% of the gross figure will ever be recoverable.

Englund: I cannot speak for other countries, but as far as we are concerned, right now about half of our production is coming from the relatively flat regular bed. As pointed out here when speaking of resources, we are speaking of the total coal in the ground and, if you notice, our recoverable reserve was a very small fraction of that total coal in the ground. So we do have coal beds that extend for many miles, no question about it, and we have some complexly folded ones. But the bulk of our recoverable coal will be in a relatively flat line.

Dunham: What part of the coal reserves can be strip mined?

Englund: About 45 billion short tons or about 25% of the US coal reserves can be mined.

Clarke: Dunham has cited the proportion of UK coal reserves that are both accessible to existing mines (average age, 80 years old) and thought likely to support the lives of these mines if they were all to be worked under the economic conditions prevailing at the time of April 1973 (1973-1974 assessment). Furthermore, this assessment takes account of national aggregate productivity, cost, and market proceeds-and thus is a "multimarginal estimate" for all mines. (In many other nations' assessments of coal--in a condition that is marginally supportable in one unit of one undertaking, provided the average cost per ton is low enough--all coal in such a physically or geologically marginal condition is included as "economic". This the UK does not do.)

The interesting point in this UK figure is not its actual value in 1973-1974 but the annual rate of change in the economically workable reserves. After nearly a decade of "hi-grading" or "creaming off" the more easily producible coal, causing an annual reduction in currently accessible, economically (senso stricto) workable reserves, equivalent to 10 times the rate of extraction, additional capital investment in the last two years in searching for new mines and help from OPEC has more than doubled the 1973 figure quotes by Dunham.

In the UK we have found, in trying out a central data bank of point data, such as Englund's Phase II Project, that a kind of "Law of Indeterminacy" applies. More geological detail is taken into account locally in policy decision making than is reported. However, the local assessments take no notice of the more distant unworked coal--such as that with which Englund is concerned.

In the light of the above, may I ask how often will the US resource assessment be revised? In view of the difference between "the next parcel of reserves to be worked" at any moment in time and the different parcels of resources--how close will the Phase II data points banked be?

<u>Häfele</u>: During the session on classification of resources I posed a question, asking what the viewpoints or additional categories or constraints for considering resources are. I think the technology required to harvest these resources is certainly one constraint, and one thing that we are trying to accomplish here at IIASA is to understand which resources require which technologies. Maybe for coal it is necessary to go to a drastically different technology. By drastically different, I mean something in the domain of mental block-breaking--fully automated devices in great depths below 1000 meters where perhaps the operator is in an air conditioned capsule, or maybe liquid leaching of coal in the style of chemical leaching of copper ores. If we stay with the present technology, probably coal mining will decrease.

<u>Ross</u>: Mr. Kausch, what is the time between the beginning of coal removal and the use of the land for agricultural purposes?

<u>Kausch</u>: In general, there is 10 years from the first digging of the overburden to the land being recultivated. It takes about three to five years' course to get the humus content in the earth on the basins to 1.5%, and there we have to stick to the cycle of the seasons because we do it on a natural basis, not by fertilizers. And so we have the sequence of plants that are planted. After a maximum five years, this farmland is given back to the farmers or sold. The quality is at least the same as it was before, and the crops are mostly better.

Ross: How long does it take before the lakes become biologically productive?

Kausch: A very short time. Together with the Max Planck Institute, we isolated and made one lake, and it took about one year until we had the first life, biological and zoological, in it; and after three years you have all kinds of fish and plants without doing anything. This comes in through wind and by birds carrying seeds in their feathers.

Masseron: What is the share of environmental costs within the total production cost?

Kausch: 10%, including reclamation, resettlement, building new roads and riverbeds, as well as dewatering the mining area.

Styrikovich: But this is for what thickness of coal?

Kausch: The coal is up to 100 meters thick. The ratio that we had in general until now was 1:2. That means 1 part coal, 2 parts overburden. But this ratio will go down to 1:7 at the end of the 1970's because then we will start a new open cast mine that will reach a depth of 600 meters.

Odell: What is the cost per ton?

Kausch: The price per ton of coal today is DM 6 to 7/gigacalorie.

Styrikovich: What are the calorific values and conversion coefficients in hard coal units?

Kausch: The calorific value can be as low as 2000 kilocalories per kilogram, and may go up to 2800 in deeper mines. Generally, we use a factor of one third for conversion to hard coal units.

Schanz: What is the total employment of a mine of 50 million tons per year of brown coal?

Kausch: In this special mine there are 2000 people, including staff, engineering, board of directors, and so on.

Clarke: Kausch quotes efficiency figures in terms of output per man-shift, an index suitable for long lasting labor intensive industries like deep mining. If the capital value of access ways in deep mines is neglected (since they last, say, 100 years), then there seems to be a possibility that German open pit mining will lead to the closure of the less productive deep mines--especially if, as Kausch says, open pit coal will be used for iron ore reduction and as a coal chemical raw material. However, it takes a decade to replace a deep coal mine. Is there any danger of increased efficiency in open pit mining reducing the long term productive capacity of his country?

Kausch: First, the investment for new deep open pits is high. The Hambach mine near Cologne has a total coal content of 4500 million tons. The first investment for machinery and opening up will cost more than DM 5000 million.

Second, the production cannot be raised too high because of environmental conditions, especially the need of land for the operation. There is a possibility of raising production in a mine, to a certain degree. Today's annual production--about 115 billion tons--can be raised within certain limits.

Bauerschmidt: To what extent may your project be a guideline for the American continent, especially with regard to Canadian tar sands and the oil shales of the USA?

Kausch: For the Canadian tar sands, for example, we have done some successful converting work for this particular technology but, of course, it took some development work because of the hardness of the rock. We work here in new sediments. The great Canadian tar sands are hard sands, so you have to fix the excavators.

In the USA, if environmental laws become reality, then the industry will have to go to large scale operations to cover environmental costs, and they need a continuously operating technique. You cannot work a large scale mine, for example, with truck and shovel or with a drag line and a truck or such. So our technique can be of special importance for future developments in other countries too.

Styrikovich: The program for investigation of economically recoverable resources of coal is only in an initial stage. In many countries very different methods are used to tackle this difficult problem. First is the exploration for deposits. As you know, the cost needed for the exploration of coal resources is only a small fraction of the price of the coal; for oil and gas it is sometimes 50% or more. With simpler geological structures, it is sometimes enough to have distances between holes of two to three kilometers to be sure about the amount of the coal, but in some other cases with broken geological structures it is not enough to have two holes for each kilometer.

Another comment is related to the very interesting presentation by Kausch. Reclamation costs were said to be only 10% of the price of coal, but I think this occurs because of very thick seams--100 meters or more. This means that you have very large amounts of coal extracted from one hectare of land needing reclamation. If you have big deposits, but not such thick seams of coal, the cost of reclamation--as in many cases in the USA--may be as high as 30% or more. Because of this, it would be advisable to clarify deposits of coal not only by ratio of overburden to one ton of hard coal equivalent, but also by amount of hard coal equivalent per hectare.

About the possibility of new methods mentioned by Häfele, until today I did not know of any new method that would drastically change the position for deep mining. In our country, we have had some good experience on the industrial scale--several million tons per year--in deep mining with hydraulic methods. Under favorable conditions for such a method, some specialists think that it will be possible in the near future to have about 400 tons per miner per month. It would be a good result, somewhat comparable to some open pit performances. Several experts even think about having 1000 tons per miner per month. This is somewhat too optimistic.

First, it is necessary to investigate the distribution of known resources among several groups that are different in economic conditions. If you have everything in one group, it will be impossible to think about new methods because for one type of condition your methods would be preferable, for others, unpromising.

If we remember the coal survey of the 1974 World Energy Conference, with an estimate of 10 trillion tons for all resources and only 500 billion tons (only 5% of the total) as economically recoverable, I think that the last figure is too low.

Dunham: I have already given some indication of my own view that the global figures, like the 10 thousand billion tons that you have just quoted, are really useless, that we waste our time on them, that they do not really provide a figure that Häfele can use in his project. We want to get figures that you can safely use in energy systems analysis if we are going to produce results that mean anything. Now, it is interesting to note that our friend from Czechoslovakia gave us a figure of 40% of workable resources as compared with geological resources. Others have elsewhere--it was quoted in Fettweis' paper--mentioned that the figure was perhaps 50%; that is, 50% of the global resources might be recoverable. I think this figure is much too high. I have personally used a figure of no more than 10%, and Styrikovich has just mentioned 5%. I think we have to be extremely careful about this. We do need to be, if we are going to get something meaningful, and not just a vague piece of geological calculation, which anyone can do on the back of an envelope. We need to have a figure that really takes into account the mining methods.

There are two questions, then, that I want to ask. The first one is this: can Englund, or indeed anyone else who has spoken this afternoon, give even approximate figures for the amount of coal that should be recoverable by the open pit technique. Given a virgin area, how much can one expect to get by the open pit? I was very interested in the figures quoted for Rhine lignite, that as much as 600 meters depth was being contemplated. This is an enormous depth for open pit coal work.

The second question, and I want to address this to you, Mr. Styrikovich, is: what about new methods? There was a time when it was said that in your country the business of burning the coal and converting it to gas in situ underground was actually being done.

Styrikovich: Without success.

Dunham: I am sorry to hear that.

Styrikovich: After many years of experiments and several semi-industrial enterprises, this work was abandoned.

Dunham: And we hear rumors of the same thing in Wyoming. But you see, if this technique were possible, then these global estimates might have some meaning. We might be able to think that they could be recovered if you could recover them without a labor force worth mentioning, in the ground by means of gasification. There is, for example, underneath the North Sea basin a resource of coal that I suspect--I do not know whether Clarke agrees with this-is greater than we have underground in the UK, and yet the only way in which we shall ever get at it is by actual underground gasification. Now, is there some hope in the foreseeable future of a real investment in this kind of investigation, or has what has been done in the USSR and what is now being done in Wyoming sufficiently proved that we cannot do it?

Marchetti: My question is in a sense a sideline. When people try to extract coal by underground gasification they are actually working against nature. What one has to do is to inject air into the coal seam and get fuel out of it. The final natural product of air plus coal is nitrogen plus CO_2, and this means that it is very difficult for an operation run 100 meters or perhaps 300 meters underground to be controlled to such a fine level that the product is really CO or hydrogen. Now by observing what is done to recover oil from oil fields where pumping is no longer effective, I ask myself a question. The oil men restart the exhausted fields by injecting liquids that are in essence solvents or surfactants separating in various ways the particles of oil from the rock which contains them. On the other side, in order to reduce pollution a method has been devised to solvent refine coal where the ashes and inorganic sulfur are not dissolved. My question is: can the two methods be joined together in order to make an in situ solvent extraction? In this case, one would not work against nature since the dissolved state is the equilibrium one, and one could hope to transfer oil technology, usually very efficient, to coal extraction.

Styrikovich: Has there been any experience in this field? Is there some inexpensive solvent?

Marchetti: Certainly, there is a large pilot plant. The solvent is extracted from the coal itself, but as it is a hydrogen donor it must be regenerated with hydrogen. You have, however, a kind of breeder from the point of view of the solvent because the solvent itself is produced from the coal. Similar effects would be produced by liquids which actually disrupt and fragment coal by penetration of natural interfaces. Ammonia or methanol seem to be very efficient at least at the laboratory stage.

Clegg: Could I just comment upon that last point of Marchetti's with respect to the injection of liquids and gases.

In fact, a similar thing to underground gasification is carried out with oil fields but it is called underground combustion, where one attempts to inject heat into the oil reservoir by means of injecting air and creating a combustion front that grows through the reservoir. This is being tried with varying degrees of success, and I think that some reservoirs in the southwestern United States, in California in particular, have been produced commercially in this way. It has been tried, and it was hoped that it would be successful with the Athabasca tar sands, but I think the general feeling is that it has not been successful so far. The problem really is one of establishing permeability in the reservoir, or in the coal itself.

In order to create channels for your air or liquid to move through the coal you have to create permeability channels and, in general, if you are dealing with deep deposits, this means artificial hydraulic fracturing of the material. The problem is that you are not able to control this very well. Having created a path through which your fluid is moving, you will tend to get a cumulative effect, and you will get your very permeable channel becoming more and more permeable. You then create a very rapid break through to your next well, and you leave a large amount of the material in situ. So the prospect is one of a very inefficient recovery mechanism. I think, in which you are going to leave a large portion of the material in the ground. This indeed is the sort of thing that you can find in most of the oil reservoirs that have been tested in this way, except with one or two rather special types of reservoir that have particular characteristics in California.

So the prospects are not very good, and I think the same thing applies to an in situ retorting of oil shales. You have exactly the same problem of creating channels for the air to be pushed through, and the difficulties in the uniform spread throughout.

Fettweis: I agree with Clegg's remarks on coal. Additionally, coal has another big problem for a controlled combustion process. That is roof control, in mining terminology. For oil, there is a matrix of sand, etc., that will remain in place after combustion. But for coal, you will get openings without such a support. I cannot imagine how to control the roof of these openings and to prevent them from collapsing at the wrong place and at the wrong moment. For normal coal mining, too, when you are in the seam, roof control is a major problem. There can also be other reasons that make in situ combustion of coal probably more complicated than that of oil. In many cases one reason will be the different form of the deposits.

Generally, oil deposits are more compact than coal deposits. As a result of tectonic forces, seams often are interrupted and are found in more or less limited pieces that you cannot know about from the surface. So it may be very difficult to bring the combustion process through such a deposit. On the other hand, there may be some coal deposits with favorable conditions too, but probably not very many. These are some reasons for my opinion that the hope for a qualitatively and quantitatively successful in situ combustion of coal in the next 20 to 30 years is on the same order of magnitude as--related to the total energy question--the hope for energy production from the sun in this time.

Styrikovich: For about 30 years in the USSR we carried out some industrial experiments on underground gasification. We did not work only in one geological formation, and we used rather large installations. One was near Moscow, with brown coal; one, also with brown coal, was in Central Asia; one was in the Donetz Basin, with bituminous coal; and one was in the Kuznetz Basin, also with bituminous coal. Even with a favorable geological structure, it was very difficult to obtain even a low but constant value for the gas. For underground gasification, it is necessary to have a simple combustion process with a very stable ratio of air to coal. We also made some attempt to use oxygen. But the percentage of oxygen losses was too high for any economic consideration. Even air losses were very large, and the quality of the gas was very poor.

After many years of unsuccessful operation, all installations were closed. However, I do not think that underground gasification is impossible. Maybe today--or tomorrow--it will be possible to use some new method. Our experience began before World War II and ended 20 years ago. Maybe some new method will.be better; I do not know. But I do not have much hope for success here. Of course, careful investigation of our experiences will be profitable for any new enterprises in this field.

Another point, raised by Marchetti, is the possibility of dissolving coal underground by means of some solvent. I think that again the biggest question is the possibility of preventing a large percentage loss of such a solvent, because a solvent for coal, in my opinion, will be expensive. And to introduce this into some geological structure will be very difficult without large losses. The situation is quite the opposite for oil and gas, because oil or gas deposits are watertight, and the process of injection of some solvent, water, steam, or heat, is possible in good closed structures proved for tightness over many millions of years.

It is not the same for coal. All the miners know very well that each coal deposit has in the process of mining a large flow of water. It is not a watertight structure. Because of this, I do not believe in such a success. I think that it is necessary, first of all, to make clearer what amounts of coal are workable with the existing methods, or improved existing methods. In open pit, for instance, we are making progress and are very rapidly increasing the productivity for each worker. And the same applies to hydraulic mining.

Häfele: I do not know how far to go, but being here at IIASA and being concerned with questions about coal and other energy options, I am not completely satisfied with the present state of the discussion. Let me, for argument's sake, slip for a moment into the position of the nuclear opponent (I am not a nuclear opponent). I know them well and I know their arguments, and to some extent I share them. The nuclear opponent in my place would say that if what you coal people and resource people are telling us is true, then nuclear power will undoubtedly come. But nuclear power is opening such a new domain, and new dimensions in terms of waste disposal and all the other things that we have not been used to dealing with, that it is such a radically new category that you coal people had better go back and think about your business more thoroughly. We do not mind if coal is expensive, even if it becomes 10 times as expensive; this is not my argument. Can you tell us how expensive the coal should be in order to multiply its production by, say, 10? I really wonder whether you think radically enough about that question.

Odell: If we take that argument a little further, thinking of coal in terms of being 10 times more expensive, could we come back to you, Sir Kingsley, and think of miners beng paid 20 times as much as today? I wonder whether your argument does not collapse, thinking of a society where every man has his price. And so this will not be an unacceptable method of producing coal, provided that the right price is paid. And that will lead us from your 5% perhaps up to the 10% or the 20% or the 30% or even the 50% recovery that has been mentioned in other instances.

Dunham: This is a quite open question. After all, it is in my lifetime and Odell's lifetime that people have done this sort of hand coal mining by which these resources could be recovered and of course no one has even suggested that at two or three times the price they might be willing to do it again. I do not know the answer to that--it is a very interesting question. I have been making the assumption that since we have a fully automated, fully mechanized method of coal mining the people would never go back. So, I am not sure about the answer.

Löennroth: Häfele wanted people to think you were ready to pay enough for coal. I would like to raise another awkward problem: although methodologies for meteorological problems are not yet completely developed sciences--and we are especially working on this in Sweden--there is some indication that already now the resources of coal are much more than we can ever use, because of the effect on climate if we release these vast amounts of carbon dioxide.

Fettweis: I would like to answer Häfele's question. First, I would say that for 10 times higher coal prices, in my opinion as a mining engineer, on the large scale and as far as we can judge it today, it would be more promising to continue primarily the modern kinds of mechanized coal production in open pits and underground and the research efforts in this direction than to try alternatives like in situ combustion or solvent extraction. I see the problems of the alternative processes mainly in the difficulties associated with controlling them under the conditions of a geological environment with its unforeseeable inhomogenities and discontinuities. On the other hand, for instance, it would probably not be such a problem to continue the development of modern open pit technology with economic success or automatic but man-supervised mechanized underground devices as the National Coal Board tried to do with its famous ROLF faces about 10 years ago.

Furthermore, of course, with 10 times higher coal prices it would be possible to mine more coal economically than we can now. We already have mature mechanized methods that today are not economic under unfavorable geological conditions but would be if there were higher prices. We could also find new methods for now sub-economic deposits, or we could take over methods from mining ores with higher values. It is difficult to give a figure for the increase of coal resources and reserves under such circumstances without special research for answering this question. But as a first rough estimate I believe the factor of multiplication would be nearer to two or three than to 10.

Styrikovich: One last word. I have attended many discussions of this type in the USSR. I do not think it is possible to compare coal or nuclear in absolute terms. In some cases coal is cheap enough to compare even with breeders, because of good geological conditions, good working conditions. In the USSR, as in other countries, there have been many struggles among the coal industry, oil industry, and others, and the result is that probably a best solution is a good combination of oil, cheap gas, cheap coal, and the best nuclear power source available. It is a question of proportion, but not of contradiction or confrontation. And to have a good, sound result, a percentage that is optimal, it is necessary to know how much economically recoverable coal you have, and not only the total quantity of coal reserves and resources. We always come back to the same fundamental point.

URANIUM RESOURCES

Uranium is a special material, and its present situation is no less special. Unlike other minerals, even mineral fuels, its use is unique for the time being, namely to produce energy, and almost exclusively electricity, through nuclear reactors.

Many burners for reactors have been studied and progressively abandoned. To develop a full reactor line is no trivial matter. Today almost all countries--apart from a very few, like Canada--have based their nuclear development on the pressurized or boiling Light Water Reactor (LWR). By way of interest here, say, for the fuel resources, it is clear that this type of reactor is the most demanding. It is somewhat paradoxical--and it is surely a subject for preoccupation--to consider that the most sophisticated of all energy industries has "invented" a product that will appreciably release the pressure on natural resources--I mean the breeder, operating with fast or thermal neutrons--and is heading toward dependence, probably for a long period, on the less efficient and most resource demanding of all the reactor types.

Assuming that the nuclear industry will be able to overcome its present difficulties (that are really more of an institutional, than purely technological nature), probably one of the main questions is how long will the LWR era last before the true commercial development of the breeder?

Regarding uranium resources, we can say that at present the mining industry seems to be getting out of a long period of market depletion, highly unfavorable to research and exploration. It is probable that more development--including methods and models for assessing uranium resources--is to come in the years ahead.

As in the sections on other energy resources, the first paper is a broad review. Its principal conclusion is that there is still tremendous scope for the discovery of uranium deposits up to the (1974-1975) $30/lb limit. But two different questions have to be answered. The first one is, where are these uranium deposits? The answer is a matter for exploration. The second question is probably more complex: will the necessary efforts to find this uranium really be made, or even more, are they possible, in view of institutional (political, financial, legal, etc.) problems?

Most of the other speakers confirm, one way or another, Cameron's general statements and conclusions. One model, one of the very few models developed to date for uranium resources, Brinck's Mimic, is even more promising, or more optimistic.

Then comes the problem of low uranium content ores, such as the Chattanooga shales. As for oil shales, the resource base seems huge. But also for oil shales, mining and other associated problems such as ecological impact are potentially so great that oil shale exploration on a very broad scale seem questionable, and exploration was anyhow questioned by representatives of industry. This justifies a thorough ongoing and parallel examination of the possibilities of extracting uranium from seawater, for which a possible technological breakthrough can compensate for being obliged to handle tremendous amounts of seawater. Uranium is a unique material. But fortunately, its forms of occurrence are very numerous.

A REVIEW OF LONG TERM URANIUM RESOURCES, PROBLEMS AND REQUIREMENTS IN RELATION TO DEMAND 1975-2025

J. Cameron

INTRODUCTION

The total requirement for uranium until the end of this century has been estimated at about four million short tons U_3O_8. Up to the decade 2020 to 2030 a quantity of as much as 16 million short tons may be required. To satisfy the requirements of the year 2000 and maintain an eight year forward reserve, some eight million tons U_3O_8 need to be identified by that year thus pointing to very high annual discovery and production rates at about the end of the century. To meet this demand some two million tons U_3O_8 probably extractable at a cost of under US $15/lb U_3O_8 are currently indicated.

The future of uranium is, therefore, a huge challenge to the geological, exploration and mining profession. A sum on the order of 17 billion dollars may be required for uranium exploration up to the end of this century. Past history (see Figure 1) indicates that uranium discovery has been very sensitive to sufficiently attractive price stimulation and, as exploration for uranium is, in world terms, at a very early stage in its history, the pattern of most other metals may well prevail whereby the fear that economic resources may come to be in short supply will call up a positive response of supply through economic incentives over long periods of time without major rises in real costs.

This hope is encouraged by the estimate that probably less than 15% of the world's geologically favourable potential has been thoroughly examined for low cost deposits, that even less of the world's potential for para-marginal (that is, 0.01% - 0.10% U_3O_8) has been examined and that very large resources of submarginal (<0.01% U_3O_8) is already known to exist. In the writer's view no shortage of uranium may be expected from any natural insufficiency of uranium resources in the earth's crust and that there is still a tremendous scope for the discovery of deposits which could be worked to produce uranium at a price acceptable to the nuclear power industry.

The problems are the maintenance of a sufficiently attractive price to stimulate exploration and production on a world scale, the availability of exploration and development finance, the identification of favorable ground and its availability for exploration, the development of new exploration techniques and,

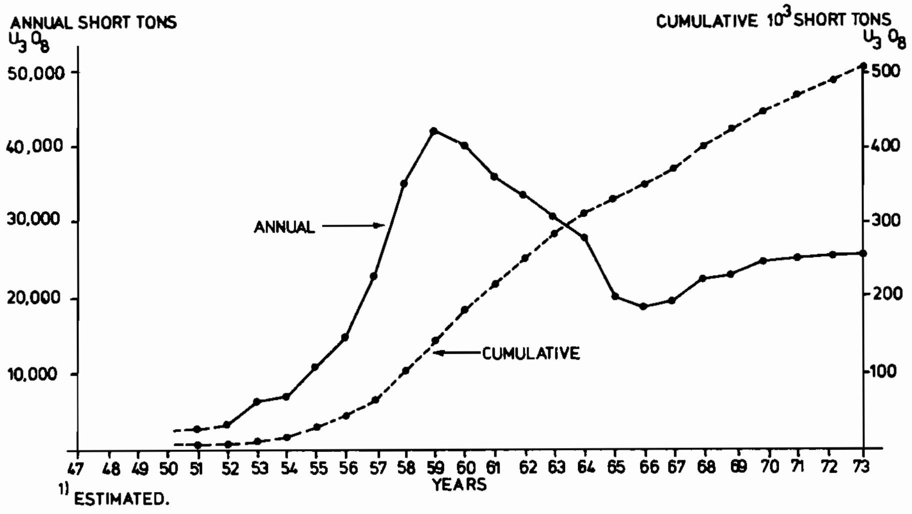

Figure 1. U_3O_8 production 1950-1973 in Australia, Canada, Zaire1), France, Republic of South Africa, United States and some other countries.

with the lower grade ores, problems related to uranium recovery, mining and environment despoilation and definition of cost acceptability limits by the nuclear power utilities. The overriding factor in the whole situation will be to establish a sufficiently attractive price level throughout the next decades to stimulate the necessary major exploration and development effort in all countries.

FUTURE DEMAND FOR URANIUM

Up to the end of 1974 about 65,000 electrical megawatts (Mw) of generating capacity were installed in the world's nuclear power stations and projections show that this is expected to increase to over 1,000,000 Mw by 1990, and to between 2.5 and 4.0 million Mw in the year 2000. The corresponding annual and cumulative world requirements for uranium up to 1990, taken from a survey by the joint NEA/IAEA Working Party[1]

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[1] Because of lack of information on the long term plans for nuclear power in the countries with centrally planned economies and a total lack of data on their uranium resources, the present analysis does not cover these countries. They are assumed to be more than able to meet their uranium requirements from their own sources and may even become potential exporters.

on "Uranium Resources, Production and Demand",[2] completed in 1973, are shown in Table 1 and illustrated diagrammatically in Figure 2. The medium range estimate shows a cumulative requirement between 1973 and 1990 of approximately 1,400,000 tonnes U or 1,820,000 short tons U_3O_8.

Table 1. Annual world uranium requirements.

(Assumes recycling of plutonium in LWRS; the use of a US stock of 38,500 tonnes U to enable the existing US enrichment plants to be operated at a tails assay of 0.30% U235 up to 1980, despite the continuing national use of a tails assay of 0.20% U235 in all contracts for USAEC enrichment services, and the operation of all enrichment plants after 1980 at a tails assay of 0.275% U235.)

	Lower Limit		Medium Range				Higher Limit	
Year	Case B_1		Case B		Case A		Case A_2	
	Annual	Cumu-lative	Annual	Cumu-lative	Annual	Cumu-lative	Annual	Cumu-lative
1973	16	16	17	17	17	17	17	17
1974	19	35	20	37	20	37	21	38
1975	23	58	25	62	25	62	26	64
1976	27	85	30	92	30	92	31	95
1977	31	116	35	127	35	127	37	132
1978	35	151	40	167	40	167	43	175
1979	39	190	45	212	45	212	56	231
1980	51	241	60	272	61	273	66	297
1981	56	297	67	339	69	342	76	373
1982	63	360	76	415	78	420	88	461
1983	68	428	84	499	87	507	99	560
1984	74	502	93	592	97	604	112	672
1985	79	581	103	695	108	712	127	799
1986	83	664	112	807	120	832	145	944
1987	89	753	124	931	133	965	163	1,107
1988	94	847	135	1,066	145	1,110	181	1,288
1989	98	945	145	1,211	158	1,268	201	1,489
1990	100	1,045	156	1,367	173	1,441	224	1,713

Reproduced from NEA/IAEA report completed 1973.

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[2] See "Uranium Resources, Production and Demand", A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, Organization for Economic Cooperation and Development (August 1973).

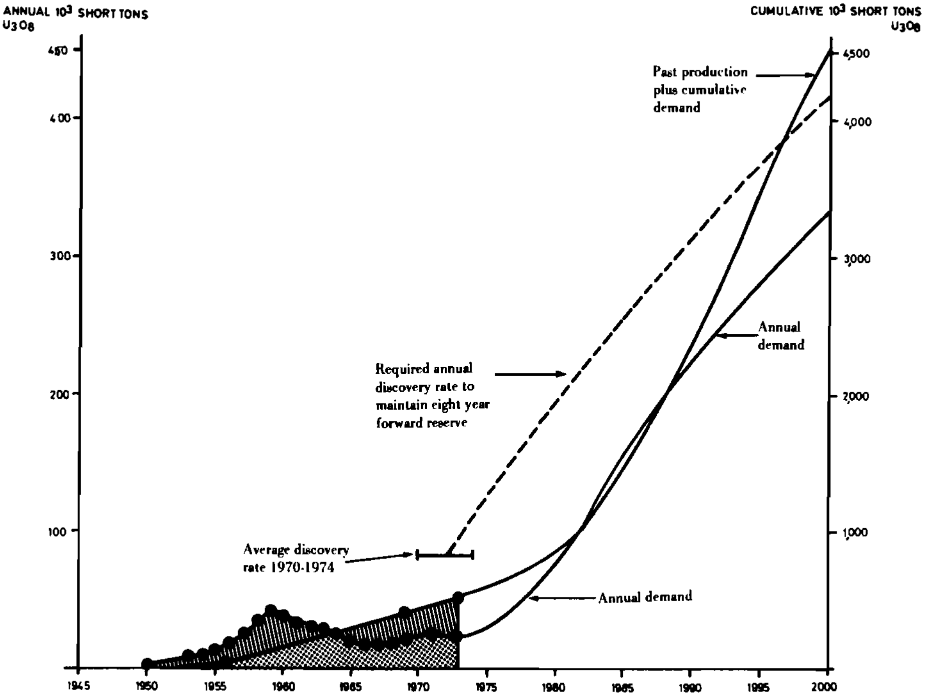

Figure 2. U_3O_8 past production 1950-1973 and projected annual and cumulative demand to 2000.

The joint NEA/IAEA report also indicates that from a present production level of just over 25,000 short tons U_3O_8 per year, the demand will rise under relatively conservative assumptions to an annual production requirement of 80,000 short tons U_3O_8 by 1980, 140,000 by 1985 and 225,000 by 1990. Few, if any, mineral production industries have been called upon to plan for a tenfold increase in production in a space of about 15 years as these forecasts imply.

Looking further ahead, it has been estimated that the requirements up to the year 2000 will be at least four million tons U_3O_8. (A comparison with the projected growth rate of eight other principal minerals up to the end of this century is shown in Figure 3.) A study group on reactor strategies convened by the IAEA in late 1973 to consider even longer term requirements indicated the probability that up to the years 2020/2030 a cumulative quantity of as much as 13 to 16 million short tons U_3O_8 might be required.

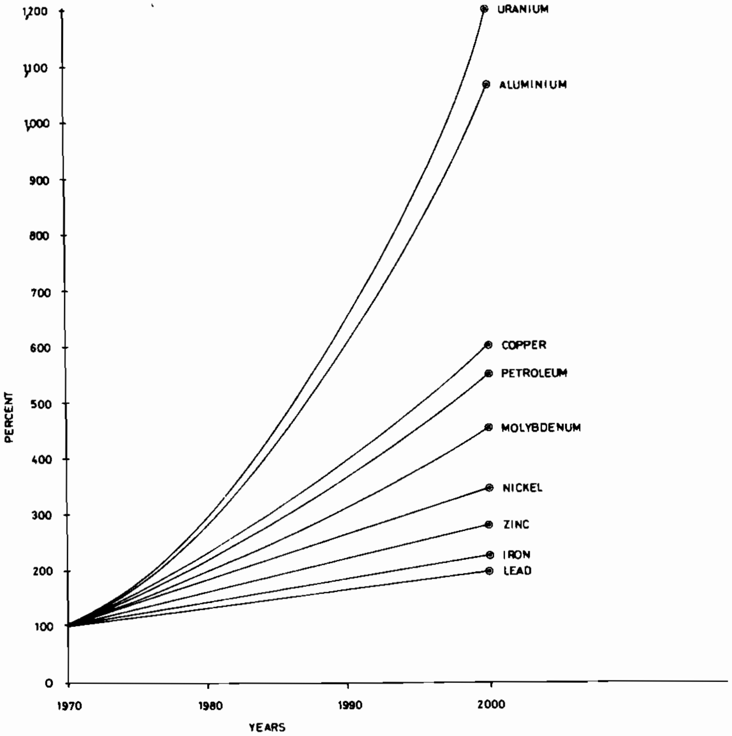

Figure 3. **World annual mineral production projected growth comparisons as from 1970 production rates.**

On these assumptions demand will continue to climb for some years after 2000 even if there is a successful commercial introduction of breeder reactors in the 1980's or 1990's. Light water reactors, installed in the last two decades of the century will, according to the present projections, require uranium supplies for their lifetimes of 25 to 30 years. The forecast of cumulative total uranium demand of more than 4,000,000 short tons of U_3O_8 up to the year 2000 and close to 16,000,000 by 2025 gives only the cumulative totals of consumption up to these dates and not integrated lifetime requirements and thus there is a further uranium requirement beyond 2025 that has not been quantified. The annual demand in the first 15 years of the 21st century will depend on the concentration of reactor type and installation rates in the 1980's and 1990's. If the currently predicted figures are approximately correct and even assuming a steady falloff in uranium requirements for nonbreeder reactors, there could still be a considerable increase in total uranium demand around the first 10 years of the twenty-first century as shown in Figure 4. In order to satisfy the estimated cumulative figures, annual demand might rise from 335,000 to nearly 600,000 short tons some time in the period 2005 to 2015 and might then fall to below 200,000 tons by 2025 pursuant to the full takeover by breeder reactors.

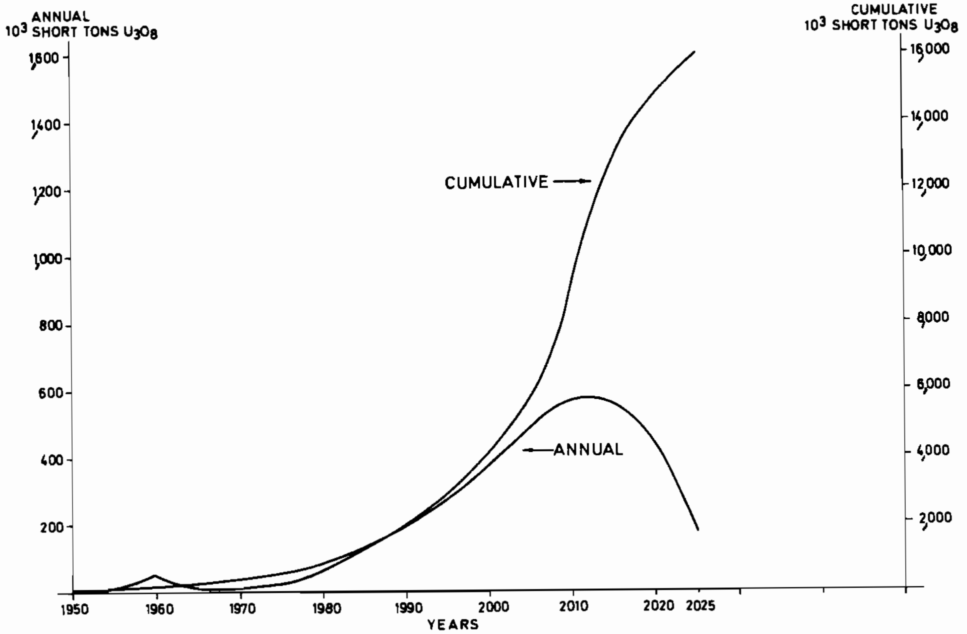

Figure 4. Past production and projected annual and cumulative demand to 2025.

URANIUM RESERVES AND RESOURCES

World surveys of uranium resources have been made at roughly two year intervals by a joint working party organized by the OECD Nuclear Energy Agency and the International Atomic Energy Agency. While a new study is currently underway (1975), the latest published survey is dated August 1973 and provides data up to mid-1973. At that time the "reasonably assured resources" in the less than US \$10/lb U_3O_8 category[3] (which are equivalent to reserves in the mining sense) amounted to 966,000 tonnes uranium or 1,126,000 short tons U_3O_8. The geographical distribution of these reserves and of the estimated additional resources and the resources in the US \$10/lb U_3O_8 price range is given in Table 2 (reproduced from that report). Since the date of compiling these reserves the principal alteration in the column showing less than US \$10/lb U_3O_8 reserves has been the considerable increase in the Australian reserves. In place of the figure of 92,000 short tons U_3O_8 given in the table it is now unofficially

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[3] Throughout this paper all monetary estimates refer to March 1973 US dollars of constant purchasing power, and should therefore be escalated from that date to cover intermediate inflation.

Table 2. Estimated world resources of uranium (data available January 1973).

Type of Resources / Country	Price Range < $10/lb U_3O_8 [1]				Price Range $10-$15/lb U_3O_8			
	Reasonably Assured Resources (Reserves)		Estimated Additional Resources		Reasonably Assured Resources		Estimated Additional Resources	
	10^3tonnes uranium	10^3 short tons U_3O_8	10^3tonnes uranium	10^3 short tons U_3O_8	10^3tonnes uranium	10^3 short tons U_3O_8	10^3tonnes uranium	10^3 short tons U_3O_8
Argentina	9.2	12	14	18	7.7	10	23	30
Australia	71	92	78.5	102	29.5	38.3	29	38
Brazil	-	-	2.5[2]	3.3	0.7	0.9	-	-
Canada	185	241	190	247	122	158	219	284
Central African Republic	8	10.5	8	10.5	-	-	-	-
Denmark (Greenland)	5.6	7.0	10	13	-	-	-	-
Finland	-	-	-	-	1.3	1.7	-	-
France	36.6	47.5	24.3	31.5	20	26	25	32.5
Gabon	20	26	5	6.5	-	-	5	6.5
India	-	-	-	-	2.3	3	0.8	1
Italy	1.2	1.6	-	-	-	-	-	-
Japan	2.8	3.6	-	-	4.2	5.4	-	-
Mexico	1.0	1.3	-	-	0.9	1.2	-	-
Niger	40	52	20	26	10	13	10	13
Portugal (Europe)	6.4	9.3	5.9	7.7	1	1.3	10	13
Angola	-	-	-	-	-	-	13	17
South Africa	202	263	8	10.4	62	80.6	26	33.8
Spain	8.5	11	-	-	7.7	10	-	-
Sweden	-	-	-	-	270	351	40	52
Turkey	2.2	2.8	-	-	0.5	0.6	-	-
USA	259	337	538[3]	700	141	183	231	300
Yugoslavia	6	7.8	10	13	-	-	-	-
Zaire	1.8	2.3	1.7	2.2	-	-	-	-
Total (rounded)	866	1,126	916	1,191	680	884	632	821

[1] $ value of March 1973: $1 = 0.829 EMA, u/a = 0.829 SDR (Spec. Draw. Rights). This $ value corresponds to $42.22 per fine ounce of gold.

[2] Plus 70,000 tonnes U by-product from phosphates.

[3] Plus 70,000 tonnes U by-product from phosphate and copper production.

stated that the Australian reserves are at least 300,000 short tons U_3O_8. The changes in the other countries listed have been less dramatic for the low cost type of reserve, but nevertheless the US \$10/lb U_3O_8 reserves now exceed 1,400,000 short tons U_3O_8.[4]

A significant proportion of the listed resources in the US \$10 to \$15/lb U_3O_8 category may now be workable only at a price above \$15 per lb and much higher cost material is in the same deposits as the low cost ore and may be lost as mining continues. On the other hand past estimates of \$10 to \$15 per lb uranium tend to have been conservative. Taking all factors into account, it is probable that some two million short tons U_3O_8 exist in deposits from which it is estimated they could be extracted at costs below \$15/lb U_3O_8.

In addition to the "reasonably assured resources" the joint NEA/IAEA report lists "estimated additional resources" as 1,191,000 short tons U_3O_8 in the under US \$10/lb U_3O_8 category and 821,000 short tons in the US \$10 to \$15/lb U_3O_8 category. These figures must however be read with due note of the definition of "estimated additional resources" which is stated in the report as follows:

> The term Estimated Additional Resources refers to uranium surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts, and which is expected to be discoverable and economically exploitable in the given price range. The tonnage and grade of estimated additional resources are based primarily on knowledge of the characteristics of deposits within the same districts.
>
> Consequently the Estimated Additional Resources usually do not represent material which is definitely known to be available and recoverable, but as defined above, may include, for example, postulated deposits in known uranium districts.

THE BALANCE OF SUPPLY AND DEMAND

As was noted by the NEA/IAEA Working Party, the present \$10 reserves, if they could all be used up, would just be sufficient to provide fuel up to the period 1987 for the case of medium power growth and high LWR installation rate. However,

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[4] As in the case of the demand estimates, information from the USSR, Eastern Europe and China could not be included in the report because data have not been made available. Therefore, where the word "world" is used in this report, these countries are not included.

the mining industry must maintain a forward reserve approximately equivalent to eight years' production to assure proper development of mines and a uranium supply at the projected rate. This concept of an eight-year forward reserve can be illustrated by displacing the demand curve so that it lies eight years earlier, thus in 1979 the currently known $10 reserves of 1,400,000 short tons U_3O_8 would correspond to the necessary eight-year reserves as illustrated in Figure 2. Since a substantial portion of the world reserves are in countries (for example, the Republic of South Africa) where the reserves could not be produced in that time frame, but rather over a period of 20 years or more, the eight year reserve position worldwide is likely to be inadequate to provide needed production levels.

In order to satisfy the requirements of the year 2000 and maintain an eight year forward reserve, some 8.0 million tonnes U_3O_8 need to be identified by that year and 16.0 million by the year 2017. Thus pointing to an annual discovery rate of nearly 600,000 short tons U_3O_8 in 2000 and dropping to probably less than 150,000 short tons U_3O_8 by 2025 (see Figure 4). The exceedingly high projected discovery rate at the end of this century may be one of the greatest problems in the uranium supply-nuclear power situation.

BRIEF HISTORY OF URANIUM

To appreciate the problems of the future, a review of past history is normally regarded as beneficial but in the case of uranium, past history is mainly relevant to the future only in regard to the relationship between price incentives and discovery rates and to changes in geological concepts.

The discovery of atomic fission at the outset of World War II triggered the first major demand. Increased and secure resources were sought but the greatest hope of the geological thinking at that time was to find new Shinkolobwe type deposits and to revive and increase production of known deposits. Little thought was given to the possibility that uranium might occur in other environments. From 1946 onwards, government-stimulated uranium exploration programmes were initiated in many parts of the world, and the history of events in the USA in that period is particularly instructive. The program started in April 1948 with price incentives published in three US Government circulars. The early incentives proved inadequate and it was not until after the publication of the 1951 revision of Circular 5 that the incentives were sufficient to cross the boundary from exploration reluctance to unbridled enthusiasm. The results are well known, few earlier metal exploration booms can match the uranium boom in the USA in the 1950's. Most of the significant discoveries were in new areas or new formations and were made by prospectors and, in most cases, contradicted some accepted concept of uranium occurrence or some reason why the prospect had earlier been eliminated. In addition to the discoveries in the western United States, two other major new resource areas appeared in the early 1950's, that is the quartz-pebble conglomerate deposits in the Republic of South Africa and Canada.

The uranium boom of the 1950's was so successful that by the late 1950's a surplus of uranium was evident and this, coinciding with a diminution in the military requirement, led to a period of depression in the uranium industry that lasted from about 1959 to 1966. Many small companies closed down and many supply contracts were cut or stretched.

In the 1960's nuclear reactors were developed from the experimental to the commercial stage and an apparent reduction in nuclear power costs together with assurances by certain sections of the nuclear power industry of a rapidly increasing potential market led to what has been called the "false boom" in uranium exploration lasting from 1966 to 1969. Particularly in the United States, the resurgence of exploration activity seemed even more vigorous than the boom of the 1950's, as for example the drilling footage in 1969 reached an all time high of more than three times the earlier drilling peak of 1957.

It soon became evident that reactor construction schedules were longer than expected, completion dates were continually postponed, reactor orders accumulated and nuclear power utilities were reluctant to commit themselves to large fuel investments for the long term. Except for continuing exploration in Australia another period of depression in the uranium exploration industry, particularly in North America, ensued from 1970 to 1973. Despite the very substantial forecast of future demand and the exhortations by national and international experts that a huge uranium exploration program was required, no marked acceleration in exploration was apparent in 1972-1973, mainly because the sales prices of uranium remained low (US $6 to $8 per lb U_3O_8).

However, a new assessment of uranium requirements for the long term nuclear power program was taking place among uranium mining companies and among power utility companies interested in controlling their own uranium supplies. A new feature, the interest of the large petroleum companies in uranium exploration was becoming evident. Into this slow and hesitant resurgence of interest came the energy crises of the winter 1973-1974 and the substantial rises in petroleum prices. The full effects are not yet assessed but forward contracts for uranium were agreed during 1974 at more than double the average price figures of 1973.

The factual historical background of uranium production is summarized in Figure 1. A peak production of just over 42,000 short tons U_3O_8 was reached in 1959 and after that there was a steady decline to 1966, when 19,090 tons were produced. The low point, however, was 1966 and small increases occurred in the succeeding years with over 25,000 tons being produced in 1973. The total cumulative production up to the end of 1973 was a little over 500,000 tons U_3O_8.

The huge tenfold annual increase in production rate in an eight-year period (1951-1959) was unique in metal mining and

OUTLOOK FOR THE FULFILLMENT OF DEMAND

Of the present low cost reserves of 1,400,000 tonnes U_3O_8 95% are in five countries plus associated countries (USA, 25.5%; Australia, 22.5%; Republic of South Africa, 20.0%; Canada, 18.0%; France and associated African countries, 9.0%).

This is a remarkable situation and immediately prompts the questions: is there a freak geological distribution of uranium in the world which favours these countries, or is it merely because heavy uranium exploration investment has been made in these countries? Almost all geologists will deny the first possibility and agree with the second. Uranium exploration started virtually in 1950 and, despite the tremendous efforts of the 1950's, is still very young and it has not yet been possible to make a real world wide uranium resources inventory.

From an IAEA survey of all Member States in 1969 it appeared that only about 15% of all the surface area classified as geologically "favourable" or "reasonably favourable" in the responding states had been surveyed in any detail at that time. That figure was heavily biased by the intensive work done in the USA and if that country were removed from the statistics, the figure came down to about 6%. This can only give a very general indication of the world's future unexplored potential but it is obviously no coincidence that the five countries which now control about 95% of the low cost reserves have also spent about the same proportion of the total world expenditure on uranium exploration since 1945. The only country which looks as if it is currently getting a diminishing return on its exploration expenditure for conventional low cost reserves is the USA. The USA tends to measure success or discovery rate in terms of pounds U_3O_8 discovered per foot drilled and, as illustrated in Figure 6, this has been showing a generally declining return since 1955. However, the areas concerned are relatively limited in extent and there are other possible reasons that this may yet prove to be a trend which can be reversed when current efforts in new areas begin to show returns.

Substantially all the present proven reserves and approximately 85% of the potential reserves as determined by the USAEC, are located in currently producing areas, yet these areas make up less than 10% or approximately 45,000 square miles of the region in which uranium occurrences have been found, and amount to only a much lesser percentage of the total area of the 17 western states of 1,800,000 square miles. Great areas of the country contain sediments and structural features of the same types and ages in which uranium ore bodies are known and are still relatively unexplored. Approximately 50% of the whole of the three million square miles of the United States is prospective territory and only a very small part of that area has been explored to any appreciable extent. Furthermore, surface geography is only a partial measure of the incompleteness of the knowledge of uranium resources. In the United States, commercial uranium deposits are known to exist at over 4,000 ft based on a uniquely successful discovery and development rate. In 1951, world uranium reserves were estimated at around 20,000 tons, and in 1958 the figure was stated as being approximately one million tons. In contrast, the world is now facing very much larger requirements and the need is, therefore, for an even greater exploration effort than was deployed in the 1950's. The contrast between the past and future efforts is illustrated by Figure 2.

The relationship between net annual discovery rate and the actual average price paid annually for uranium in the United States is shown on Figure 5. A lag of about three years between a major price change and a major change in the annual discovery rate is evident. The second peak discovery period in 1969-1970 was more related to a stable price period than a marked change and other factors influenced the "false boom" of that period. The downturn in prices between 1968 and 1971 was, however, clearly reflected in the downturn in the discovery rate about two to three years later.

It seems only fair to pose the question on whether the jump in forward price rates in 1974-1975 to about US $13 to $15/lb U_3O_8 will be reflected in an increased discovery rate in 1977-1978 (Figure 5). Or, perhaps more significantly, will it be enough to bring out the necessary exploration effort?

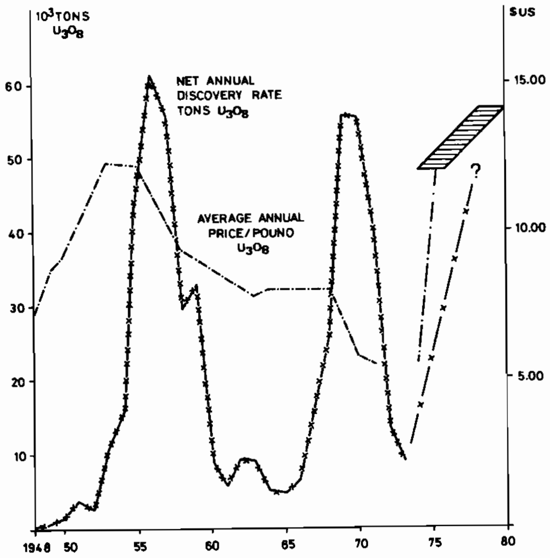

Figure 5. Net annual discovery rate and annual average price paid per pound U_3O_8 in the USA for the period 1948-1973.

The sum of the cumulative production and ore reserves in the USA is shown in Figure 6. It is salutary to reflect that in 1948, 2,200 tonnes was the listed reserve and that many respected geologists of that time reflected on the possibility of future reserves being (eventually) as much as four to five times that amount. The 1973 situation wherein production and ore reserves amounted to about 250 times the 1948 figure was not visualized by even the bravest of forecasters.

Australia has also seen remarkable changes in exploration activity, reserves and geological concepts; it is a prime example of what exploration efforts and expenditure can do in relatively new potentially favourable areas. In April 1969, the official reserves of low cost U_3O_8 were 10,700 short tons. This was contained mainly in small to medium sized hydro-thermal vein type deposits in very limited areas in Queensland, South Australia and the Northern Territory. The explosion of work which started in 1968-1969 was prompted by apparently attractive returns related to a general mining exploration boom in Australia. Five years later, reserves were over 300,000 tonnes U_3O_8 and at least three entirely new fields had been discovered, the Alligator River area, Western Australia and South Australia. At present yet another new uranium province known as the Ngalia

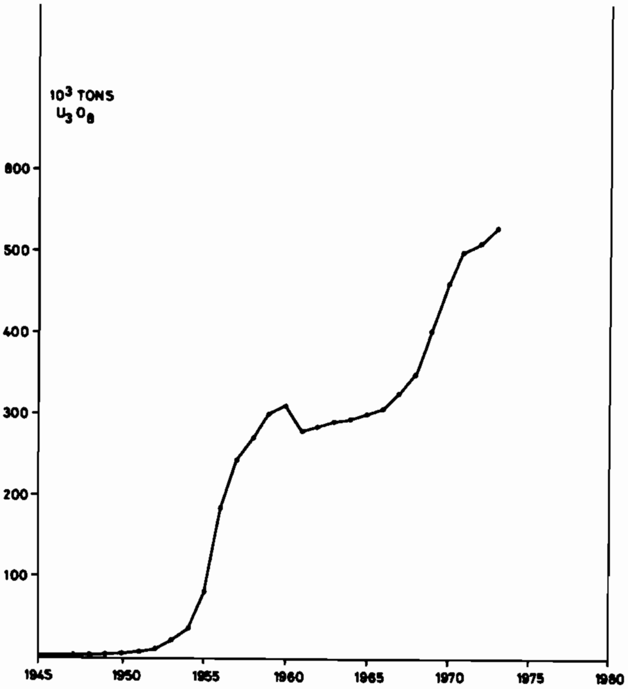

Figure 6. Sum of cumulative production and ore reserves in the USA 1948-1973.

uranium basin with apparently considerable potential is being investigated about 200 kilometres northwest of Alice Springs. These discoveries have also brought a revolution in geological concepts as at least three major new types of ore deposits have been found.

Thus in the United States, over a period of 25 years, uranium resources increased 250 times and in Australia, in the much shorter period of five years, uranium resources increased about 30 times. At the height of exploration activity average growth rates of 100% per year were reached for a period of eight years in the USA in the early 1950's and for a recent five year period in Australia. It is obviously impossible to imply from this that the simple input of exploration funds and competent exploration effort would result in a similar increase in any part of the world, but it is highly probable that in many countries, vast favourable areas would respond in a similar fashion if such expenditure were made. Even in the present five major uranium countries very large areas remain to be explored. These countries occupy some 12 million square miles of the world's total area and excluding the USSR, Eastern Europe, China and Antarctica there still remains some 26 million square miles of surface area in other countries of the world where there has been relatively little expenditure on uranium exploration (certainly less than 10% of the world's total). In this vast area there remains a great many favorable host areas which are almost or completely unexplored.

As in the case of crude oil, there is a long record of pessimistic predictions about running out of supply and a long record of supply response to economic incentives with only a very modest trend towards rising real cost. There is every reason to believe that the best deposits of uranium may not yet have been found. It would be somewhat fortuitous if the world's best deposits were so fortunately placed that they were relatively easy to discover so early in the history of uranium exploration. It is probable that we should not only be looking with expectation to new resources of lower grade, but also to undiscovered deposits of higher grade. The Narbalek deposit in Australia, Shinkolobwe and Great Bear Lake may not be unique high grade deposits.

In summary, uranium exploration is young and low cost resources or at least resources within a cost level acceptable to nuclear power utilities, and of a quantity sufficient to fuel reactors until well through the next century are geologically likely to exist in deposits not very dissimilar to those already known. Intensive investment in exploration will, however, be necessary to achieve the desired result. Exploration expenditure will be heavy, possibly of the order of 17 billion dollars (present value) before 2000 or 35 billion dollars before 2017 to achieve the required uranium.

HIGHER COST URANIUM RESOURCES

In considering the next higher cost category of uranium resources it may be noted that up to the 1967 issue of the NEA/IAEA Working Party report a reasonable assured resources category for $15 to $30/lb U_3O_8 was identified and amounted to 664,000 short tons U_3O_8. However, the category was abandoned in later editions up to 1973, as it was felt that such material was not likely to be worked in the short term. In the new price situation such resources will now have to be reconsidered. As little interest has been given to work on this material, the validity of the estimates will also require more detailed assessment. If a figure of this order of magnitude is accepted for the $15 to $30/lb U_3O_8 category the present situation for all uranium below $30/lb U_3O_8 is of the order of 2,700,000 tons U_3O_8. Such a figure would, however, have to be severely qualified by availability.

Past exploration has generally been directed to deposits with average grades greater than 0.1% U_3O_8 and at the other extreme a good deal is known about the characteristics and the problems involved in the very high cost material such as the Chattanooga shales, granites, phosphates, etc. There is, however, a considerable gap in knowledge about uranium between these two extremes and it is a reasonable expectation that once exploratory effort is directed towards sources of uranium with grades lower than 0.1% U_3O_8 substantial resources may be identified. With increased prices and assured markets deposits the potential for the discovery of deposits with grades in the range 0.1% to 0.01% U_3O_8 may be so considerable that it may not be necessary to rely on sources in shales and granites over the next 50 year period.

In the past, the history of other metals has followed a pattern that as grade declined, technology was developed to maintain extraction and recovery costs close to their earlier levels--or even below them--so there is some possibility that the present higher $15 to $30/lb category reserves may become relatively lower cost reserves in the next decades.

Enormous quantities of uranium have been identified in marine black shales, marine phosphorites, granites, seawater and other unconventional sources. At present these resources are not an economic source of uranium, but with improvements of technology and higher prices, they have the potential to provide ample uranium past the first quarter of the next century. However, to produce these resources at a reasonable cost of say 50 dollars per lb of U_3O_8 it would be necessary to fund a research and development program on exploration, milling and mining techniques, principally to select the economically most favourable material. Some potential forecasts from an informed basis have been attempted in the USA such as those listed by R.D. Nininger.[5] In his paper, reserves in shale of the order of five million tonnes U_3O_8 in the \$50/lb U_3O_8 category are listed for the USA alone. Other high cost resources in shales, granites and seawater exist in quantities far exceeding any visualized nuclear power requirement. There is no problem in the existence of more than adequate tonnages of low-grade high cost uranium such as could be recovered from these sources. It is not likely to be worthwhile expending time and energy on identifying and quantifying this material. The energy balance of material from low grade deposits of less than 0.01% has been analyzed and it was concluded that this factor need not necessarily be a fundamental constraint to the production of such resources.

As an example of the energy balance, a study has been conducted by the Battelle Pacific North West Laboratories on Chattanooga shale. An average concentration of uranium oxide in the Chattanooga shale[6] is assumed as 0.006% and from this that 1% of the uranium atoms mined are eventually fissioned. One ton of shale contains about 0.118 lb (0.054 kg) of uranium and 1 kg of material fissioning produces thermal energy of 69×10^9 Btu; therefore, each ton of shale contains the equivalent of 37×10^6 Btu. Taking a typical coal figure of 10,000 Btu/lb, the gross energy per ton of coal is equivalent to 20×10^6 Btu. Thus on a gross basis, Chattanooga shale is superior to coal as an energy source; however, these calculations do not include certain steps in the processing of both shale and coal which involve energy consumption or material losses. In a final analysis which involves the whole net energy balance throughout the mining to fuel reprocessing cycle, it was concluded that coal and Chattanooga shale give equivalent quantities of electrical energy per ton in terms of net energy delivered per uranium mass. Coal and Chattanooga shale, down to a grade of 0.006% can be considered equivalent.

The limiting factors on the utilization of low grade material of this nature will be the price which the utilities can tolerate and the environmental constraints on mining the huge ore tonnages necessary to recover the required uranium tonnages. Ultimately there are huge resources of uranium in seawater but opinions on the cost and practicability of extracting it are divided and uncertain.

Each resources category must be qualified by cost and until the nuclear power utilities can define the upper limit which they could tolerate for uranium yellow cake cost it will continue

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[5] See R.D. Nininger, "Uranium Reserves and Requirements", Atomic Industrial Forum Uranium Seminar, Oak Brook, Ill. (March 1973).

[6] See "Assessment of Uranium and Thorium Resources in the United States and the Effect of Policy Alternatives", Battelle, Pacific Northwest Laboratories (December 1974).

to be difficult for the mining industry to decide long term exploration and production policies. It should be noted, however, that even at $15/lb U_3O_8 the cost of the raw material is of the order of 10% of the total cost of generating electricity in typical nuclear power stations at present in use, hence doubling of uranium costs would only imply a 10% rise in the cost of nuclear electricity.

REAL AMOUNT OF URANIUM RESOURCES, ESTIMATING METHODS

Any attempt to make a quantitative appraisal of the ultimate size of the world's uranium resources, based on information currently available is extremely speculative. The only course is through exploration extended greatly in both quantity and scope and coupled with continuous speculative and intelligent interpretation of the geological data.

Continuing and greater efforts must be made along the lines of the IAEA studies to identify what is and is not favourable geology for uranium deposition[7] and also further efforts at regular intervals, similar to the IAEA's 1969 survey, must be made to identify areas of the world which have already been surveyed in sufficient detail to enable it to be said with some confidence that surface evidence of uranium mineralization is adequately known. Attempts to compute the division between favourable and unfavourable ground should continuously be made. In addition to the statistics, intelligent speculation about the unknown, based on past history must continue.

In recent years new definitions for such crucial terms as reserves and resources have been adopted by the US Bureau of Mines and the US Geological Survey. The new definitions are intended to describe more accurately the estimated production potential of mineral deposits. The classification system agreed on is based on the extent of geologic knowledge about the resource and the economic feasibility of its recovery. The system devised has been publicized but attention is drawn to it (Grenon's Figure 4) and it is suggested that the definitions used should be respected in any attempt to quantify uranium resources both for the present, intermediate and long term future. A modification of the system has been proposed by the Department of Energy, Mines and Resources, Canada, in a document published in early 1975 entitled "Departmental Terminology and Definitions of Reserves and Resources". This is illustrated in Figure 7.

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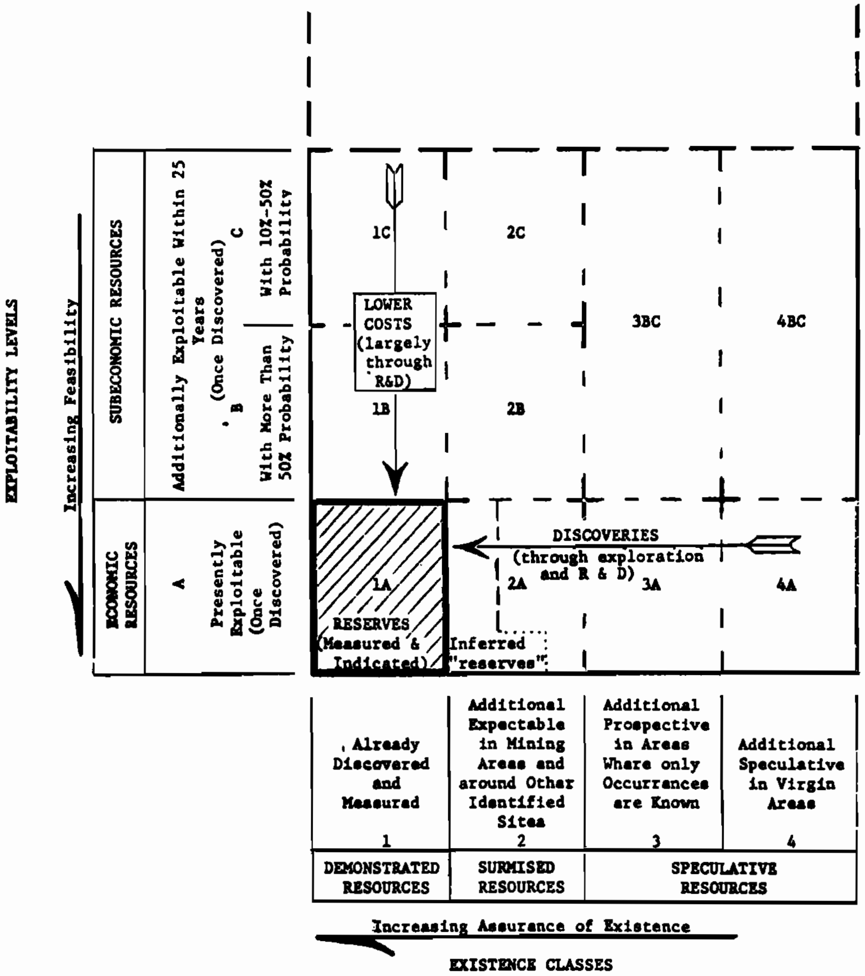
[7] See "Uranium Exploration Geology", Proceedings of a Panel, Vienna, 13-17 April 1970, International Atomic Energy Agency, Vienna, 1970; and "Formation of Uranium Ore Deposits", Proceedings of a Symposium, Athens, 6-10 May 1974, International Atomic Energy Agency, Vienna, 1974.



RESERVES (measured & indicated) = 1A (that is, demonstrated economic resources)
RESOURCES = RESERVES + all other numbered areas
RESOURCE BASE = RESOURCES + indefinite area beyond top of diagram

Note: It has been found impossible in practice to make distinctions between 3B and 3C, and between 4B and 4C.

Figure 7. Terminology and definitions of reserves and resources as proposed by Department of Energy, Mines and Resources, Ottawa, Canada.

Studies designed to estimate total uranium resources have been attempted in the past are of two basic types, firstly those that use current geological knowledge of uranium deposits as a basis for the estimating of undiscovered resources and, secondly, those that are basically statistical. Examples of the first type can be found in many areas and normally are simply extensions of favourability criteria from a known deposit into surrounding or nearby areas with similar geological features. On a small scale this is common. On the larger world scale the attempt to identify uranium bearing quartz pebble conglomerates as advocated by the IAEA[8] Working Group No. III is an example. In two areas of the world this may have some success and importance for the future.

In Brazil the Moeda conglomerate is currently being investigated near Belo Horizonte and, in the Jacobina area, several hundred kilometres to the north, similar uranium-gold bearing conglomerates have been known for many years. It is thought that similar conglomerates extend throughout the intervening area which is almost totally unexplored. How to quantify this potential on present evidence is a daunting task but if the most optimistic view were taken, very large tonnages might be involved. Similar extensive but unquantified conglomerates are also beginning to be explored in southern India. The geologic approach does, however, have shortcomings, especially if any attempt is made to use it comparatively with ultimate resource estimates for oil and gas where the problem is relatively much more simple than for uranium. The basis of oil and gas appraisals rest on a long history of exploration, a generally agreed concept of source and an understanding of the processes whereby oil and gas are trapped. None of these factors can, as yet, be satisfactorily used for ultimate resource estimates for uranium.

The second type of estimate, such as that by McKelvey (1971),[9] uses as a basis the crustal abundance of elements and the experience of other metals. This method, particularly a review of the exploration history and the resulting reserves for metals that have a much longer history than uranium, could be a useful indicator of the future of uranium. Studies of the economic histories of other metals showing world reserves, exploitable grades, production levels and prices at say 10 or 20 year intervals from the early nineteenth century onwards could be compared with uranium history from 1945 and suitably modified by all relevant geological data might be useful in predicting uranium potential for the next 50 years.

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[8] See "Formation of Uranium Ore Deposits", Proceedings of a Symposium, Athens 6-10 May 1974, International Atomic Energy Agency, Vienna 1974.

[9] See V.E. McKelvey, "Relation of Reserves and Elements to Their Crustal Abundance", A.M. Journal of Science, Bradley Volume (1960).

Statistical studies by Brinck are well known[10] and employ a statistical analysis of a sample population: The statistical approach has the advantage of being unaffected by our present conceptual biases. However, it can only be successfully applied if we have an adequate sample and, owing to the short history of uranium exploration and the small proportion of the earth's crust that has been examined, it is doubtful whether we do have, as yet, an adequate sample. The statistical approach alone is not sufficient and imaginative forecasting both on types of occurrence and on techniques will be necessary to achieve a better evaluation of future possibilities.

Brinck's calculations based on 1967 uranium reserves required modification in 1971 because of the changes in reserve figures and would now require further modification because of the recent changes in reserves and prices. Nevertheless, this author has considerable sympathy for Brinck's general conclusions (in "Calculating the World's Uranium Resources"): "... compared to all foreseeable requirements no shortage of uranium ... may be expected from any natural insufficiency of uranium resources ... the long-term supply question appears to be essentially a politico-economic problem ...".

POLITICO-ECONOMIC PROBLEMS

The problem of ensuring future uranium supplies is not likely to be purely geological nor even of the capability of the geological and mining profession to discover and develop deposits. It is more likely to be compounded of politico-economic constraints limiting the availability of search areas and of exploration and capital investment funds at the right times and the right places. Even in the main uranium reserve countries, governments are currently not sure as to what uranium resources policies should be followed. There are signs of governments imposing restrictions on the opening of new deposits and of governments imposing conditions of sale and limiting the activities of companies wishing to undertake exploration. For the governments of the less developed countries the problems are frequently even more complex.

Nuclear power forecasts to 1990 show that 95% of all projected installations will take place in approximately 18 advanced industrial countries and only 5% in developing countries. A similar proportional relation is likely to continue over the following decades. On the other hand, 95% of the world's present low cost reserves are in Australia, Canada, France and associated African countries, the Republic of South Africa

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[10] See J.W. Brinck, "Calculating the World's Uranium Resources", Euratom Bulletin, VI, 4, 109, and J.W. Brinck, "Mimic", Euro Spectra, X, 2, 46 (1971).

and the USA and, as it is problematic whether these countries can continue to supply the very great requirements of the future, it would be desirable to make very considerable exploration expenditure in other countries, including developing countries.

Two, not always clearly defined, groups of developing countries exist, first, the more advanced countries which expect to have their own nuclear power reactors and whose first interest will be to discover and develop uranium deposits for their own utilization. Only if obvious excess reserves were found would these be likely to be available for export. Up to now, uranium exploration in such countries has nearly always been restricted to national organizations. Despite considerable efforts in many such countries the financial resources and, at times, the skills necessary to make exhaustive national surveys in depth have not always been available. The danger is that underfunded surveys may result in a false impression of the real potential of geologically favourable areas in some of these countries. The less advanced, low population countries with little expectation of having their own nuclear power program in the foreseeable future are more likely to think in terms of direct commercial export of uranium but are unlikely to have the finance and/or the skills to mount the exhaustive and costly uranium exploration and development programs that will be required.

Whether developing countries of both types will wish to invite major organizations either commercial or national from the advanced countries to either assist them or to take up exploration and development concessions will largely depend on the political outlook of their governments. An understandable caution is likely to be evident but certain factors may influence their decisions: 1) the commercial importance of uranium on a large scale may be limited to 50 to 70 years (see Figure 4); 2) the scale of the finance required for major exploration and development programs is likely to be only available in the commercial or national organizations in the advanced countries or through OPEC development funds; 3) the rewards, depending on the agreements made, should be attractive.

On the other hand, many major mining organizations in the advanced countries that could provide the finance and the skills required may be very cautious in their approaches to some developing countries. The past history of the nationalization of metal mining in many developing countries has induced this caution. The more accommodating developing countries and the more accommodating national or international mining groups are likely to reap the greatest mutual benefits.

One of the biggest challenges of the future will be the financing of the required exploration and development effort, particularly against a background of a frequently unpredictable future relationship between financial sources and the potential foreign host countries of all stages of development. Future contracts will have to give consideration to floor prices to provide protection for producers, formulae for sharing the risk of currency fluctuations and substantial down payments to finance producer expansion.[11] International-multinational aid through such organizations as the United Nations Development Program or intergovernmental banking institutions is attractive but unfortunately there is little expectation that finance of the order of magnitude required could be provided.

Some part of the problem might be resolved if the purchasing utilities were willing to pay a higher price than is strictly necessary over the next 10 to 20 years simply to encourage exploration and production capacity construction. How to convince the utilities that such short term philanthropy would be in their long term self-interest is difficult to envisage, unless there is a trend (already evident) towards a vertically integrated industry with the reactor utilities themselves getting increasingly into the business of uranium exploration and production.

A problem that remains, however, is whether sufficient mutual confidence can be built up between the financial sources and the governments of developing countries with uranium potential to allow enough exploration to be done within the time scale required. If this cannot be done it is probable that the search will be intensified in the present uranium countries and in other advanced countries both to find new low cost subsurface deposits and to promote the technologies required to exploit lower grade deposits. Geologically and technically it is not impossible that adequate supplies could be found in these countries although probably at a higher cost and with environmental problems.

The vast waste disposal problem and the environmental despoilation arising from any major attempt to produce from low grade ores in the advanced industrial countries may be of such a magnitude that it will encourage the industry to try to resolve any problems with developing countries and increase the search for higher grade ores with their lesser environmental problems. A sufficiently attractive uranium price would facilitate this objective.

A consequence of any failure to establish major uranium sources in developing countries will be a continuance of the dominance of the present main uranium countries. This would gradually assume increasing politico-economic importance as the proportion of the world's electrical energy generated from nuclear sources increases and the petroleum reserves of the world decrease. In these circumstances, the balance of politico-economic power deriving from control of primary energy resources might well be very different by the end of this century from what it is now.

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[11] See R.M. Williams, "Uranium to 2000, An Exploration Challenge", Dept. of Energy, Mines and Resources, Canada, Annual Meeting of the Prospectors and Developers Association, Toronto (March 1975).

CONCLUSIONS

An attempt has been made to present the views given in this paper in Table 3. The system used approximates to that recommended by the US Bureau of Mines and the US Geological Survey but also attempts to indicate what in this author's view are the main problems and requirements of the future.

The principal conclusion is that there is still a tremendous scope for the discovery of uranium deposits up to the \$30/lb limit. Geologically there is a good probability that such uranium exists, and up to the quantity of 16 million tonnes U_3O_8 that the reactor strategy studies indicated are needed to service nonbreeder reactors up to about 2025 assuming a significant introduction of breeders only from the mid-1990's onwards. The problems, however, are a) locating the deposits (and this means having both the technique and the funds to do so), and b) having located the deposits, being able to exploit them.

The fulfillment of the currently predicted demand for uranium is not likely to be an impossible task for a well organized, well stimulated uranium exploration and mining industry but the building up of confidence in the now predicted nuclear power timetable will be vital in assisting the mining industry in actually achieving the targets envisaged.

Considerable potential remains to be explored in developing countries but whether such potential can be realized will depend on the building up of confidence between the governments concerned and the sources of finance and technical skills which are mainly available in the more advanced countries and, most important of all, in the establishment of a sufficiently attractive price level to stimulate the exploration and development of uranium resources in all countries.

In summary, exploration for uranium is at a very early stage. The pattern of most other metals may well prevail in the case of uranium whereby a fear that the world may run out of economic resources calls up a continuing positive response of supply through economic incentives over long periods of time without any major rises in real costs.

In considering higher cost reserves, that is about \$30/lb U_3O_8, enormous quantities of uranium have been identified in marine black shales, marine phosphorites, granites, seawater and other unconventional sources. At present these resources are not an economic source of uranium, but with improvements of technology and higher prices they have the potential to provide ample uranium for any visualized nuclear power requirement. The limiting factors on the utilization of low grade material of this nature will be the price which the reactor utilities can tolerate and the environmental constraints on mining huge ore tonnages necessary to recover the required uranium.

Table 3. Summary of a view on ultimate uranium resources, problems & requirements in relation to uranium demand 1975-2025.

Categories $/lb U_3O_8	Grade % U_3O_8 (approx)	Reserves Short Tons U_3O_8 (demon.)	Reserves Short Tons U_3O_8 (inferred)	Indicators of Undiscovered Potential (Hypothetical & Speculative)	Problems	Requirements
< $15 (Reserves)	>0.1	2,000,000	2,000,000	Probably less than 15% of the world's geologically favourable potential has been thoroughly examined	1. Establishing confidence in the nuclear power industry's forecast 2. Maintaining an attractive uranium price 3. Availability of exploration and development finance 4. Politico-economic problems with developing countries 5. Identification of geologically favourable ground and its availability for search 6. The limited life of high uranium demand and the very high annual discovery and production rate required for a limited period near the turn of the century	1. A sufficiently attractive price incentive 2. Sufficient exploration finance 3. An intensive exploration effort in all countries 4. Stat. studies on completed exploration to help indicate remaining favourable ground 5. Stat. comparisons with histories of exploration & devel. of other metals 6. Development of new exploration techniques & research 7. Solution of politico-economic problems 8. Sufficient finance for mine & mill capital invest.
$15-$30 (para marginal)	0.01-0.1	1,000,000	500,000	Possibly less than 10% of the world's favourable potential has been examd	Same as all of the above plus 7. Technical recovery problems 8. Mining environ. problems	Same as above, plus 9. Specific explor. programmes for this cate. of ore 10. Ore process. research 11. Studies of costs on environ. rehabilitation
$30-$100 (submarginal)	< 0.01	> 13,000,000	Very Large	Very large unquantified resources are geologically indicated	Same as all of the above, except for five, plus 9. Defin. of cost acceptability limits and/or energy balance limits by the nuclear power utilities	Same as above, plus 12. studies on limits of acceptability of cost by the nuclear power utilits.

DISCUSSION

Häfele: First, what is your observation about resources in the class beyond \$15/lb (and below \$30/lb)? The figures officially given (500,000 tons) are smaller than the ones in the class below \$15/lb (2 million tons). This must be artificial--one did not look into such uranium before, and the real figure is probably significantly larger.

Second, the various reactor strategies considered give differences only beyond the year 2000. If technological strategies are to be assessed, should one not extend the time horizon of the official studies? Also along these lines, the side effects of large scale mining should also be identified. Could you comment on that?

Cameron: I agree with you that the main reason for the lower price category showing the greater tonnage figure is that in the short history of uranium exploration and development there has been less interest in searching for low grade material, in the range of say 0.01% to 0.1% U_3O_8, in normal types of uranium deposits. The probability is that at the present time it is simply a lack of knowledge. I have tried to reflect this in my paper by saying that perhaps less than 10% of the world has been looked at for this type of low grade uranium.

With regard to your second question, I agree that in official documents we have up to now been fairly cautious and made predictions only up to 1985 or thereabouts. I am perhaps expressing personal opinions in going up to 2025 and making forecasts of this kind. In my view, there is enough exploration left in the world to encourage us to continue to look for relatively low cost uranium deposits. If found, these would have no greater individual environmental problems than the mines of the present time. If, however, we have to go down to the very low grade material, the environmental problems are considerable indeed.

Khazzoom: You emphasized the need for stable price expectations. This obviously has a carry over to electric utilities and to policies adopted toward utilities.

Bauerschmidt: The figures you have shown us do not include the socialist countries.

Cameron: No.

Bauerschmidt: Can you give some idea of the figures for the socialist countries?

Cameron: No, I regret that I cannot give you such figures. The socialist countries are IAEA Member States, but their figures on uranium supply and demand have not been made available to the IAEA.

Polliart: We consider that the potential for uranium demand in socialist countries is sufficiently covered by supply within these countries.

Hutber: Referring to Figure 4 of your paper, the bulge in production shown in the early years of the next century is the first half of a transient cycle covering the adaption to the fast reactor system and caused by the fact that the cumulative production of uranium up to the introduction of the fast reactor can be used to fuel the fast reactor. What is the underlying level of uranium production required to support the fast reactor in the early years of the next century?

Cameron: The net consumption of uranium in fast breeder reactors over their lifetime is calculated to be on 2% of that which it would be for light water reactors. Making very broad assumptions on the mix of fast breeder and light water reactors and the total demand up to 2025 we estimate that there might still be an annual requirement of between 150,000 and 200,000 short tons of U_3O_8 in the year 2025.

Sickler: Have you also looked at thorium resources in the world?

Cameron: I have not dealt with them in this paper. The reserves are very considerable and it has barely been worth any serious estimating attempt at the present time. There are technological problems on recovery perhaps, but reserves as such are very high.

Sickler: Did you consider thorium as well because there is a certain substitute possible in the design of atomic reactors?

Cameron: If the nuclear demand experts tell us that we should consider thorium in more detail, then we must do so.

Clegg: The scale of mining operations involved in producing about five million tons or even up to 50 million tons of U_3O_8 over the next 30 years or so from source rocks containing 0.01% to 0.1% of uranium seems small compared with those likely to be necessary in the development of coal tar sands or oil shales. Why are the environmental problems associated with U_3O_8 production, therefore, likely to be so severe?

Cameron: For one thing, coal is almost totally consumed, while with uranium the fraction that is being removed is about 0.1% or less. Everything else goes in a dump. That is one very big difference.

Clegg: But you have that problem in shales or in tar sands. And in the tar sands you already have something on the order of 70 million tons of material handled per year. I was wondering whether it is a pseudo-problem or a real problem for uranium.

Cameron: I think it is a real problem. For example, in Sweden there are already some very considerable doubts about the use of the uranium resources there, and with the Chattanooga shales it is the same. The problems are largely connected with the environment.

Häfele: For clarification: these types of concerns came up only recently--I mean only in the last few years or so. The Chattanooga shales have something like 60 ppm or something on that order of magnitude, and if you face the pollution impacts with respect to the energy content harvested, they are indeed very much the same kinds of problems that you have with oil shale. But these are only recent observations, first of all, because a couple of years ago such reserves or resources were not considered. The considerations for oil shale were not of interest then, and neither was the use of low-grade uranium. So all this is a recent development, and one has to be careful to make it distinct as compared with discussions before the oil crisis.

Cameron: What biases me towards looking for low content uranium is that I think the potential for discovery of low cost uranium still exists.

Grenon: Anyhow, I think that the uranium shales, with the figure you gave of 150,000 tons of uranium per year, will mean about two billion tons per year of uranium shale, which is not a small problem.

Dunham: We have been assuming through this that the fast breeder will work on a commercial scale and, of course, we do not know this. It may, but we do not know for certain. It probably will. But supposing it does not. How does Cameron feel about the capacity of the industry to keep the ordinary present type of reactors going?

Cameron: If the fast reactor does not come in as a major producer by the early part of the next century then there will undoubtedly be a uranium supply problem. Whether advancing technology can help to alleviate the problem is impossible to forecast at this time.

Fettweis: Of course there will be environmental problems mining the low grade uranium resources. But these are technological problems and on the same order of magnitude as, for instance, those we have and can solve in the copper mining industry. So I think there is no limit for mining these deposits.

URANIUM RESOURCE ASSESSMENT IN THE UNITED STATES

Robert W. Schnabel and Warren I. Finch

INTRODUCTION

Uranium is a ubiquitous element--a little is found in nearly every naturally occurring material, and it is concentrated in many different geologic environments. Thus, uranium differs markedly from the fossil fuels both in its occurrence and how its resources can be assessed. On the one hand uranium behaves like other metals in its mode of occurrence. On the other hand, as a fuel it is like the hydrocarbons in that it is a non-recyclable resource. In addition, uranium occurs in two isotopes that potentially may supply energy--U235 and U238. Present technology utilizes only the isotope U235, which constitutes only 0.7% of natural uranium. New technology is being developed to utilize the more abundant isotope U238. Consequently, the U238 obtained from uranium ores that have already been mined and processed (which is now stockpiled) is a resource that may be used in the future.

PRESENT METHODS OF RESOURCE ASSESSMENT

Assessment of uranium resource in the United States is in a rather primitive stage. We have not yet applied complex mathematical techniques nor sophisticated computer manipulations to our data. In many ways our position is similar to the position of the petroleum industry in the early part of this century. Although we have collected much data and seemingly know much about the occurrence of uranium, we still need to know a great deal more before we can make really reliable estimates of our resources of uranium.

Assessment of uranium resources in recent years in the United States has mostly followed the traditional analog approach. We have concentrated mostly on high-grade sandstone and vein deposits in the western part of the United States, particularly in Wyoming and Texas and on the Colorado Plateau in Colorado, Utah, Arizona, and New Mexico. Our reason for doing this has been mainly economic. Uranium has been in abundant supply, and we tend to ignore resources that are unlikely to be exploited in the near future. A result of the energy crisis of the past few years is that we have increased our efforts in studying the geology and resources of uranium. The increase in effort has been so recent that little new information has been acquired. We, therefore, will talk more about what we plan to do than what we have done.

Before discussing our methods of resource assessment, we must define the terminology we use. In April 1974, the United States Geological Survey and the United States Bureau of Mines adopted a series of definitions for mineral resource terminology (Economic Geology, 1974). These terms are shown in Figure 1, and defined in the Appendix. We shall use these terms throughout this report.

Figure 1 is generally known as the McKelvey diagram. It is intended to show relations between various kinds of resources; it does not imply quantitative relations between the kinds of resources. Horizontal lines on this figure are sensitive primarily to economic factors. They move up when supply exceeds demand; they move down when demand exceeds supply. In a general way, we may say also that the horizontal lines represent grade of material; low-grade resources are more expensive to recover than high-grade resources.

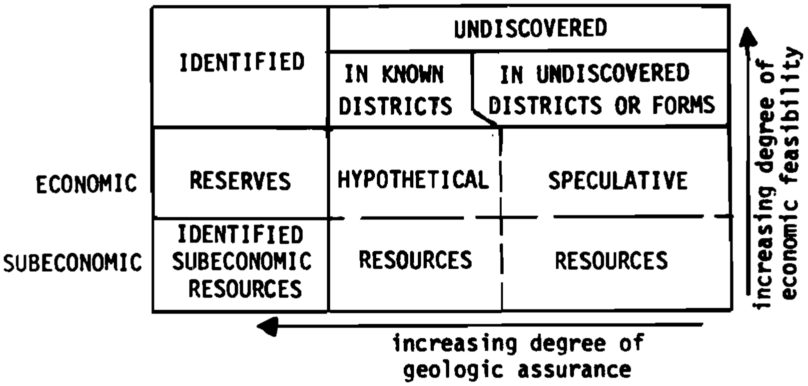

Figure 1. Classification of mineral resources.

Vertical lines on the figure are sensitive both to geologic knowledge and to use of the commodity. As geologic knowledge increases they will move toward the right. As a commodity is used up they will move toward the left.

Figure 2 shows how the materials represented in the diagram act. Mankind's first efforts in the exploitation of natural resources involve removal of rich high-grade easily accessible materials--the tendency is also to search for similar deposits--and thus when mined, materials move out of the diagram first along vector 1. After most of the high-grade resources have been recovered ways to extract resources from lower grade sources are invented and then materials tend to move out of the diagram along vector 2. As resources approach exhaustion, they are looked for in places represented by the lower right hand corner of the diagram, and they move out of the diagram along vector 3.

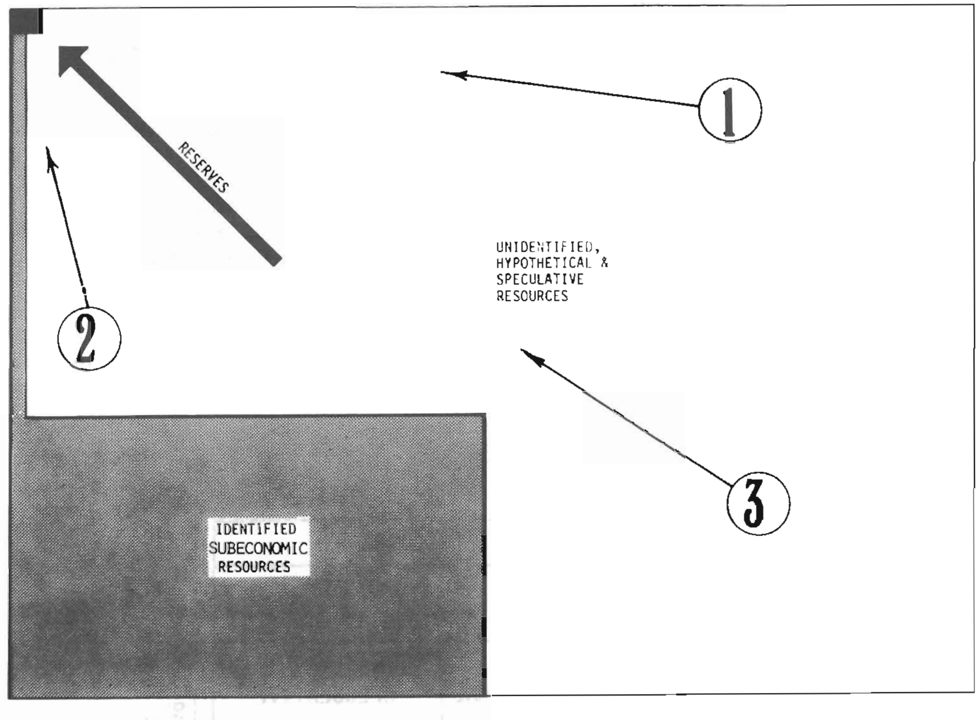

Figure 2. Movement of resources, from McKelvey diagram.

This diagram is, of course, schematic. It is not easily amenable to graphically depicting actual quantities of total resources. Figure 3 is a diagrammatic portrayal of the quantity of uranium in the United States using values obtained from crustal abundances by Erickson (1973). The large rectangle represents the total quantity of uranium in the crust of the United States to a depth of one kilometer, the tiny dot represents the amount of uranium resources at a grade or greater than 0.1% that may be found in the crust (also to a depth of one kilometer) under the United States. Figure 4 depicts the relative quantities of identified uranium resources in the United States (values are from A.P. Butler, Jr., oral communication, 1975). It is clear from this figure that most of the identified uranium resources in the United States are in black shales and, of the rest, most are in phosphates and the Conway (New Hampshire) and other granites. If the resources represented by the black shales were an economically viable source of uranium, clearly there would be no need to continue our search for new supplies. Recovery of uranium from black shales is not likely in the near future both because the cost of extraction is estimated to be at least 10 times that of conventional deposits and because mining of large quantities of shale would cause great environmental and industrial distress. Recovery of uranium from phosphates is possible, but is economic only as a by-product of the production of triple superphosphate. Only a small amount of uranium can be expected from this source, and much of the uranium in the phosphates will be lost because not all of the phosphate that is mined is converted to triple superphosphate.

Recovery of uranium from black shales or granites seems highly unlikely unless significant improvements can be made in technology. These are the principal reasons for our decision to concentrate our studies on sandstone and vein deposits and attempting to locate large intermediate-grade deposits.

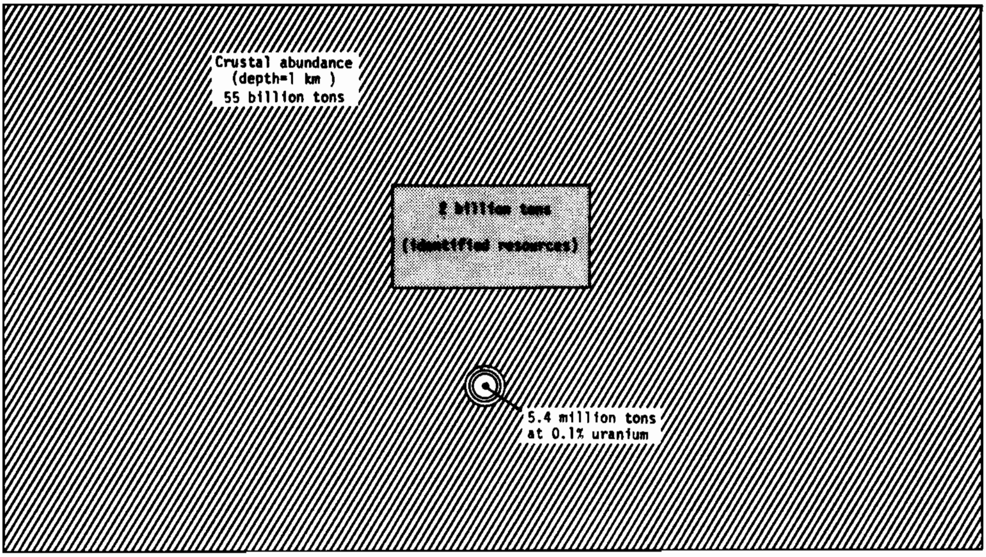

Figure 3. Abundance of uranium in the United States.

ANALOG METHOD

Two essentially different types of resources have to be assessed: identified resources and undiscovered resources. The first type is a resource purely because of economic factors. From a geologic standpoint the amounts of uranium in resources of this type have been established with a rather high degree of accuracy; their recovery is dependent upon economic factors beyond the realm of geology. The second type (undiscovered) includes all those resources that we have not yet identified. It includes the deposits not yet found in known districts, the deposits in districts not yet found, and the deposits in geologic environments not yet identified. Resources of the first type are very much akin to reserves;

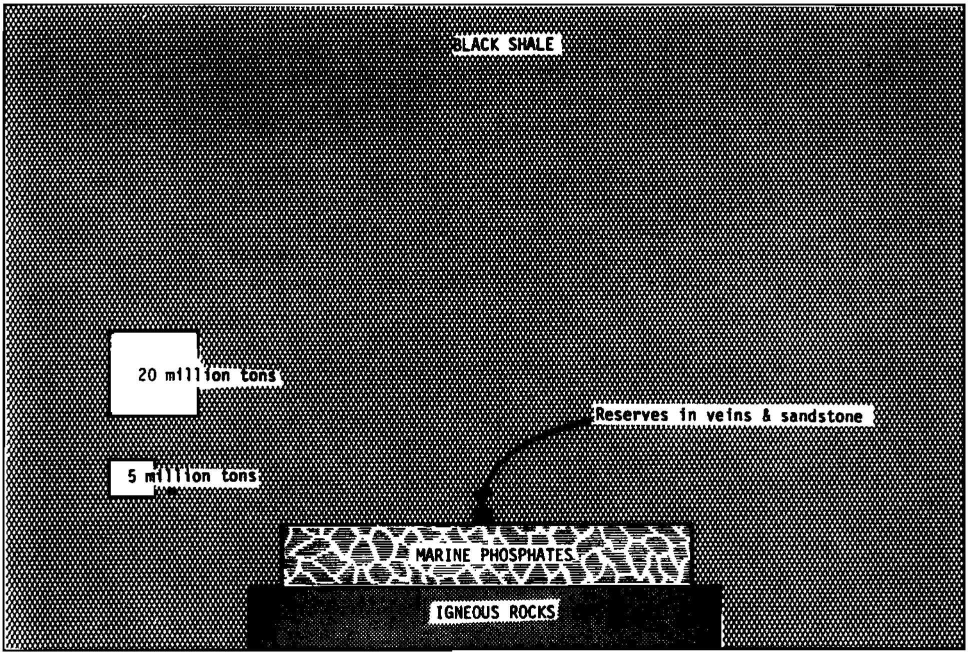

Figure 4. Distribution of identified uranium resources in the United States.

we know where they are and how much is there and we feel comfortable in our knowledge. Resources of the second type are very much less reassuring. The probability of discovering additional resources in known districts is relatively high, but as our geologic knowledge of the occurrence of a deposit, or type of deposit decreases, our assuredness concerning those resources decreases accordingly.

Resources in phosphates, shales, and granites belong mainly to the first type. Concentrations of uranium in these deposits tend to be uniform throughout the entire body. The calculations therefore require only a knowledge of the volume of the body and the percent of contained uranium. The certainty of the values thus obtained are a function of purely geologic considerations, their accuracy is a function of our geologic knowledge. In any event, disagreement over these values is slight because we do have reasonably accurate information concerning them.

Assessment of resources in sandstone deposits is less precise. This is partly so because such deposits are not uniformly distributed throughout the sandstone beds, and partly so because our three dimensional geologic understanding of the basins in which the deposits are found is imperfect at present. In addition we have not yet reached a thorough understanding of the processes whereby uranium deposits form in sandstones.

Arthur P. Butler, Jr., and R.P. Fischer of the US Geological Survey have addressed themselves to the problem of assessing ore-grade deposits in the sandstone basins of the western United States. They worked on the assumption that in the deeply incised parts of ore-bearing areas, the ratio of ore-bearing to barren sandstone in the outcrop can be extrapolated to give the probable area of ore-bearing sandstone in an unexplored area.

Using this assumption, they calculated in the early 1950's that the Uravan belt in Colorado eventually would yield a total 15,000,000 tons of uranium ore. The Uravan belt, one of the most thoroughly tested areas, has thus far yielded 12,000,000 tons of ore. Enough unexplored ground still exists within the Uravan belt that their prediction may yet prove to be extremely accurate.

Another method was predicated by G.W. Weir of the US Geological Survey upon the observation that exploration tends to proceed inward from the outcrop. This observation allows one to derive a fraction which relates the quantity of ore found in an area defined by the outcrop length and the width of the explored belt. Applying this fraction to an unexplored basin in Utah, he arrived at a potential resource of 2,800,000 tons for that particular area. This area has not yet been fully developed and we shall have to await further exploration before we can evaluate the results.

Applying similar concepts to basins that have not yet been fully studied is at best a tenuous technique. Although concepts of what constitutes favorable ground are rather well developed in well-explored basins, similar concepts may not apply adequately in unexplored areas. Stratigraphic, structural or compositional differences may profoundly affect such assumptions and may create false impressions, either too high or too low, concerning the quantity of ore to be expected.

Resources of uranium that may be contained in vein deposits are very much more difficult to assess than those in sandstone. Veins most commonly occur in steeply dipping structures and have very small surface areas in proportion to their size. In addition, weathering processes tend to leach uranium from the surface parts of the veins, thus reducing the radioactivity at the surface. Veins, therefore, present small but alluring targets for subsurface exploration.

In the United States we have developed only two large vein deposits of uranium, one in the Schwartzwalder mine near Golden, Colorado, and the other in the Midnite mine near Spokane, Washington. These two deposits represent less than 5% of our total reserves. Vein deposits form a much larger percent of world reserves, and we are concentrating our efforts on the study of their geology in order to make better resource assessments.

Many structurally controlled deposits, such as the Midnite deposit, do not fit a precise definition of a vein deposit. Deposits referred to as veins fit many differing geologic categories and until we have precise knowledge of their geometry, we may well be in error if we group them together as vein deposits. Assuming that we can arrive at acceptable definitions, we can then begin to evaluate various terranes in terms of whether or not they contain the proper geologic environments for possible deposits. Our present state of knowledge does not permit this evaluation; thus, most of our resource estimates for vein and related deposits are speculative rather than hypothetical.

One possible method for assessing speculative resources in vein deposits has been suggested by A.P. Butler, Jr. (oral communication, 1975). He measured the area of France underlain by rocks of Hercynian age and evaluated the identified resources in that area. Working on the assumption that the Appalachians in the eastern United States were essentially the same as the Hercynian, he arrived at a factor for calculating speculative resources in the Appalachian area.

The least studied resources in the United States are intermediate-grade material that contain an average of 0.0X% uranium. There are small intermediate-grade resources adjacent to some sandstone deposits in the United States, but we have not yet identified any large intermediate-grade sandstone bodies. Much of the US Geological Survey's exploration research is aimed at finding large intermediate-grade deposits in new geologic environments, such as the one at Rössing in South West Africa.

CRUSTAL ABUNDANCE METHOD

Estimates of the ultimate quantity of domestic uranium resources to a depth of one kilometer have been made on the basis of theoretical relations between current economic reserves and crustal abundances of uranium (McKelvey, 1960; Erickson, 1973). In 1960, V.E. McKelvey of the US Geological Survey recognized a near-linear relation between crustal abundance and reserves of a number of metallic elements that had been intensively explored for in the United States. He observed that, for the well-explored-for elements, minable reserves were proportional to their crustal abundances. Extrapolating this information to uranium, he arrived at a figure of 3,300,000 tons of total minable resources in the crust of the United States to a depth of one kilometer. Erickson (1973), using different abundance data but following essentially the same method, arrived at a figure of 5,400,000 tons. Erickson's calculations indicate that there is about 20 times as much uranium in undiscovered deposits in the United States than is currently included in our known reserves.

SUBJECTIVE PROBABILITY METHOD

In 1973 several members of the US Geological Survey participated as experts in a study of a subjective probability analysis conducted by the US Atomic Energy Commission (now part of the US Energy Research and Development Administration). This method was based on a synthesis of the judgments of members of a panel of experts knowledgeable in a given area. The area chosen for the study was the state of New Mexico. The state was divided into a number of equal-size rectangular cells, and each expert was asked to estimate the number, size, grade, thickness, and depth of undiscovered uranium deposits in every cell. The initial estimates were then analyzed and appraised using the Delphi method. Each participant was then asked to review and revise (if he thought that was necessary) his estimates in the light of the synthesized data. The data then were reappraised, and the final results showed a range in value that varied by one order of magnitude. Throughout the study, all of the experts remained anonymous to eliminate the bias that might have been introduced by an "authoritarian figure". Estimates of the resources of New Mexico made by both the US Geological Survey and the US Atomic Energy Commission, using analog techniques fall near the upper end of the range of values produced in this study.

RESEARCH TO IMPROVE RESOURCE ASSESSMENT METHODS

Current efforts of the United States Geological Survey are directed toward improving our methods for resource assessment. More than 50 professional geologists are involved in studying the various aspects of uranium and thorium geology in the United States. Their efforts range from studies of the theories of origin of uranium deposits through basin analysis, geochemistry and geophysics to detailed studies of known uranium districts and reconnaissance studies in areas we suspect may be favorable for the occurrence of uranium. We believe these studies ultimately will lead to a more substantial understanding of uranium deposits, and that they will lead to resource methodology considerably more sophisticated than we are using today.

To this end, we are currently developing a computerized data bank which will contain the considerable amount of data in our files that were generated during the 1950's and 1960's. We hope to be able to add to that data much information from our current investigations and we hope that in the near future we will be able to develop statistical methods for resource calculations based on more extensive geologic knowledge than we now possess.

CONCLUSIONS AND SUMMARY

The continuing demand for increased supplies of energy in the United States will require a much better understanding not only of the volume of our uranium resources, but also of methods for locating those areas where new, large deposits will be found. To this end, we in the US Geological Survey will concentrate our efforts on understanding the fundamental geologic principles that guide the formation of uranium ore deposits.

Future assessment of uranium resources by the United States Geological Survey will probably follow the traditional analog technique for most areas, because this technique furnishes a relatively firm estimate of resources that are likely to be exploited in the future. Other methods will have to be applied in attempts to locate new environments in which we may find uranium deposits. Only two essentially different methods are available. One, an extension of the analog approach, will involve careful evaluation of both domestic and foreign environments favorable for the formation of uranium deposits. We will then carefully examine the geology of our country for similar environments, and then examine those environments for possible uranium occurrences. The other method will utilize all of the various statistical methods that have been developed by various investigators in the recent past.

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APPENDIX. DEFINITION OF TERMS

Resource: A concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such form that economic extraction of a commodity is currently or potentially feasible.

Identified resources: Specific bodies of mineral-bearing material whose location, quality, and quantity are known from geologic evidence supported by engineering measurements with respect to the demonstrated category.

Undiscovered resources: Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

Reserve: That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination. The term ore is also used for reserves of some minerals.

The following definitions for measured, indicated, and inferred are applicable to both the Reserve and Identified-Subeconomic resource components.

Measured: Material for which estimates of the quality and quantity have been computed, within a margin of error of less than 20%, from analyses and measurements from closely spaced and geologically well-known sample sites.

Indicated: Material for which estimates of the quality and quantity have been computed partly from sample analyses and measurements and partly from reasonable geologic projections.

Demonstrated: A collective term for the sum of materials in both measured and indicated resources.

Inferred: Material in unexplored but identified deposits for which estimates of the quality and size are based on geologic evidence and projection.

Identified-Subeconomic Resources: Known deposits not now minable economically.

Paramarginal: The portion of subeconomic resources that a) borders on being economically producible or b) is not commercially available solely because of legal or political circumstances.

Submarginal: The portion of subeconomic resources which would require a substantially higher price (more than 1.5 times the price at the time of determination) or a major cost reducing advance in technology.

Hypothetical resources: Undiscovered materials that may reasonably be expected to exist in a known mining district under known geologic conditions. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as a reserve or identified-subeconomic resource.

Speculative resources: Undiscovered materials that may occur either in known types of deposits in a favorable geologic setting where no discoveries have been made, or in as-yet-unknown types of deposits that remain to be recognized. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as reserves or identified-subeconomic resources.

URANIUM RESOURCES ASSESSMENT WITH "MIMIC": A DESCRIPTIVE MODEL OF MINERAL RESOURCES AND LONG-TERM PRICE TRENDS IN THE MINING INDUSTRY

Johan W. Brinck

INTRODUCTION

World demand for uranium during the remainder of this century has been projected at somewhat over 3 million tonnes. It could surpass this amount if the trend towards the use of more electricity is accelerated and if other fuels continue to become more expensive.

World reserves in 1973 were estimated at 1.8 million tonnes U. Estimated paramarginal resources at best would add some 1.3 million tonnes to this figure. They would require improved technology or somewhat higher prices to become economically viable. About half of the thus estimated resources and reserves still need a considerable exploration effort to be developed into demonstrated reserves (Nininger, 1974).

A production capacity of 50,000 tonnes annually for these reserves is attainable by 1979 and will be required at about the same time (NEA/IAEA, 1973). The currently estimated reserves and resources, however, would not be able to support anything like the 100,000 tonnes per annum required by 1985 and the indications are that for the annual requirements of 225,000 tonnes likely by the year 2000 a total of some 9 million to 10 million tonnes of uranium resources will have to be identified. Demand will continue to climb for several years after 2000, even with the successful commercial introduction of breeder reactors in the 1980's.

A number of questions and problems are presented by the magnitude of the uranium supply problem. They include estimates of the resource base on which reserves and production capacities have to be developed, the geo-political distribution of these resources over the earth's crust, the development of costs and prices and the substitutability of uranium, all of which will influence the ultimate importance of fission technology, as well as the relative importance of thorium and plutonium as supplementary fuels.

The "Mimic" model was developed originally at the Commission of the European Communities to infer the physically available potential reserves of uranium in the upper part of the earth's crust (Brinck, 1971) from carefully selected data on uranium reserves and resources regardless of social or political considerations. Contrary to an apparently rather common misbelief, this model is purely descriptive, and it is based on the single assumption that element concentrations in the geological environment tend to be log-binomially distributed, for which there is ample evidence both from geochemical surveys and mining exploration. The model does not speculate or hypothesize on technological improvements still to be realized, nor on the possible existence and discovery of better than the current average ore deposits. For this reason, all estimates made by the model necessarily are minimum estimates.

For the purpose of this study a cursory examination will be made of the different parameters entering into the "Mimic" calculations and their significance for the availability and future development of uranium resources into reserves, and the different ways to estimate their magnitude. For a better understanding of some concepts and terminology used in this study, the terminology and some definitions of mineral resources and reserves, as used in different modern classifications, will be explained shortly and compared with each other.

I. CLASSIFICATION AND TERMINOLOGY OF MINERAL RESOURCES AND RESERVES

Figure 1 illustrates the classification and terminology of resources and reserves as used by the Commission of the European Communities (EUR 5011, 1972). Like other modern classifications it is a modification of the Blondel-Lasky classification of 1956 (Blondel and Lasky, 1956). All go in the same direction of highlighting the importance of the degree of certainty (quantitative aspect) and feasibility of recovery (qualitative aspect) variables.

Both the Commission's and the more recent US Geological Survey's (USGS) (McKelvey, 1973) and Canadian Department of Energy, Mines and Resources' (1975) classifications have been developed with the aim that resources categories and definitions should be applicable to all naturally occurring concentrations of metals, non-metals and fossil fuels. All classifications limit the definition of reserves to that portion of the estimated resources, which at the time of estimating can be economically extracted with current technology (the USGS definition explicitly adds the aspect of legality).

Some relatively minor differences in definitions and terminology should be noted. In the USGS definition resources are limited to concentrations of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such a form that economic extraction of a commodity is currently or potentially feasible. Thus, a distinction is made between economic (reserves) and subeconomic resources, the latter being subdivided into paramarginal and submarginal resources. In the Canadian classification a similar subdivision of subeconomic

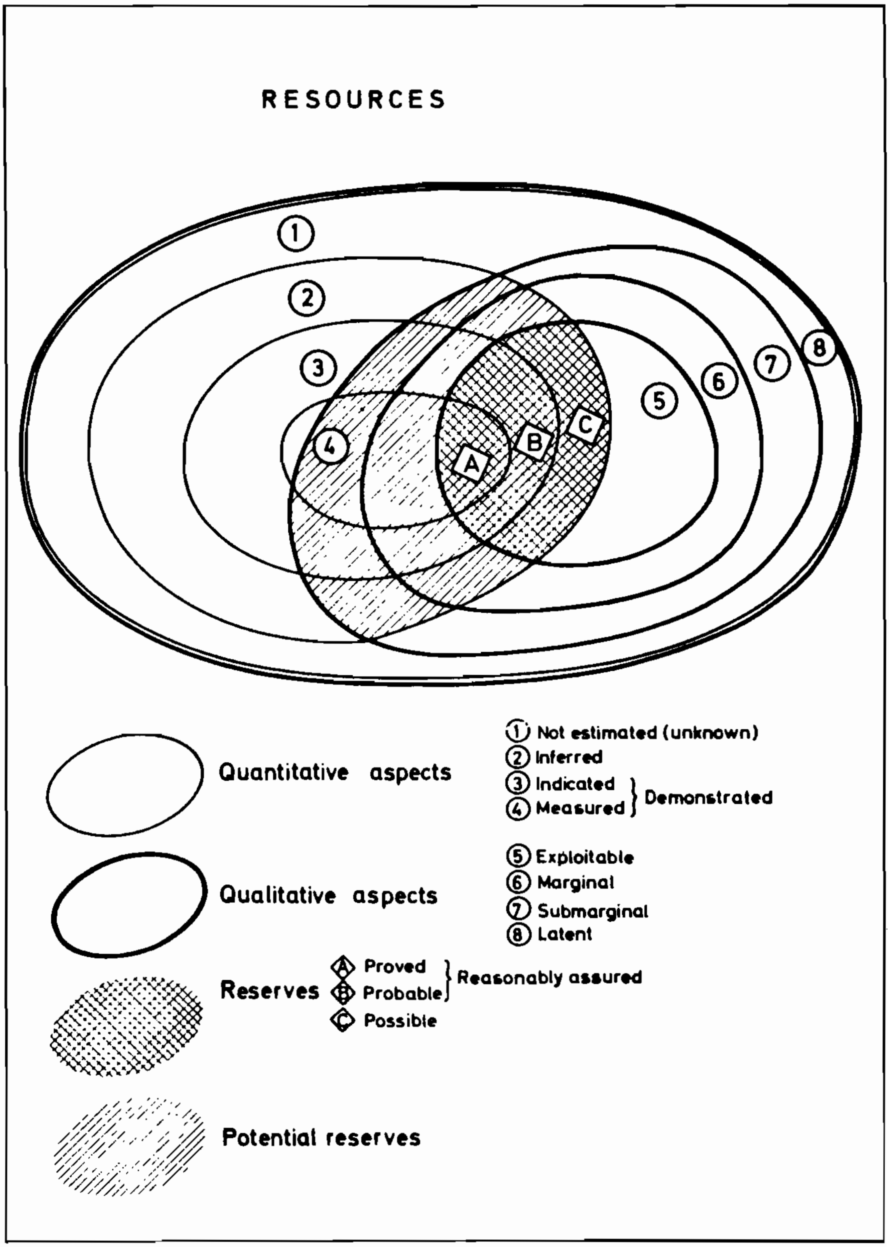

RESOURCES
1
2
3
4
5
6
7
8
A
B
C
Quantitative aspects
Qualitative aspects
Reserves
Potential reserves
1 Not estimated (unknown)
2 Inferred
3 Indicated
4 Measured
Demonstrated
5 Exploitable
6 Marginal
7 Submarginal
8 Latent
A Proved
B Probable
C Possible
Reasonably assured

Figure 1.

resources into B and C resources is proposed. They would become exploitable within the next 25 years with respectively more than 50% and from 10% to 50% probability.

Such resources are developed from a resource base, which taken to its extreme can be expressed in terms of crustal abundance of elements in a particular area. Thus, although some of the boundaries are differently defined, the USGS and Canadian economic and subeconomic resources are roughly comparable with the Commission's reserves + potential reserves, whereas the resource base taken to its extreme is directly comparable with the Commission's total resources which include all higher classified material.

In the USGS classification, the rather ambiguous terms probable, possible and consequently proved reserves are omitted. These terms, which are used by the mining industry for economic evaluations in specific deposits and districts, commonly have been used loosely and interchangeably with the terms indicated, inferred, and measured. The terms proved and measured are often essentially synonymous. The terms probable and possible, however, are not necessarily synonymous with indicated and inferred and especially when these terms are used to describe partially sampled deposits they would be described in all three classifications by the term indicated. On the other hand, the terms demonstrated and reasonably assured, the latter being commonly used in uranium resources estimates (NEA/IAEA, 1973), appear to be largely synonymous.

A subdivision of yet unmeasured mineral deposits in the USGS classification into identified inferred, undiscovered hypothetical and undiscovered speculative resources refers mainly to geographic distribution and type of such resources and does not correspond with the Commission's inferred and not estimated (because unknown) resources. Apparently both the identified inferred and undiscovered hypothetical and speculative resources would largely fall under the Commission's definition of inferred resources.

The Commission's classification has been developed partially to accommodate the "Mimic" model. Therefore, a class of not estimated (because unknown) resources was explicitly introduced to reflect the fact that the "Mimic" estimates, although covering the whole range of possible size-grade specifications for inferred resources in the geological environment, are necessarily minimum estimates. For the analysis of the global resources of uranium, therefore, the Commission's classification will be used in this study.

II. THE DISTRIBUTION OF ELEMENTS IN THE GEOLOGICAL ENVIRONMENT

Different models have been proposed to describe the distribution of elements in the geological environment. Although the log-normal model of element distribution (Ahrens, 1954; Matheron, 1962, 1963) is most frequently used in geochemical exploration and ore-reserve evaluation, our own observations made us choose the closely related log-binomial model as proposed by De Wijs (1953) for the "Mimic" model.

Apart from giving more consistent results when applied over very large probability ranges ($\alpha \pm \geq 3\sigma$) the model has, for most geologists, the important, added advantage that observations on the distribution of mineral resources and ore deposits in metallogenetic provinces and districts can be easily understood. In this model the geological environment of weight R is considered as an inhomogenous mixture of a given element with a fixed average concentration (X) and a matrix material consisting of all other elements ($X << 1$).

Ore deposits represent, in this environment, extreme concentrations which are related to the average concentration through a series of intermediate concentrations. The weighted frequencies of the logarithms of these concentrations tend to fit a binomial probability curve that, for a given deposit size, is determined by a median concentration (γ) and a standard deviation (σ). For any given average mineral deposit size, the standard deviation and median concentration are determined by the average concentration of the element in the geological environment and by a dispersion coefficient, which is typical for each element in a given environment. This dispersion coefficient reflects the tendency of an element to occur in concentrated form and therefore has been named the "specific mineralizability" (Q) of the element (Brinck, 1967).

Knowing the average concentration and the specific mineralizability of an element for a given geological environment, the probability of occurrence of mineral deposits of all possible size-grade specifications (inferred resources) can be calculated (Brinck, 1972).

$$M = R \cdot X = \sum_{k=0}^{\alpha} \frac{\binom{\alpha}{k}}{2^{\alpha}} R \cdot X \cdot (1 + Q)^{\alpha-k} \cdot (1 - Q)^{k} \qquad (1)$$

where

M = total resources of an element in R,
R = size of the environment in tonnes of rock,
X = the average concentration of the element in R,
Q = the specific mineralizability,
α = a rational number indicating the order of subdivision of the environment,
k = an integer 0,1,2,...,N ($\alpha - 1 < N \leq \alpha$) .

Two boundaries limit the validity of the model:

- the minimum size of the concentrations for which the model is valid is determined by the size of the individual minerals making up the environment. Although this limitation does not pose a problem for resource evaluations, it always should be considered when determining the specific mineralizability from geochemical and mineral survey data.

- no concentration greater than 1 could possibly occur and for all practical purposes the highest concentration which should be considered in resource estimates is the concentration of an element in its most common ore mineral. Especially with elements of high natural abundance ($\geq$ 0.1%) or high specific mineralizability ($\geq$ 0.25) a large part or all of the reserves may occur in deposits for which the average grade approaches this theoretical maximum concentration. In such deposits the element concentrations are not log-binomially distributed any longer (overflow conditions).

By logarithmically plotting the thus inferred resources for mineral deposits of equal metal content, but decreasing grade, against the moving average concentration of such resources, an equal probability distribution (IRIS diagram) is obtained on which resources of all possible size-grade specifications are inferred for the given geological environment. However, only those of possible economic interest (potential reserves) are calculated and shown on the diagrams. The only parameters required for their estimating are the average concentration (X), the specific mineralizability (Q) and the size of the environment (R).

III. QUALITATIVE ASPECTS

Average unit production costs can be determined for the mineral deposits of different size-grade specifications making up the inferred resources. By superimposing lines of equal production costs on the IRIS diagram, a distinction then can be made between reserves and marginal, submarginal and latent resources. Unit production costs are calculated by discounting cash flow for the moment when a fully equipped mineral deposit enters into production. Using the current average cost of finding, developing and mining mineral deposits of given size-grade specifications, the inferred resources of an element can be determined for any given geological environment.

There are three distinct cost factors:

- exploration costs,
- capital investment costs,
- operating costs.

It has been observed by John R. Menke (quoted by Schurr and Marschak; McKelvey, 1960) that "the cost of mining and refining per lb of ore of widely differing minerals is remarkably alike. In other words, then, the cost of minerals won by similar mining methods is determined in good part by the number of lbs of ore mined per lb of pure mineral."

A very similar observation was made with regard to exploration costs (Brinck, 1970) which depend on the chance to discover deposits of given size-grade specifications in the geological environment. This chance can be determined with the log-binomial model and is proportional to the number and size of the available targets in the geological environment. Therefore, for about equally mature mining industries with similar cost structures, the cost differences per unit weight between different mining products appear to be largely determined by the natural parameters average abundance and specific mineralizability of the elements in the accessible part of the earth's crust. Thanks to economies of scale, mineral deposits with a rather large range of size-grade specifications can be exploited at about equal unit cost and this explains why these average long-term cost differences between elements with similar mining cost structures and rather different degrees of industrial maturity are reflected also in the average long-term price differences between these elements, as contained in these mining products.

This relation, which is illustrated in Figure 2, was first established by non-linear multiple regression analysis on the long-term average prices until 1 January 1971, the average crustal abundances and the specific mineralizabilities of gold, copper, zinc and lead. Originally used to determine a target price for uranium (EUR 5011, 1972) this relation has been found to be valid for many other mining products. The less than 30% differences between the observed long-term price and the predicted target price for the different elements should be seen in the light of unit price differences covering 4.5 orders of magnitude (US$0.05 to $1,170), six orders of magnitude for abundance values (10^{-9} - 10^{-3}) and Q values between 0.19 and 0.39. These differences can be easily explained from relatively small differences in mining, milling, refining and marketing costs and from differences in industrial maturity between different mining industries.

This observation strongly supports our opinion that the average price ratios between different raw materials constitute a valid reference set of values for our technological civilization which is based on the use of these materials. Allowing for a gradual, but by no means critical, depletion of different mineral resources, as well as for changes in the demand pattern, these largely naturally defined long term price ratios can be expected to change only very gradually under free market conditions. However, the price ratios between elements with higher and lower specific mineralizabilities will show a systematic tendency to increase with continuing demand.

Geo-political factors also could play a more pronounced role for mineral commodities with the higher specific mineralizabilities ($Q \geq 0.25$) such as gold, mercury, chromium, tungsten, tin and, by analogy, petroleum. The energetical aspect (energy for mining, concentration, transportation, processing, refining and environmental protection and reclaiming) has not been specifically treated in this study. It could somewhat influence the price ratios and in general the economic and ecological consequences of ever increasing exploitation of mineral resources.

The monetary crisis of August 1971, the subsequent devaluations of the dollar in 1971 and 1973 and the factual, but rather unilateral, demonitarization of gold followed by the energy

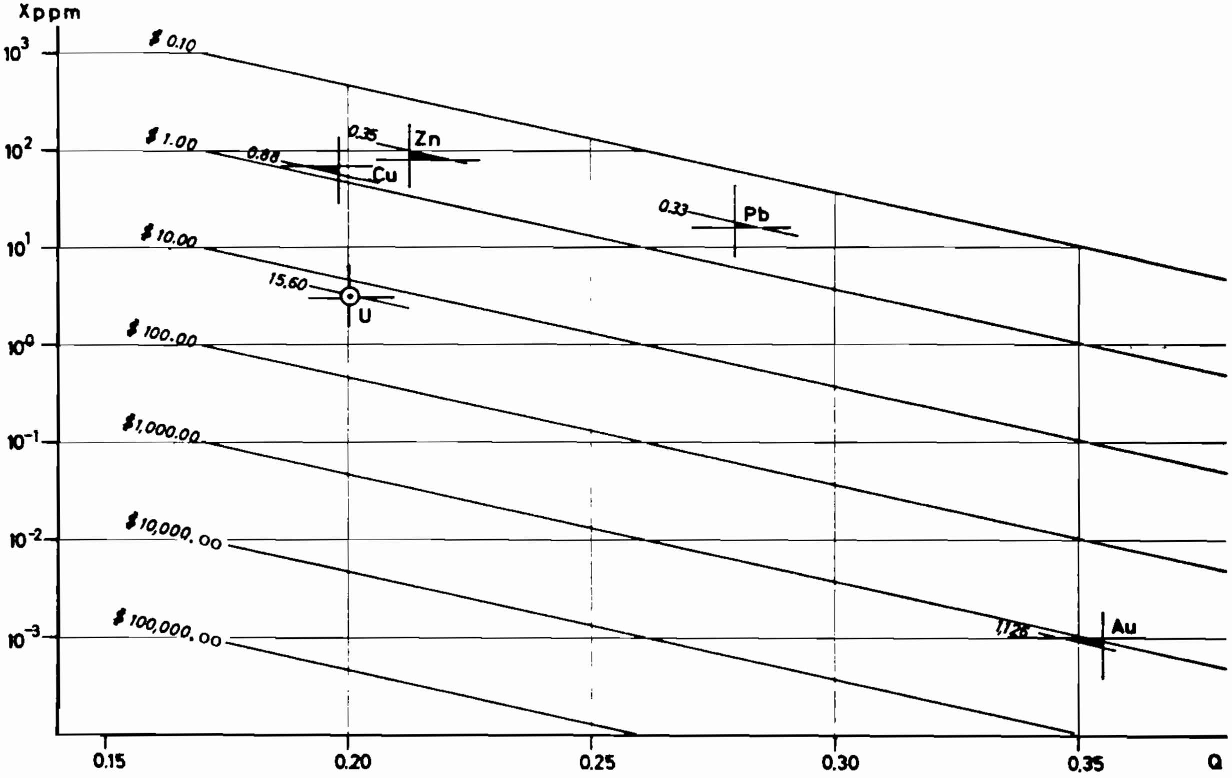


Figure 2. Long-term metal prices per kg as a function of the average concentration (x) and the specific mineralizability (Q).

crisis and unprecedented price increases of many mineral commodities during 1974, although predictable in their general trend, made it very difficult to assign any monetary value to the boundaries between reserves and subeconomic resources for any mineral commodity. However, these developments do not change our basic concepts on reserves and resources. In particular, the price increases by a factor three to five of several mineral commodities did not bring, almost overnight, latent or submarginal resources into their reserves.

Therefore, and in order to compensate as much as possible for the unavoidable differences in mining, milling, refining and marketing cost between different elements, all costs are calculated on the price base of 1 January 1971 and expressed in respect to the target price of an element, which is considered as the statistical price unit (SPU). Thus all deposits with costs up to 1.00 SPU, per definition, can be considered as reserves, whereas deposits with higher costs are to be considered as potential reserves. In our calculations for uranium, deposits with indicated average cost up to 1.67 SPU will be considered as marginal resources. This figure corresponds with the price of US$10.00 per pound of uranium oxide as used in the NEA/IAEA reports until 1971.

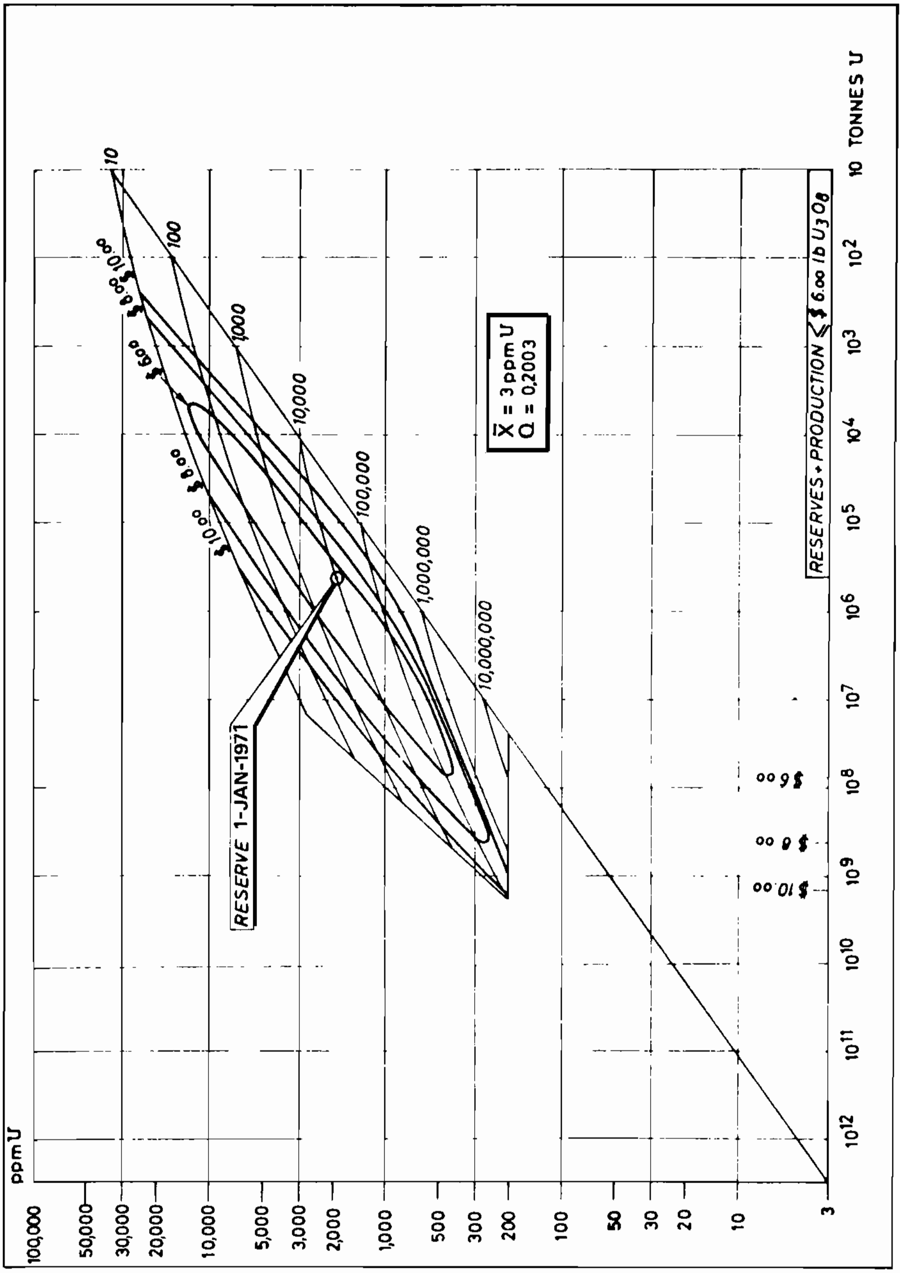
Figure 3 illustrates the estimated uranium resources of the world, based on the published reserve figures of 1 January 1971 and largely confirmed by the NEA/IAEA report of 1973. The cost boundaries which are superimposed on the Iris diagram were calculated for assumed annual requirements of 100,000 tonnes U which somewhat limits the full application of scale economies.

IV. DETERMINING THE PARAMETERS REQUIRED BY THE "MIMIC" MODEL

Resources and reserves of the different elements can be inferred by the model from only three external parameters:

1) the average concentration of an element in the geological environment,
2) the specific mineralizability of the element for that environment,
3) the size of the environment.

For most mineral commodities the global reserves and resources are confined within the upper part of the earth's crust which is considered as the geological environment of these resources.


ppmU
100,000
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2,000
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200
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50
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20
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3
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10 TONNES U
10
100
1000
10,000
100,000
1,000,000
10,000,000
$ 6.00
$ 8.00
$ 10.00
$10.00
$ 8.00
$ 6.00
X̄ = 3 ppm U
α = 0,2003
RESERVE 1-JAN-1971
RESERVES + PRODUCTION ≤ $ 6.00 lb U₃O₈
$6.00
$8.00
$10.00

Figure 3.

1) The Average Concentration of the Elements in the Earth's Upper Crust

Literature on the subject is rather extensive and for most elements reasonable agreement (within one order of magnitude) exists between different authors. The average concentration (or clarke) of an element is determined from the concentrations found in major rock types. Extreme concentrations normally are discarded and the arithmetic average concentration is taken. This practice in most cases will result in underestimated average concentrations. For resource estimates this is compensated largely by a consequently overestimated value of the specific mineralizability. However, normal concentration ranges (median ± two standard deviations) of different elements in the natural environment may show rather important differences with the theoretical ranges calculated from the clarke and specific mineralizability of an element.

2) The Specific Mineralizability of the Elements for the Upper Part of the Earth's Crust

Independent literature on the subject is still very limited and for most elements no published estimates exist at all. The specific mineralizability can be estimated in several ways as listed below:

a) from the dispersion of the element in its geological environment (Brinck, 1974).

Very few routine geochemical surveys for which data and results have been published were conducted with the purpose of determining the dispersion of an element in its environment as a whole. Most geochemical surveys are conducted in order to locate so-called anomalies (dispersion trains and primary or secondary halos) which supposedly are caused by hidden or exposed mineral deposits of possible economic size and grade. Although such surveys have proved very effective in locating many important mineral deposits, insufficient consideration normally can be given to the weight and mutual independency of the samples to result in dependable estimates of the specific mineralizability. Furthermore, such locally found specific mineralizabilities are not necessarily representative for the earth's upper crust as a whole and therefore a weighted average from many such specially conducted surveys would be required. Even then it would be highly questionable if such random sampling data would give significant results for extrapolations to probabilities corresponding to five to seven standard deviations from the mean. However, such specially conducted regional geochemical surveys do reflect the metallogenetic character of the surveyed areas much better than generally believed and it is the personal experience of this author that favourable ore potential is not easily missed by these methods.

b) from the quality and size of individual ore deposits.

Considering the enrichment in the highest grade ore deposit in a series of equally sized deposits as the maximum possible enrichment for that particular size, an apparent value for the specific mineralizability can be calculated. Repeating this procedure for different sizes, a number of values are found. As all deposits occur in the same environment, the highest of the thus found values should be the best approximation of the true specific mineralizability. This estimate on the basis of the rarest type of ore deposit depends on only one observation which is a rather poor basis for statistical interpretations.

c) from the quality and size of the ore reserves plus former production of a mineral commodity.

The size of the metal reserves plus former production is considered as the measured probability of occurrence of deposits of given average grade and size. Under free competition the price of a commodity is determined by the contribution of the marginal producer to the supply of a commodity. The production cost of this marginal producer will be below this price and, as we have seen, is largely determined by the size and grade of the marginal ore deposit. Therefore, the grade and size of the ore deposits making up the reserves of a commodity will show at least a semi-quantitative relation with the natural availability of mineral deposits of similar size-grade specifications.

Both the study of ore deposits and the log-binomial frequency distribution indicate that an inverse relationship exists between grade and size of mineral deposits. It also has been observed that the frequency of occurrence of ore deposits is log-normally distributed as a function of size, and independently, of grade (Patterson, 1963, 1970). At first sight, the latter observation would seem to render the whole concept of log-binomial (or log-normal) element distribution in the geological environment completely invalid. However, if we consider the high-grade (respectively large size) tail to be determined by the decreasing probability of occurrence of deposits with such size-grade specifications and the low-grade (respectively small size) tail by the decreasing chance of their economic viability, these observations not only become self-evident but also should make it obvious that this relation cannot be used to fix the average grade and size of the bivariate frequency distribution. Besides, there is no evidence whatsoever that the median or average size and grade ore deposit has much significance for the economics of a mineral commodity.

For the determination of the average quality of the ore deposits making up the reserves and determining the economics of a mineral industry it was found that from the relatively extensive field of possible size-grade specifications, both the average grade and the average size of the ore deposits making up the reserves can best be defined independently as the grade and size for which 50% of the reserves occur in higher grade, and greater size, deposits. For the estimating of the specific mineralizability with the "Mimic" model the quality and size of the demonstrated reserves of a commodity normally are used. For the measured probability, 50% of the metal reserves plus all former production from better than average grade and size deposits then are used.

d) from the established relationship between the average concentration in the crust, the long term average price and the specific mineralizability, the latter can be estimated as a function of the first two parameters. This, obviously, could be a rather dangerous procedure as it could lead to a vicious circle in which required parameters are estimated from their expected values. However, this procedure can be used and justified for cases where published data on these parameters indicate a range of possible values. This has been the case, for instance, for the estimate of the average grade of mercury in its ore deposits (Brinck, 1974; and Van Wambeke, 1974).

In general it will be advisable to use as many of the available methods and data as possible. Only a combination of the different methods will show possible weaknesses in the estimates and indicate the direction for further research. For the resources estimate the one which best fits the observed data should be accepted. Normally this estimate also turns out to be the most conservative one. This is in line with the observation that the "Mimic" estimates are minimum estimates in any event.

3) The Size of the Geological Environment of Ore Deposits

For the purpose of this study only the upper part of the earth's continental crust will be considered as the environment for uranium ore deposits. The weight of this environment is taken as 10^{18} tonnes of rock, roughly corresponding to the dry land surface of the crust to a depth of 2.5 km. The currently accessible depth for mining is somewhat over 3 km but the great majority of mineral reserves occur between 0 m and 1,000 m.

V. COST CALCULATIONS

Average unit production costs are determined from the size/grade specifications of the mineral deposits making up the demonstrated and inferred resources. Unit production costs in constant 1971 US dollars are calculated by discounting cash flow for the moment when a fully equipped mineral deposit enters into production. Costs are divided into exploration, capital investment and exploitation costs.

In all calculations a discount rate of 10.4% is used which corresponds to an 8% after tax return on equity for a risk capital ratio of 0.3 and 50% marginal tax on profits. Both the depletion and amortization time of investments in a mineral deposit are set at 16 years. For technical and/or economic reasons the following corrections and restrictions are made for the resource and cost calculations:

1) highest element concentrations are limited by the element concentration in the most common ore mineral.

2) costs are corrected for specific gravity of the ore minerals.

3) for deposits with annual production capability exceeding 10% of presumed annual world requirements, costs are calculated as for deposits producing 10% of these requirements. Excess ore, after amortization of investments, is valued at discounted unit exploration cost.

4) daily ore handling capacity is limited to 250,000 short tons. Excess ore is valued as under 3).

5) if daily ore handling capacity exceeds 30,000 short tons, unit capital investment cost is calculated as for a ore handling capacity of 30,000 daily short tons.

VI. THE DEVELOPMENT OF RESERVES FROM RESOURCES

Production of a commodity depletes its demonstrated reserves. This is counteracted by mineral exploration, which:

1) develops inferred reserves into demonstrated reserves,

2) attempts to discover new reserves from the "not estimated, exploitable resources" (only deposits with equal or better than average size-grade specifications can occur in this class. Their discovery will result in a revaluation of the specific mineralizability);

moreover,

3) technical improvements and economies of scale on the extraction, transport and marketing of the product, transfer potential reserves into the reserves, and

4) a rise in price of the product also brings potential reserves into the reserves.

During the relatively long mining history of many mineral commodities it has been observed that the first three factors normally can guarantee the development of adequate reserves and production capacities and that the price has a long-term tendency to stabilize or even decrease with respect to a constant currency value. Recent trends make it somewhat doubtful that this trend can be projected into the future.

Furthermore, although the inferred uranium resources and reserves, in analogy with copper resources, should be able to sustain annual requirements between 250,000-300,000 tonnes uranium without undue stress, their timely development may pose severe problems, since we still know very little about the type of deposits and geological environments from which such reserves will have to be developed. If the copper industry had some 67 years to increase its annual production capacity from 600,000 tonnes in 1903 to 6,000,000 tonnes in 1971, then according to this predicted increase of demand the uranium industry will have to increase its production capacity from some 20,000 to 200,000 tonnes within a period of between 16 and 25 years.

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SOME FACTS AND FANCIES ON URANIUM AVAILABILITY

S. H. U. Bowie

INTRODUCTION

It is important that a realistic attitude is taken towards uranium reserves and resources, but more especially towards uranium availability, if the future development of nuclear energy is not to be impeded. Over-optimism in assessing uranium availability will lead to complacency and interruptions in supplies well before the end of the century, while over-pessimism will result in unnecessary retardation of nuclear energy development.

Valid assessments of uranium availability can only be made by uranium geologists, backed by all applicable information, and with world-wide experience on the mode of occurrence of uranium deposits. From such knowledge the probable presence of additional ore bodies in terrain not yet prospected or only superficially covered, can be predicted with some degree of certainty.

It is of little value to consider the ultimate tonnage of uranium in the earth's crust (Lewis, 1972) or the total within a few kilometres of the surface. Likewise, it is misleading to refer to resources in granites, such as the Conway granite, as being able to supply fuel for "tens of thousands of years" (Wilson and Jones, 1974).

The history of mining has indicated that improved technologies have resulted in lower and lower grade material becoming economically viable, but this is not likely to be a continuing trend. Already, inflation has resulted in the cutoff grade for large scale open-pit copper workings to rise from approximately 0.4% to 0.8% Cu (Morgan, 1975). Not enough research has been done to estimate the eventual cutoff grade for uranium, but tentative calculations indicate that this might be around 50 parts/10^6 U if account is taken of energy balance as well as of ecological and environmental problems not met within the mining of conventional-grade ores.

URANIUM RESERVES AND RESOURCES

It is accepted that the ENA/IAEA reserve and resource figures published in 1973 are a realistic statement of the position at that time. Since then the only major additions to reserves have been in Australia bringing the reserve total at < \$10/lb U_3O_8 to about 1 mtU and the estimated additional resources to approximately the same figure. However, it is often forgotten that reserves in the ground are not necessarily closely related to material available over a relatively short span of years. Approximately 200,000 out of the total of 1 mt low-cost uranium are unlikely to be available over the next decade or so even if urgently required. This results from three main, and other, lesser, reasons:

1) Uranium available only as by-product (for example, Witwatersrand, South Africa).
2) Physical obstacles to mining (for example, Dennison Mine, Canada).
3) Ore of marginal grade with environmental problems limiting output (for example, Ranstad, Sweden).

It also tends to be assumed that "estimated additional resources" have been discovered and only await mining. This is far from correct. All of the ore in this category has to be discovered and assessed before being up-graded to ore. This process will no doubt lead to further "additional resources" being indicated, but the future lies in bringing in ore from new districts, not currently known to contain appreciable amounts of uranium, and from buried ore bodies in known uranium provinces. The ENA/IAEA report suggested that the resources together with estimated additional resources in the \$10-15/lb U_3O_8 of the order of 1.3 mtU. This is probably now nearer 1.5 mtU, but it should be remembered that these resources are not known with the same degree of precision as are the low-cost ones. No recent figures have been collated for uranium in the \$15-30/lb U_3O_8 but it can be stated with reasonable confidence that resources are of the order of 1.5 mtU. The question is whether these could be made available at the required rate soon enough to prevent temporary shortages.

In summary it can be said that at 1973 prices the situation is as follows in Table 1.

Table 1. Estimated uranium reserves and resources (non-socialist countries).

Prices (1973)	Reserves 10^6tU		Estimated Additional Resources 10^6 tU
< \$10/lb U_3O_8	1.0		1.0
\$10-15/lb U_3O_8	0.8		0.7
\$15-30/lb U_3O_8	0.5		1.0
	2.3		2.7
		5.0	

PROSPECTS FOR FURTHER DISCOVERIES

It is not generally appreciated that nearly all of the known uranium provinces of the world were discovered before or during the peak prospecting years of the 1950's, and also that prospecting has been undertaken in the vast majority of relatively accessible, and at the same time, geologically favourable regions of the world. This does not mean that there are no new provinces to be discovered.

Yeelerrie in Western Australia is an example. However, in many geologically favourable regions cover by instruments capable of detecting a gamma signal has been substantial and there is a diminishing return for expenditure on such surveys. It could well be that the first stage of success in Australia has already reached a peak and that new regions, for example, in South America will in turn be discovered.

In all of the major resource countries of the world there are substantial tonnages of uranium of conventional type but of submarginal grade that can be worked in the future. The problem with such uranium is to ensure that deposits are not "high-graded" to the extent that the remaining material will no longer constitute a resource.

What then is the answer to the apparent dilemma? This is almost certainly to be found in further research aimed at discovering more ore of conventional grade and type. Because the present day erosional surface of the earth is fortuitous it can be predicted with virtual certainty that there are many more uranium deposits buried beneath overburden of various types than outcrop and give a gamma signal at surface. Therefore, the aim should be to devise ways and means of discovering such ore bodies. This can be done in two main ways:

a) Increased research effort in the field uranium geology, particularly of the chemical and physical mechanisms that permitted ore bodies to form. This should include studies of mineralogy and isotope ratios both on a regional and local scale.

b) The development of techniques and instrumentation capable of detecting ore bodies with no obvious surface manifestations. An excellent example of this is the measurement of radon in ground air either by radon monitor of alpha-track etch methods. This method in favourable circumstances permits uranium ore bodies to be detected at depths of 100 or 200 metres below surface. Other methods are also possible.

As an insurance against the discovery of the required low-cost reserves, research should be initiated at a reasonable level on beneficiation techniques so that marginal or submarginal ores can be processed. This particularly applies to raw material rich in phosphate. In addition, more effort is required in the sphere of bacterial and in situ leaching and into improving methods of recovering valuable by-product elements.

Uranium recovery from seawater has been shown to be possible (Davies et al., 1964; Keen, 1968). More recently, however, Harrington et al., 1974 has estimated that the cost of recovery is likely to be in the order \$300/lb U_3O_8. The supply of uranium from this source is largely academic since the annual tonnage that is likely to be recovered, whatever this cost, is insignificant compared with the "post energy crisis" estimates of approximately 200,000 tU/year estimated by 1990.

If it is accepted that the estimated reserves and resources of uranium in the non-socialist countries of the world total about 5 mtU at a price of < \$30/lb U_3O_8, then it seems reasonable to assume on geological grounds that this figure could eventually be doubled. However, only 2 mtU have actually been found and defined as "reserves". It is thus clear that the task of doubling reserves by the required date of 1982 will prove a formidable task which is only likely to succeed if new techniques of discovery are introduced and with rapidity. Concerted effort by government organizations and all branches of the mining industry is immediately necessary if the goal of 200,000 tU/year by 1990 is to be achieved. The most important question for the future is not how much uranium exists but how much can be found and utilized over the time scale envisaged before the introduction of fast reactors commences to reduce requirements.

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URANIUM FROM SEAWATER:
A REVIEW OF RECENT PAPERS

A. Brin

INTRODUCTION

The Elaboration of Energy-Producing Substances from Seawater

The increasing need for energy linked with economic independence is causing industrialized countries to look for new supplies for and sources of power generation, different from the ones used until today. The recent offshore oil development is one of the best examples.

The oceans are the most formidable reserve of energy-loaded raw materials with the hydrogen of the water on the one hand and with uranium contained in the water on the other.

Uranium in Seawater

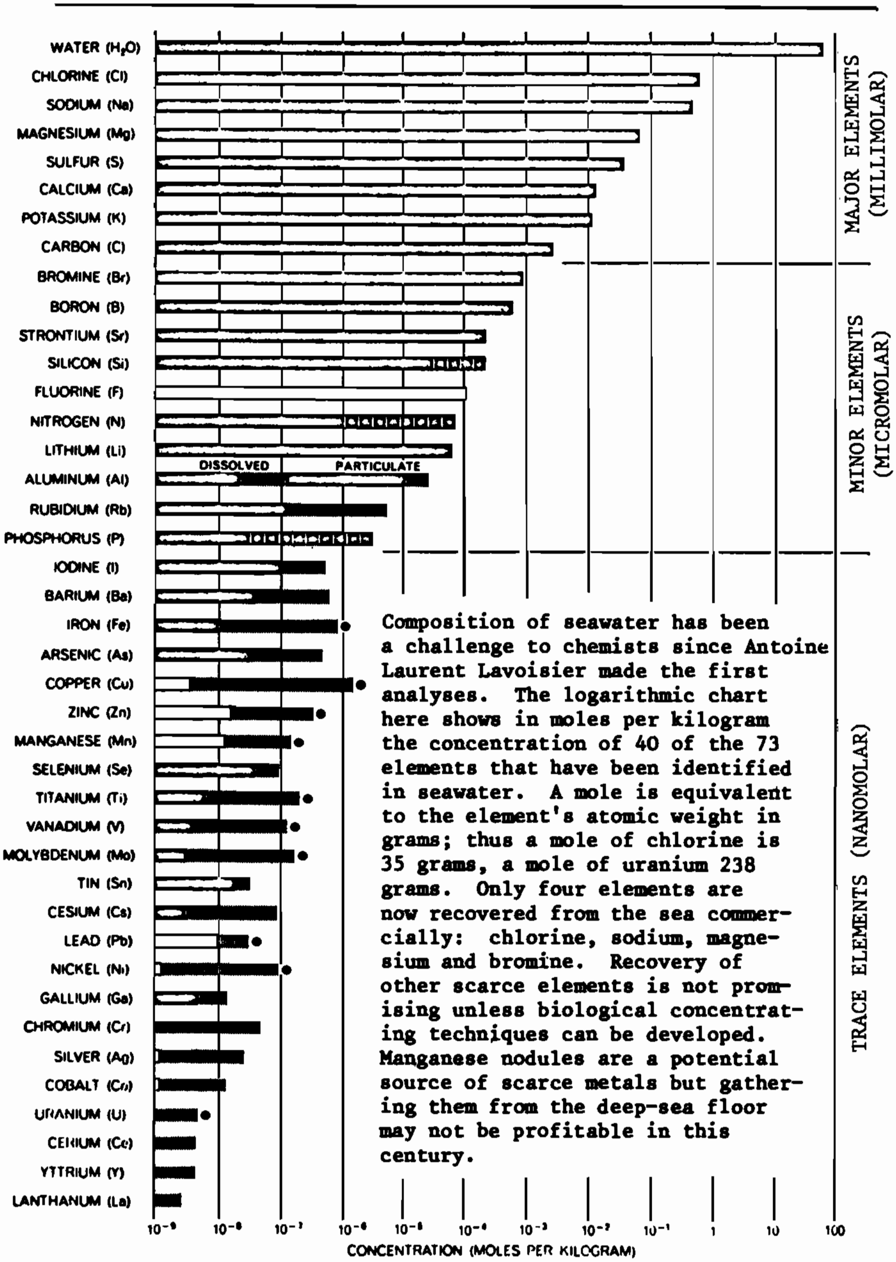
Seawater contains, in the whole ocean, about 3.34 μg of uranium per liter (1 to 4). This concentration can be regarded as constant in time and place, so that the whole uranium quantity can be estimated at 4.2×10^9 tons. Nevertheless, in some estuaries, the grade of this element is higher, owing to inputs of uranium from rivers. It has been shown that most of the uranium occurs in solution in the shape a stable ($K = 2 \times 10^{18}$) (McLaine et al., 1956) anionic tricarbonato-uranul complex $[UO_2(CO_3)_3]^4$ (Kennedy, 1965, Laskorin et al., 1958).

CHEMISTRY OF THE EXTRACTION PROCESS

A separating process must be capable of operating at very low concentrations of uranium, in competition with high concentrations of other ions (see Figure 1). It must meet the following requirements:

a) Since the volume of water to be processed is enormous, the extracting agent must be able to operate at the normal pH and salinity of seawater, because the addition of reagents to seawater cannot be considered.

b) This agent must have a long life, be virtually insoluble in seawater and resistant to chemical and biological degradation.



Composition of seawater has been a challenge to chemists since Antoine Laurent Lavoisier made the first analyses. The logarithmic chart here shows in moles per kilogram the concentration of 40 of the 73 elements that have been identified in seawater. A mole is equivalent to the element's atomic weight in grams; thus a mole of chlorine is 35 grams, a mole of uranium 238 grams. Only four elements are now recovered from the sea commercially: chlorine, sodium, magnesium and bromine. Recovery of other scarce elements is not promising unless biological concentrating techniques can be developed. Manganese nodules are a potential source of scarce metals but gathering them from the deep-sea floor may not be profitable in this century.

(From: F. MacIntyre, Scientific American (November 1970).

Figure 1. Concentration of the elements in seawater.

c) It must be inexpensive to make and must be available in large quantities.

d) The agent's form must be suitable for bringing it into contact with large volumes of water.

e) The rate of the extraction process must be adequate and it must be possible to remove uranium from the extracting agent cheaply.

For these reasons, extraction by unmiscible solvents and flowing against the stream (Laskorin, 1958; Keen, 1968) was discarded because solvent losses would render it prohibitive on the industrial scale although the chemical yield can be about 100%. Hence ion exchange is the selected process. A wide range of ion exchangers, organic and inorganic, was tested in seawater by Kennedy and his assistants:

a) Because of their poor stability as regards seawater and breakdown by elutions agents, the ordinary ion exchange resins cannot be used for industrial plants although some of these, particularly the resorcinol arsonic acid resin, have a very good uptake.

b) Conversely, the use of inorganic adsorbers held the attention of many workers. It is with this process that the most practical experience is obtained, and some studies go beyond the laboratory scale.

Tests were carried out with hydrated ferric oxide, ferric and zinc phosphates, calcium carbonate, silicagel, basic zinc carbonate, some lead salts.

At Geneva, in 1964, the English workers of Harwell proved the capacity of hydrous titanium oxide as a uranium adsorber, combining a reasonably good rate of uptake with a very low solubility in seawater. Since 1969 the Japanese have also investigated the different ways to use titanium and its compounds as uranium adsorbers. An article in Nucleonics Week takes stock of the situation and notes that English, Russian, US and Japanese scientists subsequently confirmed that the most efficient extraction method for uranium recovery at this time is by hydrous titanium oxide.

English Extraction Process by Hydrous Titanium Oxide

Keen (1968) has done a very complete outlining of the chemistry of the overall extraction process, and he has suggested an engineering scheme for a recovery facility and for identification of likely sites for plants.

Preparation of Hydrous Titanium Oxide

Since the adsorption and physical properties of the adsorber are extremely dependent on the method of preparation, many studies have been done to perfect the method giving the best product. The method we have used obtains hydrous titanium oxide as a gel in the form of glassy and irregularly shaped granules, by precipitation of a titanium sulphate or chloride solution, the precipitate being washed, dried, crushed and sieved to required size. A typical composition is TiO_2, 60%; H_2O, 35%; Na, 5% by weight.

Now it is possible to make tens of kilograms of granules with reproducible properties. To reduce the cost of the adsorber, it has been demonstrated that impure hydrous titanium oxide, made from a crude titanium sulphate derived from leaching titaniferous iron slag, is almost as effective an adsorber as the one made from a pure titanium solution.

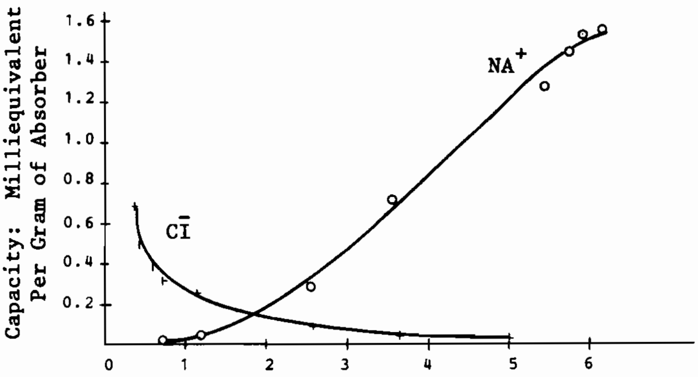
Physical and Chemical Nature of Hydrous Titanium Oxide Gel

Hitherto, hydrous titanium oxide gel has been described as amorphrous. However, recent studies (X-ray, electron diffraction, IR spectroscopy, and so on) support the view that this gel is a crypto-crystalline anatase form of titanium dioxide with crystallites (≈30 A), linked more or less rigidly by Ti-0-Ti bonds to form a random matrix; the space between the crystallite is occupied by molecular water which is possibly hydrogen-bonded to the titanium dioxide crystals. Thus, it is incorrect to term it a hydroxide or a hydrate. The ion-exchange sites are presumed to be at the surface of the crystallites, associated with terminal -OH groups. It is probably the size of the spaces in the matrix that controls the ability of large ions, for example $[UO_2(CO_3)_3]^{4-}$ to diffuse into the gel granule.

Hydrous titanium oxide is a cation exchanger at high pH and an anion exchanger at low pH, as shown by Figure 2 (see Keen, 1968), for Na^+ and Cl^- ions. At pH 8 (that of seawater), it is largely cationic. Although the tricarbonate-uranyl complex is anionic, it is probable that, as shown by Kennedy's 1965) results, uranium is adsorbed as the UO_2^{2+} cation.

Performance of the Granules Adsorber

Comparative tests were carried out at the Portland laboratory on samples contained in 1 inch diameter glass columns, between sintered glass plates in a 1 inch deep bed; water flows upwards at 10 l/h, keeping the particles gently mixed by fluidization; samples are removed periodically for analysis. At the flow rate used, an excess of uranium is always present, so that the quantity of uranium found in samples is a measure of the adsorption capacity of the gel.



From: Keen, 1968.

Figure 2. **Anion and cation exchange properties of hydrous titanium oxide.**

Analyses have shown the following results:

a) Hydrous titanium oxide adsorbs the more common cations from seawater (Na, Mg, Ca) within one day, those at lower concentrations (Ba, Sr) in two or three weeks, while uranium and vanadium build up to equilibrium more slowly. The concentration coefficients for some elements, after 30 days' exposure to seawater, are shown in Table 1.

b) For carefully prepared gel it is possible to obtain an uptake of 550µg of uranium per gram of titanium.

c) For 100-150 mesh (≃0.1 mm) granules and a flow rate of 0.33 cm/s, the efficiency of the adsorption is a function of adsorber bed depth and reach to a limit of 65%.

d) Once adsorbed, uranium is held tightly by hydrous titanium oxide, and its economic elution is a major problem. Uranium can be eluted by acids but at concentrations where the solubility of the adsorber is too high; 1.5 M ammonium carbonate solution appears to be the most promising, although the recovery is not complete.

e) The efficiency of the cycle overall was 46% and 0.26 g of uranium was separated from 170,000 liters of water.

Table 1. Concentration factors for some elements in hydrous titanium oxide granules after 30 days' contact with seawater. (From: Keen, 1968)

	Concentration		Concentration factor =
Element	In sea-water[*] mg/l	In HTO[†] (mg/g of Ti)	$\frac{\text{Conc. in HTO, mg/g Ti}}{\text{Conc. in seawater, mg/ml}} \times 10^{-3}$
Cr	0.00005	0.049	1,000
V	0.002	0.49	250
U	0.0033	0.32	97
Mn	0.002	0.17	85
Fe	0.01	0.73	73
Ni	0.002	0.12	60
Ba	0.03	0.73	24
Cu	0.003	0.049	16
Al	0.01	0.12	12
Si	3.0	12	4
Sr	8.0	2.8	0.3
Ca	400	73	0.18
Mg	1,350	24	0.018
Na	10,500	17	0.0016

[*] From RILFY and SKIRROW (1965), Chemical Oceanography, 1.

[†] By spectographic analysis (except for uranium).

Other Extraction Processes

1) Recently, adsorbing mixtures for uranium production from seawater have been elaborated. In Japan, they are mixtures of metal hydroxides (iron, aluminum, chromium, manganese, titanium); activated carbon adsorption capacities are, for example, 6 mg of uranium per gram of iron and 170 mg per gram of aluminum. Because the added quantities of carbon are not known, it is not possible to give an indication about the total weights of adsorbers to utilize (Ogata and Kakihana, 1969).

2) Galena was successfully used in Japan (Koyanaka, 1970) and also by Khan in Pakistan (1972) who uses a 10% ammonium carbonate solution as eluant and regenerates the galena by means of a weak hydrochloric acid.

3) Other scientists have utilized the co-precipitation method. Thus, titanium oxide, obtained this time in situ, showed itself to be an efficient co-precipitating agent but in working at pH 4 (Ogata, 1968).

The American school of Hawaii has pursued its research on this method but with thorium hydroxide (Leung et.al., 1972) with simultaneous use of the sodium dodecyl sulfate, the surfactant, and a compressed air bubbling. Professor Zeitlin did not try to combine the advantages of this process with the good adsorbing properties of titanium oxide.

4) The Japanese also showed that surfactant agents, used in the form of iron, zinc and particularly titanium stearates (Ogata and Kakihana, 1969), allow an excellent uranium efficiency recovery of the order of 80%.

5) Very recently the titanium adsorbing properties have also been put to use in the form of polyvinylic alcoholate fibers or textures. This has been patented in Canada.[1] This aspect of the adsorber renders its use easier than the one of a granulated hydroxide when it is necessary to immerse it in a sea current.

6) At this time the possibility of extracting uranium by means of a biomatrix specific to seawater is being tested at the Institut de Chimie du Centre de Recherches Nucléaires de JULICH (KFA); for example, sea algae fulfill this condition.

It has been found that the uranium concentration in guano was 20,000 to 30,000 times greater than in seawater. Uraniferous algae could be grown in breeding tanks and thereafter placed in seawater currents (Ozean Technik, 1975),

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[1] Canadian patent 922 900, 20 March 1973, process for recovering uranium from uranium bearing aqueous solutions.

PUMPING PROBLEMS: UTILIZATION OF EXISTING PUMPING DEVICES

The low uranium concentration in seawater will necessitate the handling of very great quantities of water. Keen (1968) has envisaged the realization of a tidal lagoon system, similar to those built for tidal power plants, where generators would be replaced by layers of hydrous titanium oxide. Schmidt-Mende (1974) thought that the water could be led into compartments similar to those of salt marshes by using the natural current of the sea or tidal streams.

The high cost of the work involved in the two systems would be a heavy charge on the cost price of the uranium thus recovered. Sikandar Khan (1972) considered reusing the waste water of the desalting plants.

A 10,000 MW, 10 Unit Nuclear Plant

Starting from this idea, that is to say the use of existing pumping devices, we are going to study the case of onshore nuclear power plants. Such plants constitute, in fact, important pumping units as the cooling of a plant made up of 10 × 1,000 MW groups shall require a flow of about 500 m^3/s.

We are going to try to determine the characteristics of a uranium extraction plant which could be thus linked to such a plant (see Table 2). Starting from the result obtained by Keen (1968), we shall make the pumped water flow through sieves fitted with hydrous titanium oxide in granulated form. For 100-150 mesh (approximately 0.1 mm) granules in layers 2.5 cm thickness and with a rate of flow of 0.42 cm/s, it is possible to recover, in eight days, 380 μg of uranium per gram of titanium.

Table 2. Use of a nuclear plant's cooling water.

Assumptions:	
1	Power: 10 × 1,000 MW
2	Cooling-water flow: 500 m^3/s
3	Adsorber bed depth: 2.5 cm
4	Granule size: 100-150 mesh (≈0.1 mm)
5	Flow rate: 0.42 cm/s
6	Performance of the adsorber: 380 μg d'uranium/g Ti after eight days
Results:	
1	Recovery efficiency of the adsorber: 0.32
2	Quantity of recovered uranium: 16.7 tons per year
3	Uranium supply for the plant: 1,600 t/year
4	Adsorber bed surface: 160,000 m^2
5	Titanium necessary quantity: 1,600 tons.

In this case, the adsorption yield is 0.4 and given 0.8 as the elution yield, the annual quantity of recovered uranium would be 16.7 metric tons.

Granted that three-quarters of the time is devoted to adsorption (the remainder to elution) the installation requires 1,600 tons of titanium and a filtering area of 160,000 m^2 for operation. The areas and the quantities of reagents to be used are, in fact, very large but still within practical limits.

However, it appears advisable to compare them with the following result: the recovered uranium represents 1% only of the annual consumption of a light water plant made up of 10 reactors. It is therefore possible to infer that the use of pumping stations does not appear significant for this type of plant.

But the conclusion would be quite different in the case of a plant made up of breeder reactors. The order of magnitude of the volumes of water needed for cooling remains the same, but the uranium consumption is divided by roughly 100. As a result, a breeder cooled by seawater, the uranium from which is being recovered, becomes autonomous as regards its fuel supply.

Tidal Lagoons

Let us come back to the use of tidal currents. From this point of view, France has an exceptional site at her disposal, the Chausey Islands. Ten years ago, Electricité de France looked into a tidal plant project with a maximum 12 GW of power capable of providing 27 TWh. The dams enclosing the basin would have a length of about 40 km; the estimated construction cost would be 13 milliard French francs.

Let us assume in this work that we replace the generators by uranium filters. The maximum water output of the tidal currents passing through the sluice gates would be 225,000 m^3/s. We can estimate at 5,000 tons/year the uranium quantity likely to be recuperated (see Table 3).

Table 3. Comparison between a tidal power plant (design) and a tidal uranium plant.

Tidal Power Plant	"Tidal Uranium Plant"
Electricity production: 27 TWh/year	Uranium production: 5,000 t/year
(equivalent to the consumption of 600-700 tons of uranium)	
Estimated cost for the construction of the dams: 13.10^9 FF.	

To produce a quantity of electricity equivalent to that of the tidal power plant, a light water plant would consume between 600 and 700 tons of uranium. The use of the dams is undoubtedly more attractive, energywise, than the tidal plant itself. However, this assumption is open to discussion because, on the one hand, the regularity of the extraction could be secured only with a sufficient renewal of the water from the oceans in the vicinity of the work and because, on the other hand, one must take into account the energy expenditure necessary for the treatment of titanium and the preparation of the nuclear fuel.

ECONOMIC DATA

Various authors, firms or organizations (Keen, 1968; Schmidt-Mende, 1974) have given, during those last few years, indications of the cost price of uranium recuperated in this way (see Table 4).

Table 4. Estimated costs of uranium per pound extracted from seawater.

References	Costs (in $ per pound)
N. J. Keen (1968)	38 - 62
U.S. AEC (1965 - 1966)	300 - 1,000
P. Schmidt-Mende (1974)	60 - 90
Nucleonics Week (1974)	35 - 1,000
MITI Japonais	50 - 60
(Applied Atomics, 5 November 1974)	

From these one can see there is a great margin of uncertainty about this price and one must underline that it cannot be easily cleared away because no author has given details concerning his basic assumptions. Moreover, the lifetime of the hydrous titanium oxide layer is not known with any precision and it is still extremely short in Keen's experiments; the lifetime will be predominant in the final calculations.

It is noteworthy that the study of the Battelle Institute gives a pumping price of $33 per pound of produced uranium for a height of 4.5 meters. The dam capital charge, in a plant of uranium production, is about 2.5 million francs[2] per ton of uranium, or $250/pound × year.

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[2] Roughly, US $500,000.

The minimum price, of the order of $50 per pound, appears to correspond to a practically unlimited supply of hydrous titanium oxide gel and to investments equal to zero for the pumping device.

CONCLUSION

The importance of the reserve built by the uranium in solution in the oceans should not blind one to realities. According to one of the classifications mentioned by Grenon (1975), it can be said that:

1) this reserve is proved,
2) it is "sub-marginal".

The caution of the authors, for the time being, does not allow for a correct idea of the position of this reserve among other low grade reserves likely to be exploited.

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DISCUSSION

Hubbert: Would you mind explaining exactly what the "analog method" is?

Schnabel: Analog methods depend upon defining the geological configuration of an area and then attempting to find other areas with similar configurations, in order to attempt to locate new areas for deposits.

Odell: Both from your paper and from the previous papers I have the impression that uranium is quite plentiful--that there is no resource question over the commodity as we discussed it this morning with oil. In the light of this, I wonder why it is necessary to go to these ends to evaluate a resource that presumably could be developed in the quantities required under the stimulus of ordinary commercial activities of those who seek to make a profit out of producing it.

Schnabel: This occurs primarily because the greatest profit comes from the small high-grade deposits. The small, high-grade deposits produce the least environmental impact when you can mine just a few hundred thousand tons--it is much better than mining millions and millions of tons. This is one of the primary reasons for doing that. In addition, we could not mine the Chattanooga shale starting tomorrow--we do not know how. There is going to be 5 to 10 to 15 years lead time before we know how to extract uranium from Chattanooga shale. Somebody calculated, just recently I think, that 700,000 miners, all the water of a major river, 10 times the quantity of sulfuric acid produced annually in the US, are required in order to extract our future annual needs from the Chattanooga shale. This is the reason we are looking for the small, high-grade deposits.

Dunham: I wonder whether we are not being a bit unduly complacent about uranium.

Cameron: Perhaps the trend of my paper appears to be optimistic, and perhaps Schnabel's also; however, we are optimistic only in the existence of uranium deposits but by no means optimistic in our ability to recover them in the time frame required. The political/economic problems outlined in my paper are very serious and I tend to be pessimistic about our ability to solve these.

Schnabel: Precisely, but I think that in the USA we have a pretty good handle on how much uranium we can expect to find in our sandstone deposits. And it is going to come nowhere near fulfilling our requirements.

Dunham: That was the point I really wanted to make.

Bowie: I agree. We are being complacent, but I do not believe that we are being too complacent, and this particularly relates to the availability of uranium between now and the end of the century.

Schnabel: It is a very important part of the work of the USGS to attempt to locate some large deposits that contain uranium in the 0.01 range. We do not know whether we have any or not.

Häfele: I have an observation along the lines of your previous comment on whether we would have to go to large scale uranium mining. It concerns the fairly large amount of the capital investment. But now there are two superimposed uncertainties about that. One uncertainty is within the nuclear field itself, namely, the question of when the fast breeder is going to come and when it is going to have its impact on the uranium economy. If the breeder comes indeed, as observed by another participant, then the question of uranium supply is on a basis qualitatively different from without the breeder.

The other uncertainty is about the nuclear option in general. It is not so much a question of nuclear reactors, but that we are able to install nuclear fuel cycles that are economically and ecologically feasible, that is, both economical and ecological. As long as that question is not really answered, private capital will not really go into large uranium mining. Therefore, these are the socio-political uncertainties--they are of a "soft" nature, and fit the other observations we made yesterday. In other resources areas we do not perhaps have soft problems to the same extent but we do also have them, not of physical availability, but of a socio-political nature.

Fiala: Mr. Brinck, as I understand it, your model works well in price assessments for natural resources, metals, and so on. If it does, I do not understand why it also works for gold. I imagine that the price of gold is manipulated much more than the price of any other resource. So I can imagine that factors affecting technology go into your model very well, but how about policies of banks, nations, etc.? How do you include these in your model?

Brinck: You are perfectly right, and I think everybody should realize we used to have gold as a monetary standard. So all mineral products went on that standard. And they follow gold.

I did not say that I can predict real prices, but I can predict price differences with the model. So if you say gold is $35 per ounce, then uranium is $6 per pound, because you take gold as a monetary standard. For the mining companies it does not make any difference if they develop gold or copper or zinc mines. They just tend to go where the best profits are.

Bowie: How can you establish a specific mineralizability factor in an area that you have not done any work on? How do you find the uranium you have told us about in the first 2.5 kilometers of the earth's crust? How do you find a part of this, say a hundred meters below the surface, let alone 2.5 kilometers? I am very pleased to see that you think we will not need to mine uranium from material below 200 ppm, but does that not conflict with your very optimistic outlook of our being able to provide something on the order of 250,000 to 300,000 tons of uranium per annum from the higher grade material? I just wondered whether you had any ideas where this material was likely to be found?

Brinck: I did not go into the determination of the specific mineralizability. It is written up in my paper. There are about five different methods to estimate it, and you should choose the best one, giving the best, that is, the most conservative, results. On the question of finding the uranium, I leave the answer to an exploration geologist. One of the possibilities is measuring the potential by geochemistry. If you know you are in the right province your chances are high that you are going to find a mine. And for the third question, sure, you do not have to mine from very large deposits if you have to mine 250,000 to 300,000 tons per year. This would be comparable to what the copper industry is mining now, and I guess that would be comparable to 0.7% copper ore.

Bowie: The 250,000 to 300,000 tons per year of uranium is about the total resources of the Republic of South Africa or Canada or Australia, and these countries would have to mine this amount each year.

Brinck: I calculated this a few years ago. I do not know if it is still correct, but the total uranium reserves that we knew about two years ago represent in terms of ore just one year's production in the copper industry. So why could we not do the same for uranium as for copper?

Bowie: And yet we have taken some 30 years to find a million tons of reserves.

Bauerschmidt: How can you manage the different rates of inflation in the world and the changes in the value of the different currences? For example, the FRG's mark has been revaluated twice in relation to the dollar within the last few years.

Brinck: You have a problem there, I agree. It is a problem for our time, one of today's main problems.

Bauerschmidt: You cannot manage it in the model?

Brinck: No, I can only say that the long-term price differences are stable. That is, if you start shaking up your standards you shake up the whole system.

Ross: I would like to ask a question of both Cameron and Bowie. How do you explain the fact that 95% of the present low cost reserves are in five countries (the USA, Australia, the Republic of South Africa, Canada, and France) while only about 15% of all the surface classified as geologically "favorable" in the IAEA states (say, those who provide information) had been surveyed in any detail then?

Bowie: I will try to comment on this, but I do not know if Cameron will agree with me. It is a very significant question whether it is fortuitous that 90% or 95% of all the uranium reserves/resources are in Canada, France, Australia, the Republic of South Africa, and the USA. I believe that uranium occurs in provinces in the same way as any other metal occurs in provinces. We have the tin province of Nigeria, of Malaysia, or of Bolivia. We have very little tin in the USA, if any. We have a concentration of uranium in the Colorado plateau and Wyoming Basin province. I do not believe that there is another concentration like that in the USA, but I stand to be corrected. We have a well-defined uranium province in Australia and in the Republic of South Africa and in Canada. And in all cases the uranium is either in Pre-Cambrian rocks or in newer strata immediately overlying Pre-Cambrian rocks, as in the case of the Wyoming Basin. And I believe that we can show, although we have not got enough data to do this yet, that uranium was preferentially concentrated in the Pre-Cambrian rocks in the early formation of the earth's crust, perhaps around 2000 or 3000 million years ago. What we have had since then is a remobilization, a redistribution, of uranium in the same district, but it never moves out of that district. It is a little bit like hunting for an elephant. You do not hunt for elephant in Greenland, you hunt for elephant in elephant country--you look for uranium in uranium country.

Bauerschmidt: Have we looked for a chance to produce a portion of the projected European demand for uranium inside Europe?

Bowie: The amount of prospecting that has been carried out in certain parts of Europe has been very extensive. The amount of prospecting in other parts of Europe at most has only scratched the surface. But the most favorable areas have been prospected and in detail.

Bauerschmidt: We project for Europe a demand of more than one million tons to the year 2000. Will we have a chance to produce a part of it?

Bowie: I do not believe that Europe can supply its own uranium requirements to the year 2000. Nothing like it, and not afterward either. It depends upon when this curve that Cameron showed you goes down. It depends upon the introduction of breeder reactors and so on.

Schnabel: Mr. Bowie, you spoke about in situ recovery. There are several companies in the US that are actively working on in situ recovery, and a few of them have experimental processes on line. I do not know what the solutions are--they do not tell us that--but they do say that the solutions they are using are innocuous enough to possibly be used on a broad scale.

Bowie: I am very pleased to hear that. I know that certain work of this kind is going on in Canada and I think that there is a great prospect for this development in the future.

Cameron: In situ leaching has also been done. It was really started, I suppose, in Portugal a long time back. But in the IAEA we have a research program going ahead that has at present eight different countries involved in research on in situ leaching.

To summarize Schnabel's, Brinck's, Bowie's, and my own papers, I think that although we may have many disagreements between us on many various smaller points, we are essentially agreed that the uranium probably physically exists in the world and would be sufficient for the reactor needs as far as we can see into the early part of the next century if it can be made available. The problems are not in its existence; the problems are availability, as Bowie has said, and all the political, economic, and technological problems that have to be overcome before we can meet this really quite exceptional rise in demand up to the end of this century. These are the problems.

Brin: I agree completely with Bowie on the problem of the extraction of uranium from seawater. The resource is very important, but it is necessary to use such great quantities of seawater that the possibility of a practical plant is very small.

Marchetti: What about biological processes?

Brin: There are some papers on biological processes. For the moment, the results are not very good. Some seaweeds concentrate uranium.

Marchetti: There are the conclusions of the Jülich group.

Brin: Uranium is concentrated in microalgae and possibly in other levels of the food chain.

Ross: I cannot help but comment on your comments about the necessity for concentrating the U235 in uranium. Being from Canada, I would like to point out that there are reactors that use natural uranium on the market today.

Roy: Does the filtering process by which you take the uranium out filter out any of the biological material, plankton, or whatever else is there? Then you pump an effluent that is barren, so you get into ecological problems.

Brin: The process is an absorptive one, so there are no chemical effects. The pumping will be slow, but the accumulation of organic water on the filter is possible and the removing of this water will certainly destroy a part of the plankton.

Roadifer: Are there any by-products extracted in addition to uranium?

Brin: Chronium and vanadium are also concentrated.

CONCLUDING REMARKS

M. Styrikovich and W. Häfele

Styrikovich: The work of this short but, I hope, very effective Conference of IIASA on Energy Resources is coming to an end. In the past two days many papers--maybe too many for such a short time--were presented and discussed. Many questions arose, and they illustrate that we need to do much work in the future on these problems.

Some words about the topics of the Conference itself. We already have many publications about energy resources. But this Conference verified clearly that this is not enough. All previous surveys on energy resources are incomplete. For the purposes of the IIASA Energy Project, they are mainly prognoses of a global type, and, for the distant future, hardly usable.

For many years I have been closely connected with the World Energy Conference as Vice-Chairman of the Executive Council. I consider the Energy Resource Survey of the Ninth World Energy Conference, consisting of a large amount of data and figures, also incomplete. Based mainly on the official answers of the National Committees, the Survey does not include data about resources for many nations. Besides, for organic fuels the Survey generally does not divide resources--mostly coal--into the several categories according to cost and production as already done more or less for uranium. Additionally, we need some, perhaps limited but universally accepted, system of classification. It is impossible to compare, for example, tons of hard coal and lignite without taking into account calorific value. It is very difficult to compare dates and figures if we do not agree to use high or low calorific value or to summarize, for example, hydroenergy, heat of combustion, atom splitting, and low temperature heat of geochemical resources.

In the evaluation of not yet discovered but probable resources, especially for oil and gas, it is necessary to take different figures with the same degree of probability, the same degree of optimism, or pessimism. In any case, it is necessary to put in clear words the principles on which these or other estimates are based.

Of course I do not think that such an extensive task will be accomplished by a small number of scientific workers at IIASA itself. But I believe that with good cooperation with national programs IIASA will be very effective in such a valuable area. Even approximate estimates of economically recoverable energy resources for the not too distant future done by such an independent international body as IIASA will be usable for all participants, and I hope for goodwill and cooperation.

It has been mentioned that global dates and figures for the not too distant future can be produced without direct influence of today's private interests involved in any estimates, for the present time or the very near future. This was clear, for example, in the question of oil from the North Sea. For global estimates, in the not too distant future, it will be possible to be more objective, and I hope that this Conference will be the base of well organized, good, and very usable work.

Häfele: At the end of the Conference I would like to remind you that the situation at IIASA is such that not only that the Energy Project is broader than the resource aspect of energy, but the whole Institute is broader than the Energy project. The Institute is decision-oriented. The idea is to provide the decision maker with assistance and clarifications on complex methods. To that extent we have not covered certain aspects of the resource problem--for example, standards, regulations, policies, or governmental actions to expedite this or that route.

Now, of course, all this remains a task of the Institute. But I am repeating this because I would like to invite you to stay in contact with us and to identify such policy questions or issues to be made, not only in terms of physical resources but also for policy and decision questions. At the same time, we are an exchange agency and I think to some extent we have managed to expedite such an exchange. Please do not hesitate to continue the contact with us in these more specific aspects.

APPENDIX A

AGENDA

Session I. General: Classifications and Activities

Chairman: M. King Hubbert

M. Grenon	Resource studies in the Energy Project of the International Institute for Applied Systems Analysis
L. Bauer and R.S. Carlsmith	WEC activities in the field of surveying world energy resources
K. Patyi	Decreasing role of resources in Hungary
M.F. Searl	Resource assessment and supply curve development: toward better methodologies
J.J. Schanz, Jr.	Problems and opportunities in adapting US Geological Survey terminology to energy resources
B.F. Grossling	In search of a probabilistic model of petroleum resource assessment
G.M. Kaufman	Models and methods for estimating undiscovered oil and gas--what they do and do not do

Session II. Coal Resources

Chairman: M. Stryikovich

G.B. Fettweis	Contributions to the assessment of world coal resources or coal is not so abundant
K.J. Englund et al.	Coal resource assessment in the United States

M. Dopita and J. Franěk	Methodology of evaluation of the mineral reserves in the Czechoslovak part of the upper Silesian basin
P. Kausch et al.	The brown coal resources of the Rhineland: geology, mining and utilization
N. Bonneau	Classification of French coal reserves

Session III. General and Petroleum Models

Chairman: M. Stryikovich

M.Sh. Modelevsky and V.F. Pominov	Classification of petroleum resources and reserves in the USSR and its comparison with classifications used in other countries
M. Albegov	A systems approach to the economic estimating of fuels
G.B. Baecher	Subjective sampling approaches to resource estimation

Session IV. Petroleum Resources

Chairman: J. Masseron

R.A. Sickler	World Petroleum Resources, Part 1: Methods and models used to estimate world petroleum resources Part 2: A survey of petroleum resources in the world outside centrally planned economies (WOCPE) status on 1 January 1974
P.R. Rose	Procedures for assessing US petroleum resources and utilization of results
E. Barouch and G.M. Kaufman	A probabilistic model of oil and gas discovery
Yu. A. Rozanov	Hypothetical probabilistic prototype of an undiscovered resources model

R.E. Roadifer	A probability approach to estimate volumes of undiscovered oil and gas
K.J. Roy	Hydrocarbon assessment using subjective probability and Monte Carlo methods
G. Gess	Methodology of hydrocarbon resource appraisal in relationship to the "Petroleum Zone" concept and probabilistic calculation
P.R. Odell and K.E. Rosing	The North Sea oil province: a simulation model of its development and exploitation
M.Sh. Modelevsky and I.Ya. Fainstein	Some models for long-term forecasting of raw material provisions for oil and gas production
A. Seigneurin	Probabilistic evaluation technique
G.B. Baecher and J.G. Gros	Extrapolating trending geological bodies

Session V. Geothermal and Uranium Resources

Chairman: J. Cameron

J.P. Herault	Evaluation of geothermal low enthalpy resources
J. Cameron	A review of long term uranium resources, problems and requirements in relation to demand 1975-2025
R.W. Schnabel and W.I. Finch	Uranium resource assessment in the United States
J.W. Brinck	Uranium resources assessment with Mimic: a descriptive model of mineral resources and long-term price trends in the mining industry
S.H.U. Bowie	Some facts and fancies on uranium availability
A. Brin	Uranium from seawater: a review of recent papers

APPENDIX B

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METHODS AND MODELS FOR ASSESSING ENERGY RESOURCES

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Michel Grenon, Editor

Any long-term energy policy must be based, not on the energy reserves that we will use in the next one or two decades, but on the energy resources that will feed our energy systems in the next century. Many important decisions have to be made now about those resources. Industry has, for a long time, been interested in estimating energy reserves, which are, to a certain extent, their "energy cashflow". Much less is known about the resources.

Various models and methods have been used to assess long-term resources of coal, oil, gas, and uranium, varying from historical statistics, as promoted by M. King Hubbert, to geological analogy or Monte Carlo simulations. Increasing attention is being paid to these methods, to their limited capacity, to their data requirements, and so forth.

For the first time, a conference convening more than 80 experts from East and West has addressed these methods and their potential applications for assessing world energy resources of coal, petroleum, and uranium. Very active discussions pointed out where progress still has to be made and what the most sound factors are on which to base future methodological developments.

The proceedings of this conference, the first of a series organized by IIASA on energy resources, are a basic contribution to the most important field of world energy resources.

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