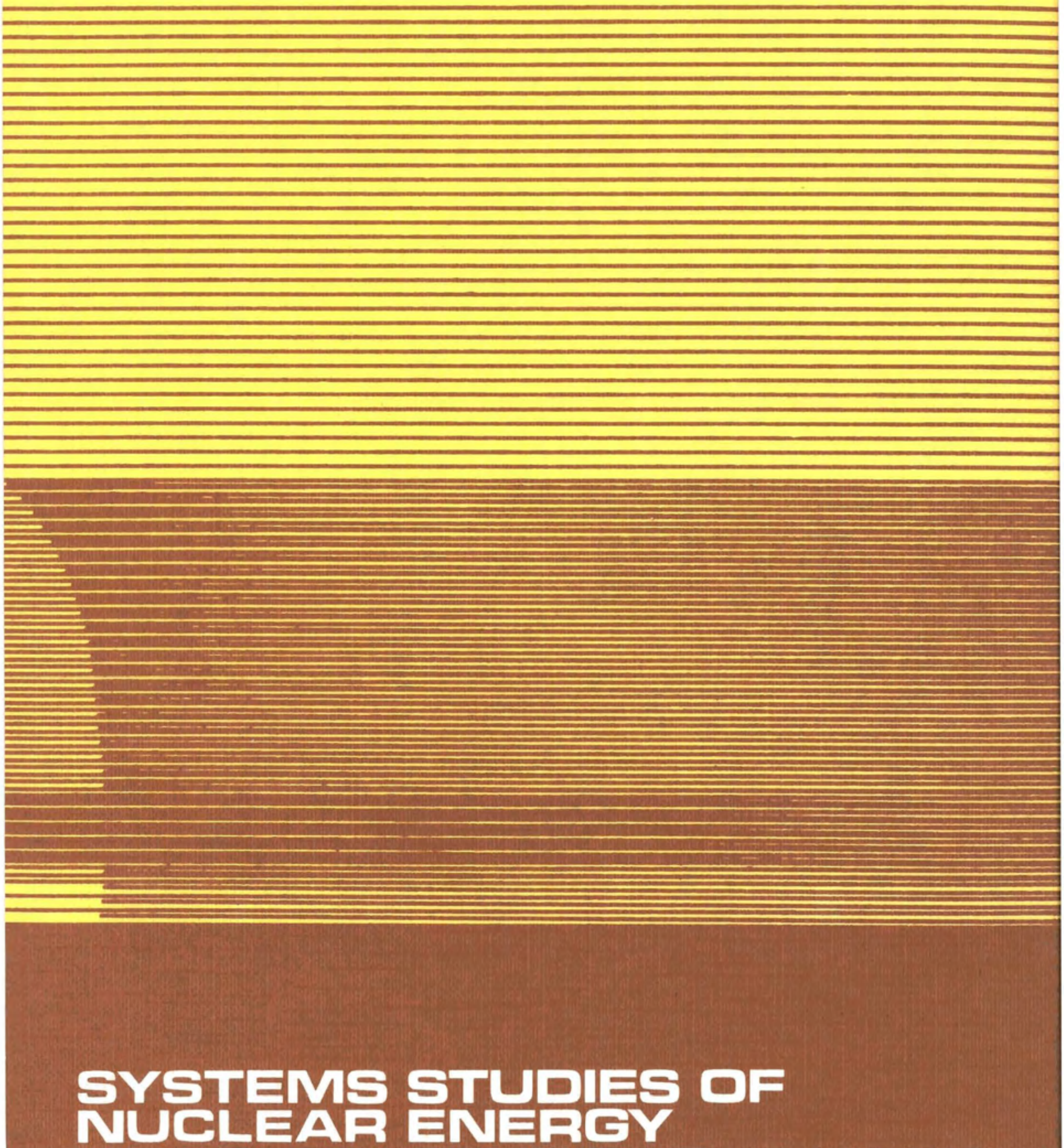

SYSTEMS STUDIES OF NUCLEAR ENERGY DEVELOPMENT IN THE USSR

L. A. MELENTIEV, A. MAKAROV, A. BELOSTOTSKY
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This work was done in loose conjunction with the IIASA Energy Program, though not as part of the program as such. It is considered one of the Energy Program's functions to communicate contributions from National Member Organizations. The report has been carefully reviewed before publication and represents, in the Institute's best judgment, competent scientific work. Views or opinions expressed herein, however, do not necessarily reflect those of the National Member Organizations supporting IIASA or of the Institute itself.

International Institute for Applied Systems Analysis
2361 Laxenburg, Austria

PREFACE

It is one of the goals of the Energy program not only to do in-house research but to promote and pursue collaborative research and exchange of information with other institutions. One may view this interest as an attempt for a broader IIASA Energy program that encourages a wider vision of energy problems. Indeed, the number of groups that closely cooperate with the program is increasing; given our premise, reports of those groups may well be seen as an output of this broader Energy program.

The present paper is a major contribution of the Institute of High Temperatures, Moscow, and the Siberian Power Institute, Irkutsk, USSR. It points to the systems implications of the development and future trends of the nuclear option against the background of the fuel resource situation in the USSR.

Tangible contributions of this kind add to the understanding of actual systems problems. It is IIASA's intention to continue with such collaborative papers and to try to follow up on this line of activities.

Wolf Häfele

SYSTEMS STUDIES OF NUCLEAR ENERGY DEVELOPMENT IN THE USSR

INTRODUCTION

The nuclear power industry (NPI) is now becoming a vital means of meeting the demand for electric and thermal power, particularly on a long-term basis. Under a socialist planned system of economy, a comprehensive study of the effects of developing the NPI can be undertaken so that the best use may be made of the advantages of adopting this new source of energy, and the maximum economic effect obtained. This means that optimal trends in the development of the NPI need to be determined and the following basic problems solved:

- Choice of an economically expedient role for nuclear power in the country's fuel-energy balance and of nuclear power plants (NPP) in the electric and thermal power supply;

- Determination of the most effective use of NPP's in the electric power systems, including the most suitable sites for NPP's in the interconnected electric power systems; elucidation of their optimal share in covering the load-duration curve (the plant factor); determination of the optimal types of NPP's (nuclear electric, base-loaded, intermediate, thermal, etc.); reasonable choice of sites for NPP's, and so on;

- Choice of long-range strategy in developing the NPI, including determination of a reasonable combination of various reactor types, taking into account the fuel supply for reactors;

- Choice of optimal parameters of various NPP types and fuel supply enterprises.

The problems listed are so closely interrelated that their reasonable solution can be obtained in a complex form only. Therefore, an analysis of the NPI as a large integral complex under development is a necessary methodological basis for solving these problems. Such studies are complicated, laborious, and multivariant. It is only logical, therefore, to use mathematical models as the main tool for this kind of research.

Naturally, it is impossible at this stage to devise a unified model for solving the given problems because it would inevitably be too cumbersome, and in general this is hardly advisable by reason of diversity of problems, varied accuracy of information used, different criteria, etc. The most efficient line of research would appear to be the arbitrary decomposition of the integral system of the NPI, with construction of mathematical models to investigate the various features of this system and with obligatory subsequent coordination of the solutions obtained for individual models, which thus form *a complex of mathematical models.*

Such a complex of models was devised in 1970-1975 to optimise the development of the nuclear power system (NPS). The composition of the model complex is given in Figure 1. For a detailed mathematical description of the models, see Ref. [1]. A brief description follows.

The model complex for optimizing the development of the NPI is based on the multilevel principle. At the top of the hierarchy is a model of the NPS development within the country's fuel-energy industry (FEI). This model is used to forecast the most general characteristics of the nuclear power branch, such as levels of its development, optimal siting of NPP's throughout the country (on a large scale), and so forth; details are given below.

The solutions obtained are then specified in the optimization models for NPP's within the electric power and heat supply systems, and also in those for the development of fuel supply enterprises. In these models the general characteristic features of power installations are optimized: the choice of the NPP types (base-loaded, intermediate), the determination of the unit capacity of fuel supply enterprises, and so on.

Next, the parameters of power installations (e.g. of nuclear electric power plants (NEPP) and nuclear thermal electric power plants (NTEPP)), are optimized on the basis of the solutions previously obtained.

The long-range strategy model of the development of the NPI is intended for investigating the long-term trends in the development of this branch, to substantiate the trends of technical progress therein, to estimate the after-effects, and to allow for their impact on the development of the nuclear power system in the FEI and in fuel supply enterprises.

The models for investigating external linkages provide for a study of the linkages of the FEI with other branches of the national economy (external economic linkages) and of the impact of the FEI on the environment. A model taking into account external economic linkages has recently been worked out which permits analysis of the varying requirements of the FEI for the products and services of other branches against the background of the development of the NPI. Details are given below.

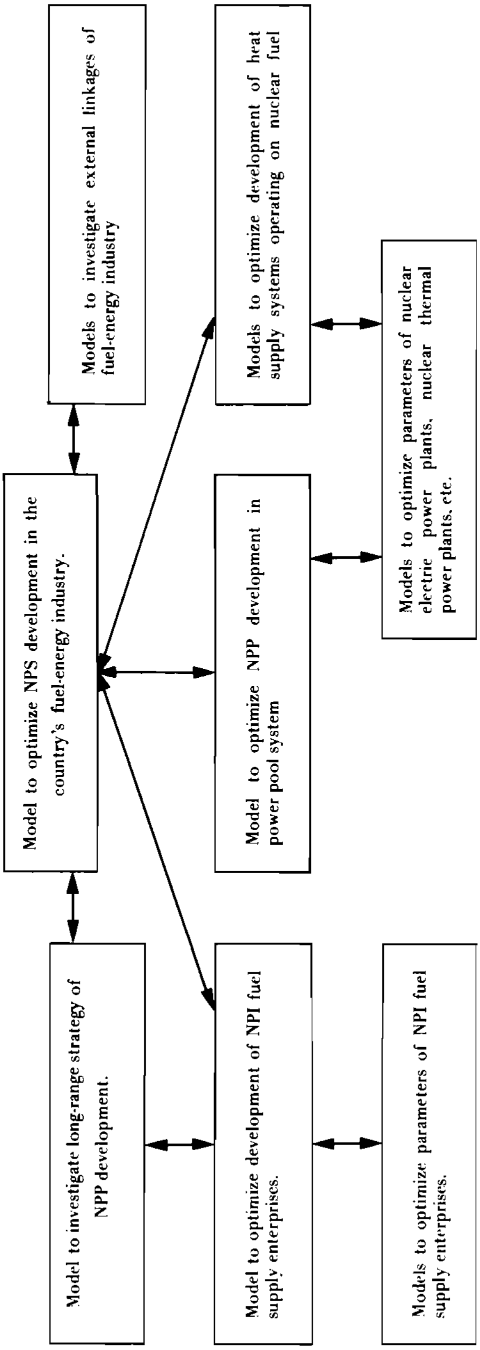

Figure 1. A multilevel complex of mathematical models for optimizing the development of the nuclear power system.

In Figure 1 the interactions between the models are shown as bilateral and involve both direct and back linkages.

The decisions made at lower levels of the hierarchy, on the basis of the data fed from the upper levels, in turn form initial data for correction of the decisions made at the upper levels of the hierarchy. For example, in selecting the type of equipment and the parameters for power plants, use is made of information about the kind of fuel to be used, its cost value, and the operating conditions of power plants in the electric power systems --this information being obtained at higher levels of the hierarchy. The optimization of the parameters and the choice of equipment type yield more accurate production-economic indices of the power plants, which are used in the iteration process when optimizing the development of the FEI. Thus, the decomposition of the NPS under consideration is combined with the coordination of the decisions for its individual parts through the iteration procedure of calculations.

The complex of mathematical models described has been used for multivariant calculations of the long-term development of the nuclear power branch, which has made it possible to study its features and to work out ideas for the development of the NPI in the USSR.

The present report contains the results of some of these studies. These results relate to the general energetic aspects of the development of the NPI and do not cover research into the branch problems proper of nuclear energy, although they are directly taken into account.

The concept of the development of the NPI has been slightly modified at different stages, in view of the varying conditions and problems. In 1969-1970, when the development program of the NPI was initiated, it was necessary to investigate the features of the new energy branch, to estimate the scope of its development and its possible share in the fuel-energy balance, and to evaluate the investments and other resources needed. The methods and results of this research are outlined in the first two sections of the present report. At present, while the nuclear power development program is being carried out and its scope has been predetermined for the next 15 years by existing enterprises and by those under construction in allied branches, the problems of optimal utilization of nuclear fuel in the country's fuel-energy industry are coming to the fore. It is natural that variations in the conditions of development of the entire FEI, must be taken into account--primarily, the modified ideas on the role therein of oil and gas. The new concept of the development of the NPI is outlined in the last section of this report.

The research has been carried out by groups of scientists of the USSR Academy of Sciences and the USSR Ministry of Power and Electrification under the general supervision of Academician L.A. Melentiev.

The research was undertaken by A.A. Beschinsky, A.G. Vigdorchik, E.A. Volkova, I.M. Vol'kenau, V.F. Zamergrad, A.N. Zeiliger, Yu.I. Koryakin, G.B. Levental', A.S. Makarova, L.S. Khrilev, and the authors of this report.

ANALYSIS OF FACTORS CONTROLLING OPTIMAL SCOPE AND EFFECTIVENESS OF THE DEVELOPMENT OF THE NUCLEAR POWER INDUSTRY

The long-term program for extensive development of the nuclear power industry (NPI) requires comprehensive technical and economic studies with a view to determining the optimal scope and methods of developing it. This research cannot be carried out (as has been done so far) by making an isolated comparison of the economic values of nuclear and conventional power plants. In fact, in the next few decades the NPI will substantially change the growth of output of fossil energy resources (oil, natural gas, and coal), substituting the most expensive fuel sources and thereby altering its own comparitive efficiency. Furthermore, the development of nuclear power plants (NPP's) will inevitably have a profound effect on the structure of the electric power systems. Therefore, the reasonable scope and methods of developing the NPI cannot be determined without investigating the optimal structure of the long-term fuel-energy balance (FEB) and of the country's power pool system (PPS).

To investigate the role of the NPI in the country's long-term FEB, it is essential to solve the problem of the duration of a planning horizon. This horizon, on one hand, should not be limited to the initial stage in the development of the NPI and therefore it lasts for more than 5 to 10 years; on the other hand, the planning horizon should not be so distant that the results of investigation become unreliable because of the error of the initial data increasing with time (especially as regards the impact of some of the cost values on the optimal structure of the country's FEB). This is why, at the first stage of research, the horizon in question has been limited to the time period that precedes the extensive use of fast reactors.

The choice of a fairly long planning horizon essentially reduces the study of the prospects of the NPI to the problem of forecasting the income part of the FEB. For this purpose a special method has been devised, based on research into the uncertainty range of the optimal development of the country's energy industry [2]. The essence of this method is the following.

A mathematical simulation model of the country's energy industry has been worked out. On one hand, it describes fairly comprehensively the conditions of the simultaneous development of the fuel industries (production and interregional transportation of coal, gas and black oil), of the PPS and the main consumers of energy resources. Described in particular detail in this model is the block of the European electric power system where the daily and yearly work routines of existing and new power plants (of various types) and of the intersystem power transmission lines are specified. The NPI is represented in the model by nuclear electric power plants (NEPP) and nuclear thermal electric power plants (NTEPP) with different plant factors and constraints on the total installed capacity of nuclear reactors. The total dimension of the mathematical model is 250 constraints and 700 variables.

On the other hand, the simulation model makes it possible to obtain from research or to generate independently a representative set of typical combinations of the possible conditions of the system development and to find an optimal variant of the FEB for each of them within reasonable terms. In the present study such variants have been obtained for 100 different combinations of the economic values of the main installations (i.e. combinations of such vital energy factors as the country's power demand, constraints on extraction of gas and oil, the total capacity of NPP's and the performance characteristics of power plants).

The energy economic factors which have the most significant impact on the optimal values of the parameters of the NPI development examined are determined from an analysis of the optimal FEB variants (options) obtained. Such parameters in the present report are the total capacity of NPP's, the relation between the development of NEPP's and that of NTEPP's, the location of NPP's of various types throughout the country, and the plant factors of NEPP's.

Conventional methods are used to plot graphs of the optimal values of the parameters cited against the important economic and energy factors. These dependences are investigated in order to ascertain whether they have pronounced "inflection points" separating the acceptable range of variation of a given factor from the region of its unwanted values.

In this context we have formulated some key indices for controlling NPI development, which take the form of extreme values for the controlled energy and economic factors (the cost of NPP's, their load-reducing capacity, siting, etc.), and for the other factors, the form of a simplified but vivid dependence reflecting their impact on the NPI parameters being investigated.

Application of the given method of forecasting to a study of the prospects for the NPI of the USSR yielded the following results. The exploration of the maximum scope of the efficient development of the NPI throughout the country is of decisive importance in determining the sphere of its utilization. To this effect the mathematical model provides for the construction of NPP's in practically all areas of the country. The optimization results thus obtained can readily be illustrated by Figure 2. Here the longitudinal axis represents (in relative units) the growth of the total capacity of the country's power plants during the last decade of the planning horizon with its distribution over the eleven major areas. The latter are located in order of the drop in estimated costs for power production by fossil-fuel electric power plants (FFEPP's). These costs have been calculated for base-loaded FFEPP's at two extreme values of the marginal costs for fuel, which correspond to the minimum and maximum levels of gas production with no constraints on the development of NPP's. It has thus become possible to reveal variations throughout the country in the range of costs for power production by those FFEPP's which directly compete with NPP's.

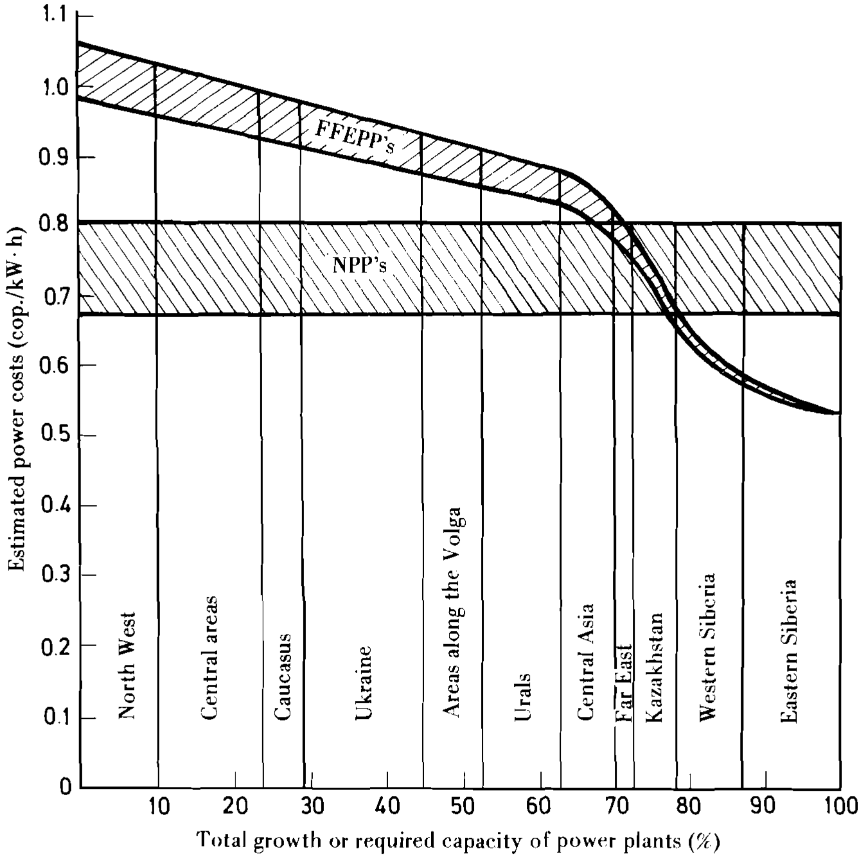

Figure 2. Characteristics of the competitive capacities of NPP's and base-load FFEPP's throughout the country.

To characterize the results of this competition, Figure 2 shows the lines of the average and minimum estimated costs for power production by NPP's. These costs can be considered constant for all areas of the country. As is evident from Figure 2, the values for NPP's in the European part of the country (including the Urals), Central Asia and the Far East are below the costs for FFEPP's. In Eastern Kazakhstan, NPP's are inferior to FFEPP's at average values, but their minimum costs are almost equal. And only in the main areas of Siberia are the NPP's inefficient compared with the electric power plants operating on Kansk-Achinsk coal and with large hydroelectric power plants (HPP), even in the most favorable conditions.

Thus, from the standpoint of territorial coverage the limiting sphere of efficient use of NPP's includes all areas of the country, except for Siberia and Eastern Kazakhstan. The territory covered accounts for more than two-thirds of the growth of the country's power consumption. Not all of this growth, however, can be provided at the expense of the NPI. This is primarily explained by a marked decrease in the comparative efficiency of NPP's when passing from steady to intermittent operation in a year or a day. A simple economic comparison shows that NPP's are able to compete with FFEPP's under operating conditions of 7000 to 4000 h/year in the expensive fuel areas (North-West) and 5000 to 6000 h/year in the cheap fuel areas (the Urals); thus they can provide no significant contribution to the peaking and intermediate parts of the load-duration curve. This means that it is necessary to reduce additionally the limiting sphere of use of NPP's (compared with the constraints obtained on the basis of territorial factors). Yet this does not give good grounds for quantitative assessment of such a decrease. In fact, by partly displacing the operating power plants to the intermediate part of the load-duration curve and by constructing specialized peak-load and intermediate-load power plants, it is possible to shift a considerable portion of the load growth to the acceptable (for NPP's) zone of the load-duration curve where NPP's are competitive with FFEPP's.

Optimal variants of the structure of the PPS (as a constituent of the FEB) have been calculated in two limiting situations for the possible composition and flexibility of the equipment of conventional power plants (in varying the capacity) for studying the impact of the load factors on the maximum capacity of NPP's. In the second structure of the PPS, the flexibility of the conventional power plants is limited (compared with the previous one).

Graphs of the maximum capacity (according to operating conditions) of NEPP's and of the saving obtained in the total costs for the FEB as functions of the load-reducing capacity of nuclear and conventional power plants are plotted in Figure 3 on the basis of the results of calculations. It follows from this figure that the NPP capacity is crucially dependent upon the composition (by type) and flexibility of conventional power equipment.

More specifically, in the case of the steady operation which is most efficient for NPP's (i.e. with no unloading at night and with a duration of 700 h/year), variations in the structure and flexibility of the other power plants within the given limits involve a 15-19% decrease in the maximum capacity of NPP's and overexpenditure of the estimated costs for the FEB of about 700 million roubles. The given data testify to the high economic efficiency of the improved flexibility of the power equipment commissioned in the previous period. Appropriate measures will be justified by a subsequent saving in costs even if reconstruction demands extra investments of 10 to 15 rbl/kW or an increase in the specific fuel consumption by 30-50 g/kW·h.

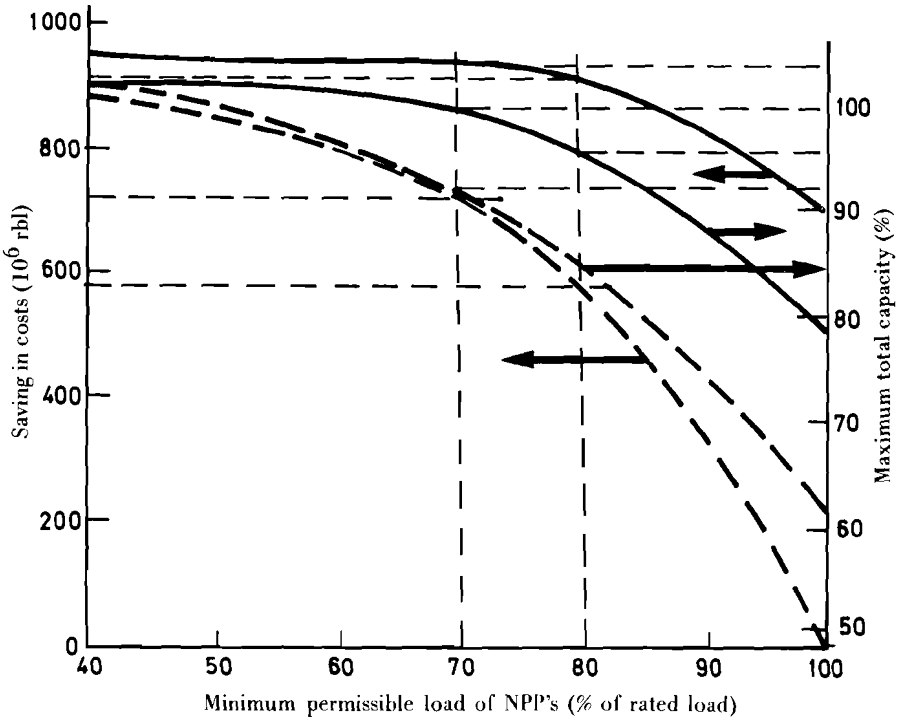

Figure 3. Impact of the flexibility of NPP's on their maximum capacity and costs for the fuel-energy industry.

Another important means of increasing NPP capacity is an improvement in the flexibility of the NPP's themselves, i.e. the technical realization of the possibility of their nightly unloading. Although this measure decreases their economic efficiency (the potentialities of cheap power production at high investments being inadequately used), on the whole it turns out to be expedient for the PPS and FEB since it largely makes up for the inadequate flexibility of the other equipment and provides a considerable general saving in costs at the expense of the increased total capacity of NPP's (see Figure 3).

However, the unlimited unloading possibilities on average for the total installed capacity of NEPP's are unlikely to be ensured even if their flexible modifications (which permit their daily shut-down) are available. This is explained by the fact that there is a transient period of about five years for construction of the NPP's [2] and for the start of construction of fast reactors. At the same time, the dependences presented in Figure 3 indicate that an increase in the minimum permissible load of NPP's from 40 to 70/80% decreases their total capacity only slightly, and adversely affects their efficiency, whereas a further increase in the minimum permissible load over 80% causes an abrupt decrease in these values. In other words, these dependences have a pronounced "inflection point", and so the unloading of NPP's down to 80% of their capacity is quite reasonable economically. Moreover, it can apparently also be realized from a technical point of view. In the latter case it would be possible:

- To increase the maximum capacity of NPP's by 15-18% with the improved flexibility of the conventional power plants (in varying the capacity and to obtain an extra saving of 150 to 200 million roubles;
- With the impaired flexibility of the remaining power plants, to completely make up for the resulting decrease in the NPP maximum capacity (increasing it by 20-23%) and to obtain an extra saving of 500 to 600 million roubles.

Taking into account the data cited, provision of the load-reducing range of NPP's at the rate of 20% (i.e. the minimum permissible load of 80%) would be reasonably economic, even with extra charges up to 20 rbl/kW (on average for all the new NPP's). This measure can therefore be considered quite reasonable.

Hence, the basic load factor controlling the maximum capacity of NEPP's is the load-reducing capacity of the conventional and nuclear power plants. Our calculations have shown that even in the most favorable conditions they cause a 35-38% decrease in the NPP maximum capacity which is established with regard to territorial constraints (where there is relatively large growth of the heating capacity of thermal electric power plants).

The development of the NPI can follow the pattern of construction not only of NEPP's but also of NTEPP's. This trend is promising, first, owing to the potentialities of a considerable expansion (almost doubling) of the permissible sphere of use of

NPP's, and second, owing to the replacement of the most deficient fuels (gas, black oil) with high marginal costs. (For details see Section IV).

The development of the nuclear power industry within its limiting sphere can be significantly affected by the following energy economic factors.

The absolute value of the economically reasonable maximum capacity of NPP's is highly dependent upon the country's overall power consumption. If the latter decreases without altering the proportions between the European areas and Siberia, the NPP capacity decreases linearly at the rate of approximately 2% to each percent of decrease in power consumption. If power production decreases irregularly, predominantly at the expense of the Siberian or, on the other hand, European zone, then the NPP maximum capacity in the former case will remain practically unchanged but in the latter will decrease at the rate of 3% to each percent of decrease in power production.

The optimal scope of construction of NPP's is also dependent upon fossil fuel resources which are able to compete in their efficiency with nuclear power. As already mentioned, among them are certainly the coal of Siberia and Kazakhstan (when used in situ) which is responsible for limiting the efficient utilization of NPP's on a territorial scale, predominantly in the European part of the country. Here also, however, the NPI may, in principle, face competition on the part of fossil fuel, namely natural and black oil.

As the multivariant calculations of the optimal FEB have shown, variations in the real range of high-grade fuel resources suggested within definite limits do not affect the NPP capacity at all and only at high rates of gas production do they cause its decrease by 15-20%. On the whole, this factor can be considered unimportant in the present study.

It is evident that the optimal capacity of NPP's should substantially depend on combinations of their own economic values and the values of the competing power plants, as well as on fuel extraction and transportation. Therefore, a correct picture of the possible variations in the optimal capacity of NPP's can be gained only from a comprehensive investigation of the uncertainty region of the optimal FEB, determined by the aggregate influence of the error of the economic values of all the installations considered.

Figure 4 gives the results of this investigation in the form of the dependence of the NPP optimal capacity on the value of factor $F = \frac{F_{npp}}{F_{ffepp}}$, i.e. on the relation between investments in NEPP's and FFEPP's. This statistical dependence is of paramount importance for understanding the prospects of the NPI.

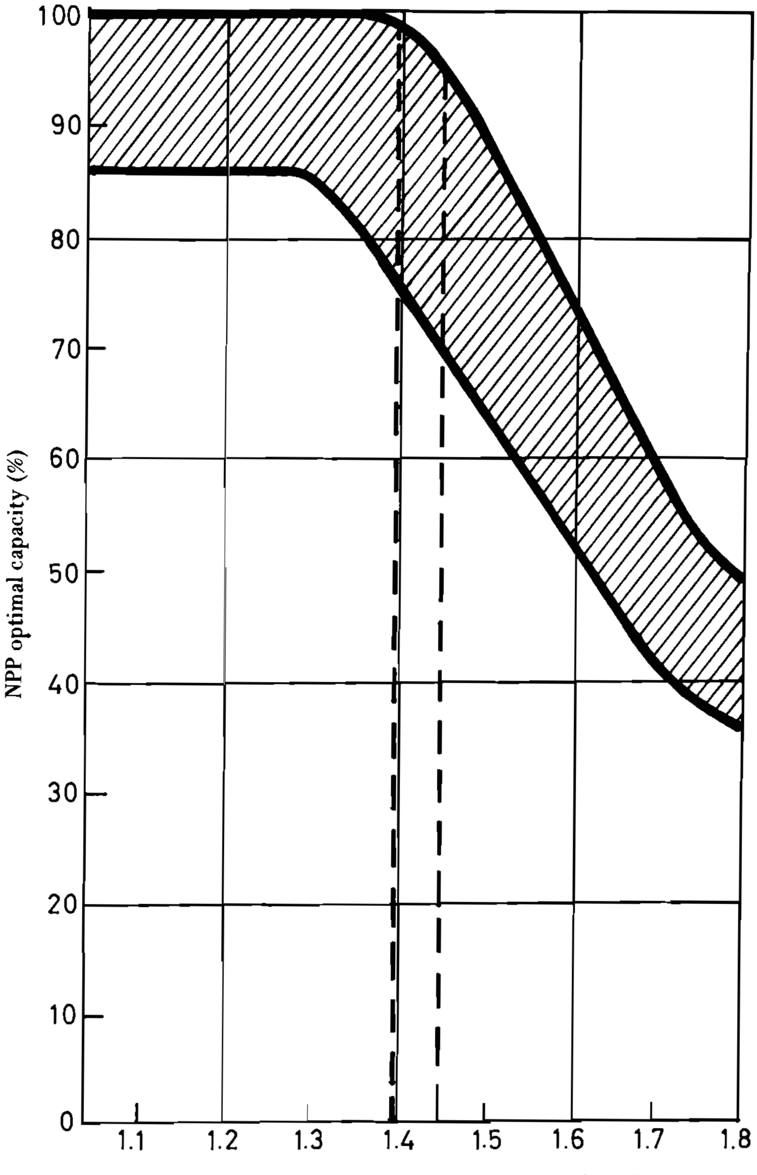

Figure 4. The optimal capacity of NPP's versus relation between investments in NPP's and FFEPP's for varying power demand.

In fact, it follows from this dependence that as long as the specific investments in NPP's are not over 40-50% (F = 1.4 to 1.6) in excess of the corresponding values for FFEPP's, the development of the NPI is slightly dependent on the economic values of the other energy resources and, for all practical purposes, can be aimed at a limiting level (with a deviation from the maximum capacity of only 10-15%).

With the cost increase factor of NPP's in excess of 1.4 to 1.5 ("inflection point"), an abrupt decrease in their optimal capacity is observed. In this case the increase in the relation between investments from 1.5 to 1.7 causes the NPP optimal capacity to decrease by 30-35% of its limiting value. With a further increase in this factor (from 1.7 or 1.8), the rate of decrease in the optimal capacity declines slightly because NPP's tend to be ousted even from the most expensive fuel areas. Nevertheless, at the given maximum values of the specific investments in NPP's (F = 1.8) their economically reasonable capacity accounts for only 40-50% of the limiting value obtained.

The levels of the NPI development described are optimal in terms of the FEB, but they may be found inefficient and even impracticable for the national economy as a whole. This circumstance is difficult to estimate economically today, but it can be taken into account as nonenergy (economic) constraints on the development of the NPI, e.g. as constraints on the total capacity of NPP's. This is why we analyze here not only the optimal scope of NPI development but also the energy economic effects of the decrease in NPP capacity as against its optimal value.

For this purpose, at average economic values of power installations, we have calculated a large series of optimal FEB variants, in which the constraints on the total capacity of NPP's were varied for different levels of power demand and high-grade fuel resources. These calculations enabled us to determine the economic damage which the country's energy industry will suffer if different (in magnitude) constraints are placed on the total capacity of NPP's. The damage value was calculated as the difference in the optimal values of the total estimated costs for energy (the functional of the FEB model) when passing from the unlimited capacity of NPP's (100%) to the ever-increasing "rigid" constraints on its total value.

The dependences illustrated in Figure 5 clearly show that in the course of a decrease in NPP capacity the magnitudes of the full and specific economic damage rise very slowly and then, on reaching a critical value, their increase becomes very intensive. There is a clear explanation for this type of dependence. At the outset, the decrease in the capacity of NPP's involves their removal from the cheapest fuel areas; at the same time, they are removed from the intermediate part of the load-duration curve in the expensive fuel areas where NPP's are preferable in view of the excessive development of relatively expensive pumped storage electric power plants, the displacement of the operating power plants to the unfavorable zones of the load-duration curve, and other inefficient measures. In other words, in the presence of constraints, NPP's are removed initially from those spheres of utilization where they and FFEPP's are almost equally efficient, and this results in little economic damage. In the absence of such possibilities, a further decrease in the capacity of NPP's cuts down their utilization with the base load in the most expensive fuel areas, thereby leading to an intensive increase in the specific and full economic damage.

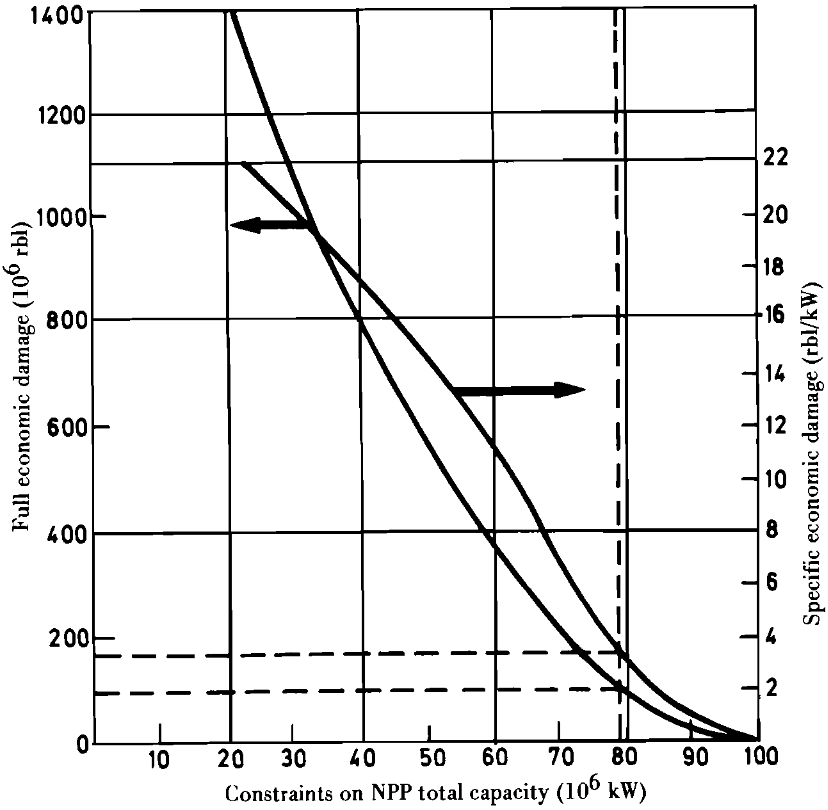

Figure 5. Economic after-effects of constraints on NPP total capacity.

The dashed lines in Figure 5 approximately indicate the "inflection points" of the economic damage dependences on the magnitude of constraints on the NPP capacity. The determination of the location of these points relative to the optimal capacity of NPP's has shown that their location is similar under different conditions of power consumption and for different gas resources and is determined by the value of the NPP capacity which constitutes approximately 80% of the corresponding optimal value.

Thus the decrease in NPP capacity to approximately 20% of its optimal value does not entail any marked damage to the power industry. In fact, the full extent of the economic damage in the FEB will in this case be only 20 to 100 million roubles (depending upon power demand and gas resources), i.e. about 7% of its possible value. The specific damage will not exceed 2 or 3 rbl/kW.

At the same time, this 20% decrease in NPP capacity seems to be justified in terms of the national economy as a whole because the difficulties involved in re-arrangement of some non-energy branches and in insurance against an eventual rise in the cost of NPP's themselves would be alleviated.

ANALYSIS OF THE IMPACT OF DEVELOPMENT OF THE NUCLEAR POWER INDUSTRY ON THE EXTERNAL LINKAGES OF THE FUEL-ENERGY INDUSTRY

In connection with the accelerated development of the nuclear power industry (NPI), there is a pressing need for comprehensive research into the economic effect resulting from the planned program for nuclear power plant (NPP) development and for elucidation of the demands made by the NPI on the national economy.

This research cannot be confined to a search for financial saving when NPP's are substituted for fossil-fuel electric power plants (FFEPP). It is very important to investigate the expected variations in material and labor costs on account of the novelty of the NPI as a branch, the instability of its economic estimates and deviation of prices in nuclear energy from real costs.

Comparison of nuclear and conventional power plants alone would not be sufficient, as such research would neglect the variations associated with fuel production and transportation. Therefore, in the present section an attempt is made to compare variations in direct material, labor and monetary costs in the fuel-energy industry (FEI) when NPP's are substituted for FFEPP's.

The nuclear branch of the FEI is formed by an aggregate of enterprises for power production, ore extraction and benefication, the chemical processing of concentrates, isotopic enrichment of uranium and manufacture of fuel elements. Coal-fired power plants supplied with fuel from the Siberian coalfields by rail have been selected as the FEI branch to be compared with the nuclear branch.

Final documents and designs for most of the existing and future power plants in the USSR or abroad, constructed according to domestic projects, formed the basis for technical and economic values of NPP's. NPP's provided with BBЭP-1000 (water-cooled) reactors of a 1,000,000-kW unit capacity serve as a primary standard.*

We have chosen the project of an FFEPP with 800-MW units of a close-coupled type as a reference coal-fired power plant. An analysis of this plant has been supplemented by the design and final data on the recent projects of FFEPP's. The technical and economic values on coal production and transportation have been selected according to the designs and standards for construction and utilization of mines and railways.

When calculating investments in the fossil-fuel branch, it is extremely difficult to take into account the costs for expanding the transport system since they depend on density of freight traffic, selected route, etc. In the absence of a specific trunk line project for the options compared, we had to make estimates according to the procedure of the USSR State Planning Commission; we also analyzed recent projects, taking into account only that part of the investments in the construction of a railway which is proportional to its loading with fuel shipment within the total density of freight traffic. For comparison of the energy supply options, all the values are given per unit of the total available energy capacity.

An important feature of the NPI, which governs its basic technical and economic values, is the extremely low mass fuel consumption as against the conventional thermal power industry. In contrast to fuel supply enterprises of thermal power plants each enterprise where nuclear fuel is converted (ranging from mines to fuel-element manufacturing plants) is able to serve a considerable energy capacity; this is precisely what determines the difference in the structure of material, labor and monetary costs between the FEI branches on the basis of nuclear and fossil fuel.

Although the specific investments in NPP's are now substantially (some 40-50%) higher than those in FFEPP's, the total investments in the entire nuclear branch of industry, including fuel-conversion enterprises, are approximately 10% (see Table 1).

In the NPI, unlike the conventional thermal power industry, most of the investments go into NPP's. This is not indicative of the low cost value of the fuel conversion plants, but implies that the share of investments in the fuel cycle enterprises per unit of the total available capacity is relatively small.

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*No attempt is made here to forecast the technical and economic values of the installations considered in the broad range of physical, technical and economic problems relating to both the fuel-energy and allied branches. Taking rapid progress into account, it may be assumed that the method of analysis adopted gives a minimum estimate of the efficiency of the NPI.

Table 1. Structure of investments in fuel-energy industry (FEI) branches.

FEI Installations	Investments		Relation between investments in installations of nuclear and coal branches %
	Nuclear Branch %	Coal Branch %	
Electric power plant	75-80	42-47	140-160
Fuel enterprises (less transportation)	18-24	18-20	90-120
Comprising:			
Mining industry	1-2	18-20	6-8
Enrichment industry	15-20	-	-
Manufacture of fuel elements	2-3	-	-
Processing irradiated fuel	1	-	-
Fuel transportation	1	33-36	1
Total	100	100	85-95

The installations involving the highest investments, electric power plants, have similar process charts and equipment; therefore an analysis of the causes of increase in the cost of NPP's relative to FFEPP's is of particular interest.

At present, each NPP unit constructed accumulates modifications associated with improvement in the design and manufacture of the equipment, in the layout of the main production buildings and structures and in the technology of construction and erection work. This accounts for the increased spread of values compared with FFEPP's. The share of construction and erection work for NPP's is somewhat lower than for FFEPP's and constitutes less than 50% of the investments. More than 50% of all construction costs for NPP's and FFEPP's are for materials. Accordingly, most of the NPP cost increase for construction and erection falls within this item as well (about 50%).

Quantitative and qualitative factors are responsible for the increase in the specific costs of construction materials and semifinished stocks for NPP's as against FFEPP's. In the construction of NPP's, the rates of consumption of main construction materials are much higher. The additional consumption of cement, metal, concrete and reinforced concrete is determined by the more stringent requirements on structural strength of some buildings and installations of NPP's, by the need to provide radiation protection for personnel, and by a much higher consumption of concrete for the hydraulic works and auxiliary installations. The complexity of layout and the multisectional design of the main NPP building require more timber and bricks, roll-roofing and steel water pipes. As a result, additional specific costs for construction materials and semifinished stocks of NPP's amount to 6-7% of the total cost increase.

The specific features of NPP's call for the use of special expensive materials which are not employed at conventional thermal power plants. Among them are heavy and special-heavy concrete, in which steel scrap, limonite, and baryta ores are used as an aggregate, as well as prestressed reinforcement of the shell and alloy- and stainless-steel facing. This increases the cost of NPP's by another 4-5%.

The cost of thermal equipment for NPP's is approximately 10% more than for FFEPP's. In wholesale prices for the thermal equipment the greater part (about 55% for NPP's and 50% for FFEPP's) is accounted for by materials and semifinished stocks. An analysis shows that the quantitative factor favors NPP's in this case since the total weight of the nuclear power equipment is by a factor of 1.5 smaller than that of the FFEPP equipment. But the amount of metal used in manufacturing equipment for NPP's, including the net weight of finished products and the weight of waste materials, is only 10% less than that for FFEPP's.

The main process equipment of the primary coolant circuit of NPP's operates in hard radiation at high pressure and temperature

(160 atm.abs, 310°C). The combination of these factors causes rapid corrosion and "aging" of the materials in the equipment; this is why high-grade, high-alloy and stainless steel is used for its manufacture. As a result, the total consumption of low-alloy medium-grade steel for NPP's and FFEPP's is much the same.

In NPP turbines operating in saturated steam with low efficiency, the mass flowrate of coolant through the condensers is about 1.7 times that in conventional condensing turbines operating at supercritical steam parameters, and, accordingly, heat-transfer surfaces in the condensers are larger. These and some other factors have necessitated a twofold increase in consumption of non-ferrous metals. The average cost of one ton of steel used for manufacturing the NPP equipment (less extra costs for casting, forging and stamping) is 1.3 times higher. The rise in the cost of NPP's at the expense of high-grade steel and non-ferrous metal amounts to 3.5 and 2.5 percent of the total sum, respectively (see Table 2).

Table 2. Approximate distribution of extra costs for construction of NPP's as against FFEPP's.

Item of extra costs	Share of given item in sum of extra costs %
Materials and semifinished stocks,	48-52
Comprising:	
Amount of materials	6-7
Quality of materials	10-12
Miscellaneous	30-35
Wages of production workers	5-7
Overhead costs	4-6
Emergency work and costs	4-7
Miscellaneous work and costs	17-20
Profit of suppliers and contractors	15-18
Total	100

The bulky all-cast and seamless forged units (reactor vessel, turbine shaft and cylinders), which are expensive, complicated in design and labor-consuming in manufacture, significantly affect the difference in cost of the semifinished stocks used for the manufacture of thermal equipment for NPP's and FFEPP's. It is impracticable and hardly advisable to determine the NPP cost increase in this item of costs at present because no experience has been gained in the lot production of such units, and the technical equipment and production process are inadequately specialized. The change-over from individual to lot production and the adoption of specialized power machinery construction enterprises will make it possible to drastically reduce the cost of manufacturing NPP equipment; this is to a certain extent confirmed by the known experience of power machinery construction abroad.

The wages of production workers and the emergency and overhead costs of NPP's are higher than for FFEPP's owing to the considerable complexity and labor consumption in manufacturing the equipment and in the construction of the power plants themselves, as well as to the novelty of many processes and the lack of specialized technical equipment. The extra costs of the radiation-monitoring equipment, instrumentation, electrical equipment, and miscellaneous costs are taken into account in the item "Miscellaneous work costs" in Table 2.

Thus, construction materials, materials and semifinished stocks of the thermal equipment account for about 50% of the total NPP cost increase. It should be noted that half of this sum can be materially reduced when going over from the individual and optional production to the flowline serial production and when the power machinery construction plants are fitted with special equipment. Furthermore, accumulation of adequate experience in the use of NPP's allows an appreciable reduction in extra costs for high-grade steel and construction materials.

NPP's are more expensive than FFEPP's, but the reasonable level of their cost increase is much lower than the real one, although it is difficult to predict accurately. Even now it can safely be said that in the element of the NPI involving highest investments there are extensive possibilities for reducing investments.

Construction materials and semifinished stocks account for most of the expenditure on construction and erection work in the FEI branches compared. The relation between these costs in the nuclear and thermal power industry, however, is inverse to that observed in the case of costs for electric power plants alone. This is explained by the increased share of the basic costs for the fuel base and for fuel transportation for FFEPP's. Since the weight of nuclear fuel consumed is almost two orders of magnitude smaller than the amount of coal required for the same power plant capacity, the specific consumption of basic construction materials and semifinished stocks for construction of external fuel cycle enterprises and transport facilities is low. At the same time, a large amount of timber (props and sleepers) and metal (rails) is used in the construction of a coal mine and railway. Given below is the ratio of the material consumption in the nuclear branch to that in the coal branch in percentage:

	%
Cement (for concrete, reinforced concrete and grout)	100
Timber, round and sawn (for fabrication of structures, sleepers, falsework and props)	30
Metal (metal structures, rolled stock, pipes and sleepers)	60

The qualitative composition of the materials used in the construction of enterprises in the FEI nuclear branch is somewhat higher than that in the coal branch owing to special construction materials needed for NPP's. The same is true of materials used in the equipment because at all stages of nuclear fuel processing the process equipment is subjected to radiation, sometimes at high temperatures and high humidity. These operational peculiarities of the equipment at NPP fuel cycle enterprises, and the need to provide biological shielding for attendant personnel and to ensure safety, call for the use of high-grade steel and nonferrous metals.

At the present stage in development of the NPI, which marks the beginning of its extensive industrial utilization, there are no reliable data on the qualitative structure of the materials used in the equipment of the NPP fuel cycle enterprises. Yet the given ratio of consumption of quality materials employed for manufacturing the process equipment of NPP's and FFEPP's adequately characterizes the specific features of nuclear power production.

Labor consumption in the construction of NPP's is approximately a factor of 1.5 higher owing to new building processes, considerable saturation of the construction with equipment and devices, the low standard of mechanization of construction and erection work, and some other factors. However, comparison of FEI branches favors the nuclear option, whose labor costs are 1.6 or 1.7 times less.

A similar pattern is observed when comparing the demand for builders and mounters. The maximum number of workers employed during the construction of NPP's is one and a half times or twice as great as that for FFEPP's, and, on the whole, for the nuclear option this value is 10-15% lower than for the fossil-fuel branch.

Wide variations are observed in the number of attending and permanent repair personnel. The highly mechanized production of nuclear fuel requires a much smaller number of attending personnel than coal extraction and transportation, with every conceivable increase in the efficiency of labor in this branch. Therefore, the efficiency of labor in power production based on nuclear fuel is by a factor of 6 or 6.5 higher than on fossil fuel. The significance of such a decrease in labor costs is particularly great owing to the intensive growth in annual construction and the rise in the total value of the available energy capacity, which call for considerable manpower.

There is also another important advantage of the NPI. The basic manpower demand for construction and operation is due to NPP's and, for the fossil fuel option, to the fuel base. When an NPP is substituted for an FFEPP, good grounds appear for a more favorable territorial redistribution of labor demands on condition that the fuel bases (including enriching enterprises) are located in the Eastern areas of the country and the power plants located in its European part.

The additional demand for labor involved in the FEI with the adoption of a 1,000,000-kW energy capacity and fuel supply enterprises in the European part of the country and in Siberia constitutes, respectively, 98% and 2% for construction and 85% and 15% for the operation of NPP's; and, respectively, 50% and 50% for construction and 20% and 80% for the operation of FFEPP's.

Hence, during the development of the NPI, the demand for labor mainly arises in the developed European areas of the country, and, during the development of the fossil-fuel power industry, in Siberia. The advantages resulting from NPI development are evident because additional labor requirements in the country's East involve extra costs for the development of an appropriate infrastructure.

The number of workers engaged in arduous work, notably underground, will be drastically reduced. And on a long-term basis, with the adoption of fast-reactor NPP's and a corresponding decrease in demand for natural uranium, the specific number of workers engaged in underground work in the NPI will be reduced still further.

Thus, the NPI has advantages over the conventional in the basic values. There is a margin of efficiency in the NPI which also holds out considerable promise for its increase over the whole process from mines to power plants. All this adds up to the fairly high reliability of the results obtained.

Comparative Analysis of Total Material Consumption and Investment Consumption by Nuclear and Coal-Fired Power Plants [3]

An analysis of the direct costs for construction of nuclear and coal-fired power plants, taking into account the fuel supply enterprises, has revealed significant distinctions in the material, monetary and labor requirements for their construction [4]. This leads to unpredictable distinctions in the trends and scope of the development of the allied branches of the national econony. Estimation of possible indirect costs and their impact on the comparative efficiency of nuclear and coal-fired power plants is the precise objective of this section.

An aggregate estimate of the efficiency of the NPI can be obtained on the basis of full costs which represent the sum of direct and indirect costs. In this section the direct costs include costs for construction of power plants and power transmission lines and for coal and uranium extraction and enrichment enterprises. Costs for the development of allied industries and railway transport are taken to be *indirect.*

In order to determine the value of indirect costs, use has been made of a special dynamic multibranch model worked out at the Siberian Power Engineering Institute of the Siberian Branch of the USSR Academy of Sciences.

Nuclear power plants with water-moderated, water-cooled reactors having a 1,000,000-kW unit capacity and thermal power plants with 800-MW units operating on coal from the Kuznetsk coalfield, shipped some 2,000 km, have been selected for comparison.

Calculations have been made for the conditions where indirect costs reach their maximum possible value. We have also taken into consideration the additional growth in power production at NPP's or FFEPP's as a result of new construction in the absence of reserve capacity in the allied branches.

An analysis shows that the full costs for some products can be several times higher than direct costs (Table 3). It is significant that in terms of both direct and full costs the alternative for the construction of coal-fired power plants takes more materials than the NPP option (except for nonferrous metals and high-grade steel). The cost of equipment is, however, much lower.

In both the options considered, the indirect costs for construction and erection work and for miscellaneous work are in excess of the direct costs (see Table 4).

For the FFEPP option, apart from railway construction, a considerable quantity of construction and erection work in metallurgy and in the construction material industry is required. At the same time, in constructing NPP's it is necessary to extend the development of specialized machine-building plants, foundries and forging shops at metallurgical plants, etc.

Summing up the costs for construction and erection, using previously obtained data on the demand for equipment and machinery, some insight can be gained into the priority of and relation between full investments in the extended development of the power industry by option (see Table 5).

The amount of investments for construction of direct-purpose installations with the adopted initial data in the NPP option is approximately 30% greater than in the case of an increased FFEPP capacity.

Table 3. Costs of materials and equipment by option (in percent of full costs in FFEPP option)*.

	Costs			
	NPP's		FFEPP's	
	Direct	Full	Direct	Full
Material and semifinished stocks				
Ferrous-metal rolled stock	15	80	19	100
Nonferrous metals	40	110	40	100
Cement	14	90	17	100
Precast concrete	24	80	38	100
Brick	3	85	10	100
Commercial and shaped timber	41	70	15	100
Equipment	130	170	70	100
Power units (complete with auxiliary equipment)	140	170	90	100
Transformers	90	105	90	100
Mining equipment	5	10	90	100
Pumps and compressors,	1500	1500	65	100
equipment for metallurgy, chemistry and construction-material industry	-	90	-	100
Miscellaneous equipment and machinery	5	85	-	100

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[*] Material consumption determined in natural form; equipment consumption determined in monetary form.

Table 4. Distribution of total quantity of construction and erection work by branch (in percent of full costs in FFEPP option).

Installations	Costs			
	NPP's		FFEPP's	
	Direct	Full	Direct	Full
Total	40	80	40	100
Comprising:				
Power plants	120	140	90	100
Fuel supply enterprises	30	35	80	100
Power transmission lines	90	100	90	100
Ferrous and nonferrous metallurgy plants	-	80	-	100
Power, transport and general machinery construction plants	-	120	-	100
Railway	-	10	-	100
Construction material and construction industry enterprises	-	120	-	100

Table 5: Comparison of full investments for realization of options (in percent of direct costs in FFEPP option).

Options	Cost	Cost items		
		Construction and erection and miscellaneous work	Equipment and machinery	Total Investments
NPP's	Direct	100	190	130
	Indirect	100	60	90
	Full	200	250	220
Coal-Fired Power Plants	Direct	100	100	100
	Indirect	150	50	110
	Full	250	150	200

The amount of indirect investments is, respectively, 70% and 110% of the full costs for the construction of direct-purpose installations in the NPP and FFEPP options. The absolute value of indirect costs in the former option is approximately 20% smaller than in the second option. Thus, when we take the external linkages more comprehensively into account, we find that the investments in the power industry development differ only slightly.

The most substantial contribution to the amount of full costs in both options comes from construction and erection costs, whereas the equipment in the nuclear option accounts for about 25% of the indirect investments and, in the coal option, some 15%.

Research on the distribution of indirect costs among the indirect expenditure levels is certain to be of practical interest. An attempt has therefore been made to estimate the costs which are formally assigned to the first indirect expenditure level, i.e. investments for the construction of enterprises which directly supply the direct-purpose power installations under construction with objects and means of work and for enhancement of the carrying capacity of railway traffic. The results of the calculation given in Table 6 show that in both options the share of costs of the second and subsequent level is about 40% of the total sum of indirect costs.

Table 6. Structure of indirect investments in options (in percent of total sum).

Allied Branch	NPP's			FFEPP's		
		Including;			Including:	
	Total	first indirect expenditure level	other levels	Total	first indirect expenditure level	other levels
Total for all branches	100	58	42	100	64	36
Comprising:						
Ferrous and non-ferrous metallurgy	100	19	81	100	29	71
Machine building	100	90	10	100	85	15
Railway transport	100	70	30	100	91	9
Construction material and construction industry	100	23	77	100	33	67
Miscellaneous	100	71	29	100	62	37

It should be emphasized that the features of the structure discussed and the values of indirect costs correspond to the maximum development of the allied branches. Such a situation is peculiar, for example, to the initial stage of development of the NPI when for the first time the need arises to set up appropriate kinds of production. A further build-up of NPP capacity requires no expansion of all kinds of production in the allied branches and, depending on the rate of development of the NPI, it affects a greater or smaller number of indirect expenditure levels. If the annual construction of NPP's remains unchanged, investments in the allied branches may not be required at all. Thus, the range of the possible values of indirect costs is fairly wide: from zero to a value close to direct costs or even exceeding them.

An analysis of the NPP options planned by a number of research institutes for the 1976-1990 horizon indicates that the indirect investments involved in their realization amount to 18-25% of the direct investments (including those in the branches of the second and subsequent levels of indirect expenditure which constitutes 3-9%).

It follows from the foregoing that, in considering the economic efficiency of the NPI in general, the costs arising in the allied branches should be taken into account since they may substantially correct the results of option comparison based on the calculations of direct costs alone.

REASONABLE TRENDS IN LONG-TERM NUCLEAR POWER UTILIZATION IN THE FUEL-ENERGY INDUSTRY OF THE USSR (NEW CONCEPT)

Present-Day Situation in the Development of the USSR Fuel-Energy Industry

The seventies and the last quarter of our century as a whole have seen a radical change in many previously formed trends and the emergence of new trends in the development of the fuel-energy and power industries. The most important of these is the significant enhancement of the economic values of natural gas and especially of liquid fuel (oil and oil products), which is determined by increasing difficulties involved in the utilization of new resources of this fuel and in its transportation from distant and almost inaccessible areas and by a drastic increase in the value of exports of the given kinds of fuel in response to the rise in world prices.

Therefore, while in the 1965-1975 decade, oil and natural gas accounted for three-quarters of the total growth in the country's fuel-energy resources and more, their future share in this growth will apparently be reduced substantially. It would be most reasonable to compensate for the reduction in the role of oil and natural gas by the appropriate enhancement of the utilization of nuclear power, which should be intensified in every possible way. Analysis shows, however, that this is hardly realizable on a full scale. The principal factors imposing constraints on the development of the nuclear power industry (NPI) are the time required for preparation of the machine building and, partly, the bases for the raw material resources, and the limited possibilities for preparing nuclear power utilizers. At present a little more than one quarter of the fuel-energy resources used is spent on power production, more than half of them being due to thermal utilities, and about one fifth to machinery. At the same time, water power, the cheap fuel areas (Siberia, Central Asia), and power production in the peak portion of the load-duration curve, in which the use of nuclear fuel is relatively uneconomic, account for 40% of the resources spent on electric power production. As much as 30% of the total power is produced at thermal power plants. Thus, less than 15% of all the fuel-energy resources is consumed at base-load and intermediate-load power plants in the expensive-fuel areas where the utilization of nuclear fuel is effective even now. Moreover, existing fossil-fuel electric power plants (FFEP's) and those under construction in the European part of the USSR should be taken into consideration. Then it appears that if special emphasis is laid only on nuclear electric power plants, the share of nuclear fuel in the USSR's fuel-energy balance (FEB) will not be more than 5-6% by 1990 and, on average, 8-9% by the year 2000.

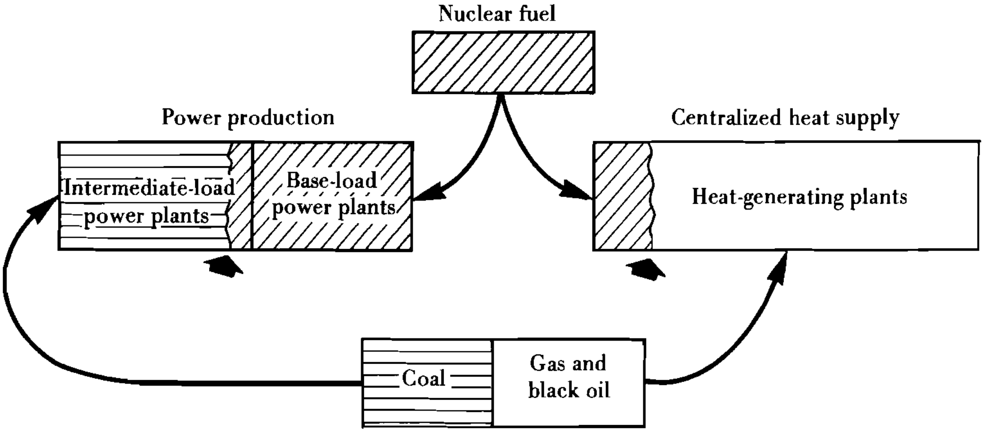
Hence, the range of utilization of nuclear fuel in the national economy should be extended. To this effect it is necessary to resolve a very important problem for which the NPI has not yet been prepared: the extensive utilization of nuclear energy (in certain solutions) for thermal processes and primarily for medium- and low-temperature processes where the consumption of gas and black oil fuel still predominates.

In particular, about 40% of the total amount of fuel is used for supplying fuel to heating-and-power plants and boiler houses, of which up to 80% is due to gas and black oil. During the five-year period of 1976-1980 alone, the consumption of gas and black oil fuel for these utilizers is to be increased by 75 million tons of reference fuel, according to the scale of planned construction. Release of gas and black-oil fuel at heating-and-power plants and boiler houses is feasible only at the expense of nuclear fuel and high-grade coal fuel, which, in practice, can only be the product of conversion of the Kansk-Achinsk coal (semi-coke, coke briquette). Supply of these products to the European areas of the country from Siberia, however, involves substantial investments in the expansion of the transport network, which will drastically increase the cost of the given method of fuel supply. Therefore, valuable gas and black-oil fuel can be released only by allocating part of the nuclear fuel for heat-supply utilities.

Procedure for Determining the Optimal Ways of Nuclear Fuel Utilization [5]

Owing to the persistence of its development, the preparedness of the appropriate engineering base, etc., the country's fuel-energy industry will develop in 10 to 15 years in conditions where all the technically prepared fuel-energy resources are used.

In such conditions, for obtaining the maximum effect from the utilization of nuclear fuel, the most efficient distribution of the resources available at the given stage must be determined. There are three ways of utilizing nuclear fuel (Figure 6): (a) at base-load nuclear electric power plants (NEPP's); (b) at intermediate-load NEPP's; and (c) at heat-generating plants (nuclear thermal electric power plant) (NTEPP's) and nuclear boiler plants.



Boundary of spheres of nuclear and fossil-fuel utilization

Including power production on heating (thermal electric) cycle

Figure 6. Determination of the ways of utilizing nuclear fuel.

The first way is the most developed, and as demonstrated in the introduction, NEPP's are quite efficient in the USSR's European areas, not only in the base-load routine (with the annual number of installed capacity utilization hours of about 6,500) but also in the intermediate-load (load-reducing) routine where the annual number of hours is up to 4,500 hrs/year in the Western areas where fossil fuel is the most expensive. Yet, a further build-up of the NEPP capacity results in coal being increasingly replaced by nuclear power (when passing to intermediate-load NEPP's). And this is not reasonable, notably if one takes into account the above changes in development trends of the fuel-energy industry (FEI). At the same time, allocation of nuclear fuel for heat supply utilities ensures the release of gas and black-oil fuel. The utilization of nuclear fuel in heat-generating plants, however, is too poorly prepared technically.

Therefore, the following priority of nuclear fuel utilization is advisable: (1) highest priority (for the next 5-10 years) utilization at high-capacity base-load NEPP's; (2) next, at intermediate-load NPP's, which will accordingly reduce the construction of fossil-fuel intermediate-load power plants (apparently, over the next 15 years these will be mainly 500-MW coal-fired steam power units operating at subcritical steam parameters); and (3) for centralized heat supply, thereby releasing gas and black-oil fuel (for details, see below).

An optimum would be to bring all three ways to an economically reasonable level, the highest priority being given to the first. For correct evaluation of such economically reasonable levels, one should keep in mind the important conclusion obtained from the numerous calculations made, namely that, in each of the variants considered, the value of monetary (estimated)* costs decreases very slightly (droops) as the optimal solution is approached. For example, an arbitrary comparison of NEPP's with FFEPP's (see Figure 2) gives the following picture.

First the nuclear power plants are sited in the most expensive fuel areas, resulting in a considerable economy. As their total capacity increases (during the same time period), the nuclear power plants (NPP's) tend to supplant the FFEPP's in cheaper fuel areas, thereby reducing the economic effect. Finally there is a growth in NPP capacity when the effect obtained is negligible and then approaches zero. The total NEPP capacity thus found will be economically maximal. Deviation from it by 15-20% in the direction of decrease causes very little damage, which is often purely formal in nature, on account of the indefinite initial data on all future values involved in the calculation.

Similar dependences are fairly versatile in nature in terms of energy. They indicate that in many instances it is possible (remaining actually within the range of equally economic solutions) to decrease the formally reasonable solution by 15-20% for noneconomic (or for any other) reasons.

An analysis shows that an optimum in the level of the development of base-load NEPP's will be reached earlier (obviously, in the middle eighties) than in the development of intermediate-load NEPP's and, even more, of thermal NPP's and boiler houses (the latter optimum will hardly be reached even by 1990). This leads to the following important conclusion: an increase in the capacity of base-load FFEPP's beyond the economically maximum level or in the zone of their practically equal efficiency will inevitably divert the corresponding material resources from the

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*The estimated costs are determined from the following expression: $3 = EK + U$, where U is annual costs; K is investments and E is the standard efficiency factor taken to be 0.12.

utilization of nuclear fuel for the heat supply. This in turn will result in the increased consumption of gas and black-oil fuel for this purpose, i.e. in the less efficient utilization of nuclear fuel.

Scope of Development and Types of Nuclear Fuel--Thermal Power Plants

The Range of Utilization of Nuclear Fuel for Centralized Heat Supply from Thermal Electric Power Plants

The estimated amount of heat production by thermal power plants (TEPP's) in the country's European areas and its possible coverage by various fuels are presented in Table 7.

As is evident from the data, in the case of use of nuclear fuel for heat supply starting from the early eighties, its share in annual heat production by TEPP's will be (by a conservative estimate) almost 15% by 1990 and in the growth of heat production by FFEPP's over 50% in 1986-1990.

Table 7: Tentative structure of heat production by thermal electric power plants in European areas of the USSR.

Energy resources	1975	1980	1990
Coal	24	21	23
Gas and black oil	64	69	62
Nuclear fuel	-	-	10
Miscellaneous fuels	12	10	5
Total	100	100	100
Variations from 1976 level	1	1.3	1.9

Types of Heat-Generating Plants Employing Nuclear Fuel for Centralized Heat Supply

Basically these plants may be of three types: combined plants, plants producing power on the heating cycle (NTEPP's), and plants delivering heat directly (nuclear boiler plants).

To grasp the gist of the matter, it will be recalled that three prerequisites apply to fossil-fuel thermal electric power plants: (1) the chief goal of development is economy of the fuel used; (2) power production on the condensation cycle* is inefficient compared with FFEPP's; and (3) it is often expedient (according to local conditions) to install the main equipment of FFEPP's with a unit capacity lower than the maximum possible capacity at present. This stems from the fact that here the enlargement of the unit capacity of the main equipment is not the governing economic factor.

On the other hand the main purpose of utilizing nuclear fuel for heat supply in the country's European areas is its maximum possible substitution for expensive gas and black-oil fuel rather than the economy of this fuel. At the same time, for NTEPP's it would be highly effective: (1) to ensure power production on the condensation cycle in view of the fact that the fuel component at NPP's is by a factor of 2 to 2.5 lower than that at fossil-fuel power plants; and (2) to install reactors with a maximum unit capacity because the economic effect obtained from enlargement of reactors (at least up to a unit capacity of about 2,000,000 kW) is much greater than that obtained at steam plants. Therefore at NTEPP's, if there are no external constraints involving sanitary engineering, water supply, power switching in the system, etc., it is advisable: (i) to install at least two reactors with the maximum possible capacity, predominantly of the BBЭP (water-cooled) type; (ii) to employ turbines with an additional condensation output at constant steam exhaust, i.e. with a variable electric capacity; and (iii) to rate NTEPP's for $\alpha_{tepp} = 1.0$ **.

The specific features of the solutions discussed for NTEPP's and FFTEPP's are exemplified schematically by the heating-appliance load in Figure 7. For clarity, we have assumed a maximum unit capacity of 1,000,000 kW (with two reactors installed) for NTEPP's and such a thermal load whose peak corresponds approximately to the thermal capacity of a single reactor (allowing for the heat consumption in power production on the heating cycle).

From Figure 7 one can draw the following important conclusions:

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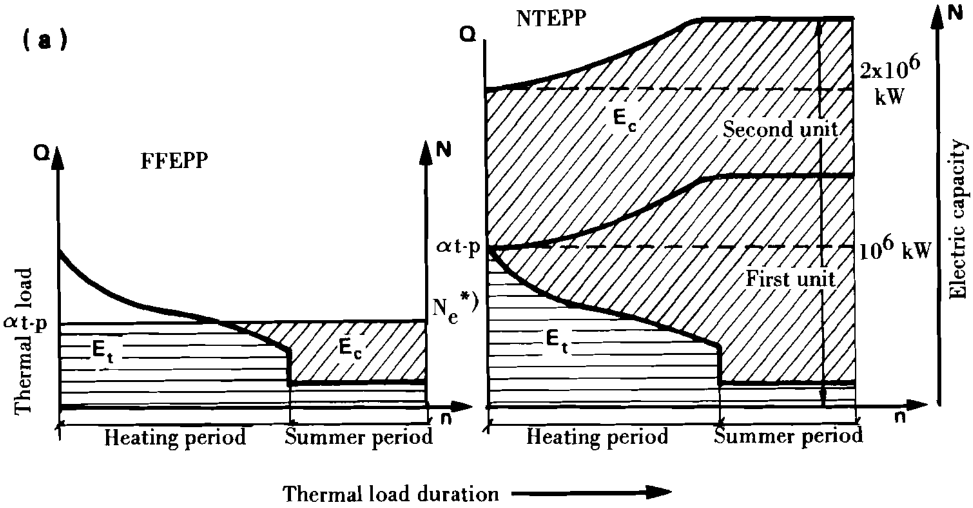
[*] This is why at FFEPP's, turbines with a significant condensation output are installed, and the estimated heating factor (α_{he}), the share of turbine bleed steam in handling the estimated thermal load, is taken to be approximately 0.5.

[**] This factor (α_{tepp}) determines the share of turbine bleed steam in handling the maximum thermal load, and the factor $(1 - \alpha_{tepp})$ accordingly determines the share of heat directly delivered from a heat-generating plant (boiler plant, reactor).



Schematic diagram of annual utilization of FFEPP and NTEPP

*) In effect, owing to higher initial steam parameters, value N_e will be somewhat higher than that for NTEPP.

E_t denotes power production on heating (thermal electric) cycle; E_c denotes power production on condensation (electric) cycle.

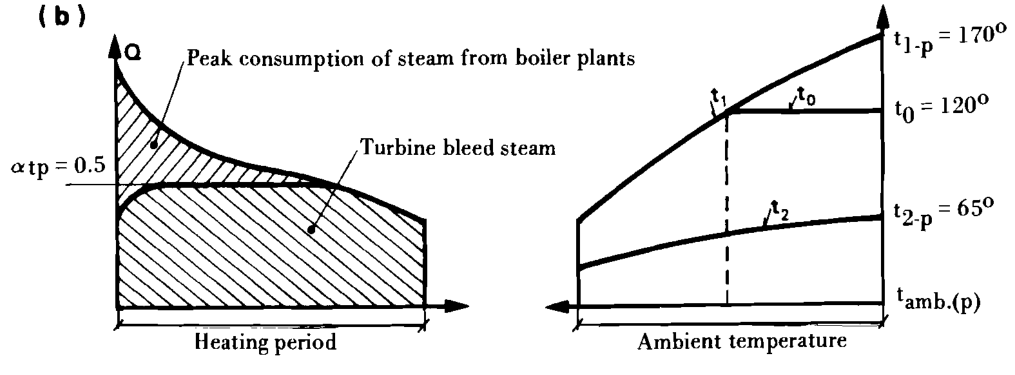


Figure 7. Performance curves of peak-load heat-generating plant and nuclear thermal electric power plant.

When using fossil fuel, a type of FFEPP is constructed which differs significantly from that of fossil-fuel steam-electric power plants. When nuclear fuel is used, this distinction disappears, and NTEPP's and FFEPP's become essentially the same type of power plants, differing only by the number of turbines from which the bleed steam is delivered for heat supply (the number of these turbines is determined by their design parameters and the value of the nearby thermal load).

The foregoing applies to the optimal solutions for NPP's proper. But in the case of hot water production and transportation for 10 to 15 km and more (for economy of metal in pipes) it is most effective to deliver hot water from NPP's at a temperature (t_{1-p}) of about 170°C. In this case the controlled steam bleeding from the turbines should exceed 2 ÷ 2.5 atm.abs., which allows water to be heated to about $t_0 = 120 \div 125^{\circ}C$. Then the estimated heating factor with the temperature conditions corrected to the heating load is

$$\alpha_{tepp} = \frac{t_0 - t_{2p}}{t_{1-p} - t_{2p}} = \frac{(120 \div 125) - 65}{170 - 65} = 0.52 \div 0.57 \quad .$$

In other words, at NTEPP's also, about 35% of the maximum thermal load (in its peak portion) should be carried either by the steam directly fed from reactors or by the steam delivered from special peaking hot-water boilers operating on gas and black-oil fuel. This problem requires special study, and when working it out one should keep in mind the pronounced peaking character of the thermal load carried by the steam bypassing the turbines. If, according to the water balance, heat can be delivered from FFEPP's over the single-pipe system, then

$$\alpha_{trpp} = \frac{t_0 - t_k}{t_{1-p} - t_k} = \frac{(120 \div 125) - 20}{170 - 20} = 0.65 \div 0.7 \quad .$$

Here t_k is the temperature of fresh water delivered to the cycle.

All the foregoing applies in the case of hot water production by NPP's. However, the steam commercial load accounts for about one third (in the maximum) and about one half (in the annual consumption) of the centralized heat supply. Modern NPP's, unfortunately, are not yet ready for solution of the important problem of heat production as steam. Prior to the development of high-temperature reactors, it seems expedient to mount one rather than two turbines on a nuclear reactor and, instead of the second turbine, to deliver the throttled superheated steam from NPP's. Such a solution is justified by a low fuel component and, hence, by the low overall cost of the heat produced (up to 2 rbl/Gcal).

Subsequently, there will be a need for solutions based on the use of nuclear reactors ensuring the increased initial parameters of the steam produced.

As already stated, one solution is the development of high-temperature gas-cooled reactors. Another, as applied to NTEPP's, could also be the advancement of channel-type, water-cooled uranium-graphite reactors with nuclear steam superheating. With such reactors, it is feasible to rate NTEPP's for high steam parameters (130 kgf/cm^2, 510-520°C).

All that has been said about the peculiarities of the optimal NTEPP's calls, on the whole, for a new approach to selection of NPP sites and to estimation of the effect of the very appearance of NPP's on the formation and location of new industrial centers in the European areas of the USSR. More specifically, the selection of sites for NPP's should be based on the feasibility of heat delivery to adjacent utilizers. The formation and location of new industrial centers, particularly large and heat-consuming ones, should necessarily be combined with the location of NPP's. A nuclear power plant is the center of the possible intensive delivery of very cheap steam, hot water and, apparently, high-temperature heat as well; i.e. it acts as an important area-forming factor rather than merely as a power production center. This is the principal concept of the utilization of nuclear fuel for heat supply.

However, there may be other cases--in particular, when it is necessary to ensure heat supply from NTEPP's to some part of a big city (Moscow, Leningrad, Kiev, Sverdlovsk) with limitations imposed on the electric capacity of NTEPP's, e.g. sanitary conditions, water supply. Here, in the first place, FFEPP's should be provided with special turbines which have a significant condensation output and, possibly, a constant electric capacity (selected at maximum steam bleeding). For these conditions, it is also important to choose the optimal value of the estimated heating factor (α_{tepp}) for the specified modifications of reactors, i.e. for conditions basically different from those adopted now.

(The technique of selecting the optimal value α_{tepp}, worked out as far back as the 1940s--see L.A. Melentiev, Heat Engineering (in Russian), Part I, USSR Academy of Sciences, 1947--was based on two premises: (i) the constant thermal load Q and the variable electric capacity of FFEPP's (N); (ii) the continuous (but not discrete) character of variation in the dependence $N = f\ (QX\alpha_{tepp})$. Neither of these premises is applicable to the given case of selection of α_{tepp} for NTEPP's. Here the NTEPP electric capacity is limited by external conditions, i.e., it is virtually predetermined. And the unit capacity of the NTEPP reactors is drastically discrete, also being virtually predetermined by two modifications of reactors: 0.5 and 1 million kW.)

Some of the calculations made lead to the conclusion that for the conditions in question the optimal value α_{tepp} will be close to the one defined above, as applied to the optimal estimated temperature of the main-water delivered from FFEPP's.

Such a specialized NTEPP type is less efficient than the "combined" electric and thermal electric type of nuclear power plant. Our calculations show, however, that when such NTEPP's are substituted for FFTEPP's, the effect obtained is fairly high, considering the high cost value of gas and black-oil fuel and the additional expenditure on coal fuel supply and sanitary engineering.

The relation between the cost value (estimated costs) of the replaced fossil fuel and the "critical" thermal load of a specialized NTEPP (below which this power plant is inefficient) is shown in Table 8.

Table 8: Approximate relation between "critical" NTEPP load and cost of replaced fossil fuel.

Fuel cost (rbl/ton of reference fuel)		20	23	25	30
"Critical" load (in round numbers)	Thermal Gcal	over 2000	1200	800	500-600

The question of the role of nuclear boiler plants in centralized heat supply systems naturally arises in view of the fact that, at "subcritical" loads, specialized NTEPP's reduce their relative efficiency (compared with combined nuclear electric and thermal electric power plants) for the reasons given above.

Calculations show that the separate centralized power supply scheme (FFEPP plus large regional and inter-regional boiler plants) is relatively less efficient than the combined scheme (FFEPP's) where nuclear fuel is used. In the case of nuclear fuel utilization, this is mainly explained by two factors: (i) the much lower cost value of the fuel component of power production and (ii) the substantially lower power production with the thermal output because of the initial steam parameters reduced at NTEPP's.

More specifically, saving in fuel costs from the heating cycle per Gcal of heat delivered from FFEPP's is $\Delta a_t = a(b_c-b_t) \times y_e$ cop./Gcal, where a is the cost of fossil fuel (cop./kg); b_c is the specific fuel consumption at FFEPP's (kg/kW•h); b_t is the same on the heating cycle; and y_e is the average annual specific power production with the thermal output. In present-day circumstances, when fossil fuel is used, we have approximately $(b_c-b_t) \approx 0.17$ and $Y_e \approx 550$ (at a bleed steam pressure of 1.2 atm.abs.). Then at a = 2 cop./kg we obtain $\Delta a = 190$ cop./Gcal. In the case of nuclear fuel for BBЭP (water-cooled) reactors, and at the heating thermal load, the calculation yields the following results. We have

$$a_n(b_c-b_t) = a_n \times q_{tn}\left(\frac{1}{\eta^{n}_{ec}} - \frac{1}{\eta^{n}_{et}}\right) ,$$

where $a_n \times q_{tn} = 0.10$ cop./kW•h (therm.) and q_{tn} is the specific consumption of heat (delivered from the reactor) as steam, kcal/ kW•h (therm.). In turn, $\eta^{n}_{ec} = 0.32$ and $\eta^{n}_{et} = 0.9$. Therefore,

$$a_n q_{tn}\left(\frac{1}{\eta^{n}_{ec}} - \frac{1}{\eta^{n}_{et}}\right) = 0.10(3.15-1.1)$$

$$= 0.220 \text{ cop./kW•h (elec.)} \quad .$$

The value of y_e in the given circumstances is approximately 300-320 kW•h (elec.)/Gcal. Therefore, for NTEPP's, approximately, $\Delta a_n = 0.185\ (300-320) = 65-70$ cop./Gcal and, hence,

$$\frac{\Delta a_n}{\Delta a_t} = \frac{65 \div 70}{190} \approx 0.35 \quad .$$

Comparison of NTEPP's with FFEPP's would not be justified for the country's European areas. Here, as previously demonstrated, the construction of such base-load FFEPP's will have been discontinued by the middle 1980s.

On the whole, it would appear that economy of fuel from power production with the thermal output (per Gcal of heat delivered) for nuclear fuel is more than three times less than for fossil fuel (in the European areas of the USSR). On this account, particular care is necessary in estimating the prospects for utilization of nuclear boiler plants. Obviously, their main advantage over NTEPP's is the lower specific cost of reactors, which can be constructed as low-temperature reactors, and the reduced costs of industrial water supply. But at nuclear boiler plants, which should necessarily be constructed and operated as NPP's, all the specific problems remain of fuel loading and unloading and expert servicing. This fact alone should apparently predetermine the expediency of the substantial enlargement of nuclear boiler plants (up to 400-500 Gcal and over). In place of NTEPP's, such boiler plants are likely to become the main source of nuclear fuel utilization for those relatively large industrial centers where, in view of local conditions, it is inexpedient to construct high-capacity NPP's of the combined electric and thermal electric type. All this urgently necessitates the accelerated developement of low-temperature reactors for boiler plants with a thermal capacity of 100-200-400 Gcal. At the same time, it is necessary to ascertain whether they should operate in conjunction or separately for hot water and process steam production. On the basis of such research, and appropriate production-economics calculations, the role of nuclear boiler plants in the centralized heat supply could be determined. Incidentally, preliminary calculations show that their role would be significant in terms of the release of gas and black-oil fuel.

On the Prespective of High-Temperature Heat Production at NPP's for the Industrial Utilities

Whereas the steam and hot water delivery from NTEPP's at nuclear boiler plants is technically prepared, so that it could be realized for all practical purposes in years to come, the potentialities of the utilization of nuclear fuel for high-temperature heat production are still to be explored. This is caused by two principal factors: the first and main cause is the need to create a reactor capable of providing a 1000-1500°C coolant at the output, and the second is the need to create a high-temperature heat-exchanger capable of operating at such temperatures. The problem of conveying heat at these temperatures from the heat-exchanger to utilizing shops is also intricate.

The greatest amount of high temperature heat is consumed by ferrous metallurgy, the construction material industry, and the chemical industry. For these purposes they consume about 19% of the total amount of gas consumed in the country. In ferrous metallurgy, high-temperature heat produced in a reactor could primarily replace natural gas in heating furnaces of rolling-mill departments and also, possibly, in steel-making furnaces. In future, with the use of nuclear fuel, it might be possible to switch over to iron production with no blast furnaces.

In the chemical industry, at present and in the future, the greatest amount of high-temperature heat is expended on the production of ammonia and its derivatives, primarily mineral fertilizers. The technology adopted is such that the exhaust gas temperature is very high. The use of exhaust gases for power production is rather difficult and their useless discharge is responsible for considerable heat loss. It might be possible to use high-temperature heat from nuclear reactors effectively in place of natural gas in such processes.

On the Selection of Sites for Nuclear Power Plants

In Selecting sites for NPP's, one should take into consideration both the general requirements for the sites of thermal electric power plants and the specific requirements associated with the peculiarities of NPP's. Among them are:

- Proximity of NPP's to power consumption centers, in view of the fairly low cost of nuclear fuel transportation and considerably lower pollution of the environment by NPP's as compared with conventional fossil-fuel electric power plants (no exhaust of ash, sulphur compounds, nitrogen oxides, etc.);
- Proximity of most NPP's to fairly large heat consumption centers to ensure the maximum possible production of heat as steam and hot water;
- adherence to the standard requirements for the sanitary engineering of NPP's to ensure the safety of the population;
- Provision of industrial water supply. On account of the lower thermal efficiency of NPP's, their specific water consumption is significantly higher than that of FFEPP's. It is therefore important to locate NPP's on sites where the cheapest water supply systems can be provided;
- Location of NPP's with high-capacity vessel reactors, type BBЭP, so that the reactor vessels can be transported to the sites by water;
- Sites sufficiently large for the construction of NPP's with a capacity of at least 10 million kW.

An analysis of the sites for the existing NPP's, and for those underconstruction and to be constructed, shows that most of them have one important disadvantage: they have been selected to suit the requirements of power production, leaving out of account the pressing need to deliver from NPP's as much steam and hot water as possible.

Therefore, in selecting sites for NPP's, the possibility of heat supply from them should be taken into account and their location coordinated with that of new industrial centers.

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