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Demand for Nuclear Fuels and Costs of Different Reactor Types in Germany

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DEMANDS FOR NUCLEAR FUELS AND COSTS OF DIFFERENT REACTOR TYPES IN GERMANY+

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Studienkreis Kernenergiereserven
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The firms and organizations mentioned below have participated in the "Studienkreis Kernenergiereserven":

Firm AEG
"   BBC-Krupp
"   GHH
"   INTERATOM
"   NUKEM
"   RWE
"   SSW

BMwF
GKSS Geesthacht
KFA Jülich
KFZ Karlsruhe
TH Aachen

The Studienkreis Kernenergiereserven was formed in fall of 1964 to promote this study and to discuss the questions located therein. A more detailed publication of the assumptions and results will follow in late 1965.

Errata

1. On page 14, equation (7) should read:

$$k_{Br} = \frac{R \cdot \delta_R}{E_1 \cdot \left[1-(1+\frac{R}{100})^{-L}\right]} \left\{ \varrho \cdot \left[k_o^* - k_1^* (1+\frac{R}{100})^{-L}\right] + \frac{k_o^* - k_1^*}{Z} \cdot \frac{(1+\frac{R}{100})^{-\delta_B} - (1+\frac{R}{100})^{-L}}{1-(1+\frac{R}{100})^{-\delta_R/Z}} \right\}$$

2. In table 5, page 22, Reactor Cost Data, the following data should read:

	D_2O(SSW)			AGR(UKAEA)		
	a	b	c	a	b	c
Spec. Investment Cost (Dpf/kWh)	1.393	1.393	1.393	1.163	1.163	1.163

Contents

1. Introduction and Statement of the Problem

Even during the early days of nuclear reactor development the problem of the uranium reserves, i.e. the nuclear energy resources, had been considered quite seriously. W.H. ZINN in particular raised this question between the years 1945 and 1950 and accordingly initiated the development of fast breeder reactors. However, the magnitude of the uranium resources was considerably underestimated at that time [1], and accordingly, the emphasis for the first generation of fast breeders (EBR-I, EBR-II. Dounreay Fast Reactor) was put almost exclusively on achieving a high breeding ratio. The development of the thermal breeder reactor was promoted by A. WEINBERG along similar lines.

Three important developments could be noted during the period 1958-1961. On the one hand, it had become clear that the optimistic expectations for the development of nuclear energy which had been nourished at the 1st Geneva Conference in 1955 would not materialize so soon. On the other hand, it had become apparant in the meantime that rather large resources of cheap natural uranium were available. Both of these facts indicated that there would not be an immediate crisis with regard to the uranium supply. Finally, it had become very obvious, that nuclear reactors had to operate economically and had to compete with fossil power stations to achieve a break-through in the development of nuclear power.

The realisation of these facts turned the attention of reactor development groups to the closed plutonium cycle for fast breeders among other concepts. Accordingly, fast breeders having large cores (5000 l) and utilizing non-metallic fuel elements were conceived, i.e. the 2nd generation of fast breeder reactors that puts emphasis on economics, even at the expense of a lower breeding ratio. In the field of thermal breeders these developments, in a similar way, led to an increasing interest in high conversion reactors, e.g. natural uranium-D_2O reactors, in addition to genuine thermal breeders. The situation of those years is best characterized by the well known discussion between K. ERGEN and E.L. ZEBROSKI: "Breeding, how soon a necessity?", as published in Nucleonics [2].

In pursuit of these ideas the proper utilization of those amounts of plutonium being produced in thermal reactors, e.g. light water reactors, became a point of view, in addition to economics and breeding. As is well known, the reactivity value of plutonium containing large amounts of Pu-240 is higher at least by a factor of 1.4 for fast reactors as compared to thermal reactors6).

In 1962 the "Report to the President" [4] created a turning point insofar as to establish the right proportions between the economics of reactor operation and efficient utilization of the natural uranium and thorium resources by presenting a condensed survey on the power policy situation in general. This way of thinking was further intensified by J. DIETRICH's paper on "Efficient Utilization of Nuclear fuels" [5]7). In this context the question of an "intermediate generation" of high conversion reactors was brought up, a question that still today is occasionally considered as an open one. Also, in 1963 the order for the Oyster-Creek power station was placed with General Electric. Many observers considered this event to be the break-through of nuclear power stations to truly competitive operation. The problem concerning the magnitudes of the uranium and thorium resources now had to be considered more seriously. It is therefore not so surprisingly that this problem now again was treated in a number of reports. The papers of R. GIBRAT [6], D. RITTER and G. BLÄSSER [7], J.J. WENT [8] and in particular the recently published EURATOM-report [9] may be mentioned in this context.

The possibility also to answer more generally questions from the viewpoint of nuclear energy resources became soon apparent. In particular, this applies to the interaction of certain reactor types. This means that costs have to be considered in addition to the uranium and thorium resources in question. Strategic games using resources, costs and reactor properties can be carried out at different logical levels. This topic will be treated

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6) Cf. E.A. ESCHBACH [3], for instance. He obtains for plutonium a relative reactivity worth of 0.8, as compared to U-235 in a thermal reactor. Calculations done by the authors of the present study have shown the criticality worth for plutonium containing large anounts of Pu-240 as compared to U-235 in a fast reactor to amount to 1.5. Strictly speaking, this results in an equivalence factor of $1.5/0.8 \approx 1.9$.

7) This publication employs rather pessimistic assumptions with regard to the development of second generation fast breeders.

more extensively in the 2nd chapter of this report. At this point we just want to state that this study follows the if-then scheme. Accordingly, there has not yet been any feedback between results and postulates. This will be done in a future study. Nevertheless, the variation of the input parameters leads to a number of important conclusions.

Among these conclusions is the specification of desirable reactor properties. By studying the boundary conditions (the general environment) as established for the development of a certain reactor type the goals of this development become clearer. The more time the development of a certain reactor type will need, the less obvious is the exact goal for this long term development. This goal rather has to be formulated by prospective studies of those boundary conditions that we expect to prevail at the time of the completion of the project. These facts may be made plain using the problem of the breeding ratio as an example. It looks like one has to find a compromise between breeding and economics for fast breeders. Assuming that the development of a 1ooo MW_e breeder-power station will take 15 to 2o years (e.g. 196o - 198o), the desirable compromise between breeding and economics that applies to 198o has to be known already by about 1965. This point is part of the original statement of the problem for this study.

Nuclear energy has had its break-through in Germany too, admittedly in a less dramatic manner, after the orders for the nuclear power stations Gundremmingen, Obrigheim and Lingen had been placed, and there are long term breeder projects being worked out in Germany: The Nuclear Research Center Karlsruhe pursues the Karlsruhe Fast Breeder Project starting in 196o, while the Nuclear Research Center Jülich became interested in the development of a thermal breeder some time ago. So there was sufficient reason to work out a study, as extensive as possible, within the framework of Germany. Along these lines this study, although being worked out at the Institute of Applied Reactor Physics of the Karlsruhe Center, was sponsored by the "Studienkreis Kernenergiereserven", which comprises almost all the German organizations interested in this field. Therefore, the results as published here are of a somewhat more general significance.

2. Methods Employed in this Study

2.1 General Remarks

To combine the problem of nuclear energy resources in form of natural uranium and thorium with problems of reactor development one has to prepare a cost study. If all the pertinent input data are available it is possible to calculate the cost for nuclear energy by means of reactor data and by assuming prices for uranium and thorium ores. The interaction with electrical energy produced by conventional power stations results in a market share of nuclear energy depending on location and time. This market share in itself then will influence the utilization of the natural uranium and thorium resources and in doing so it will establish a feedback on prices for these materials. In planning new power stations, nuclear as well as fossil, one proceeds in a similar manner, if the planning period does not exceed about 5 years. Procedures of this kind are known as "power casting" in the English literature /‾1o_/.

The present study has the objective to cover the period until the year 2o4o. It will become obvious rather soon that it is impossible to provide the proper input data for the type of interplay mentioned above. This is particularly true, as the development of nuclear reactors is still in progress and as the demand for nuclear energy, that is being discussed here, will not only feed back on the prices of uranium and thorium ores, but will also influence the reactor development itself.

Without forgetting the final goal of the above mentioned interplay, it turned out to be necessary first to limit our activities to a less ambitious strategic game that we can carry out just now. In doing so, a reasonable estimate of the demand for nuclear energy forms the basis of our investigation. To be particularly careful, this estimate was done in close co-operation with the Rheinisch-Westfälisches Elektrizitätswerk (RWE) by M. RECKER, a member of the study group at the TH Aachen that is directed by H. MANDEL (cf. chapter 2.2).

In addition, great care was taken to select data characteristic for the reactors (cf. chapter 4). It seemed justifiable to compare 1ooo MWe units only, as these units are supposed to come into operation after 197o. The reactor data, on the other hand, had to refer to 1970, because reasonable predictions seem to be possible only in the sense of a time normalization. This normalization, of course, implies that some reactor types will have been carefully tested by that time while others will still be in the state of planning or construction of the prototype, respectively.

Among the reactor types that have been selected one naturally finds the *light water reactor* (LWR). Here we made use of the data block for a pressurized water reactor supplied by the reactor development department of the Siemens-Schuckertwerke (SSW) as well as of the data block for a pressurized water reactor as was reported in an ORNL-study [11]. Both cases deal with a pressurized water reactor, so it can be clearly seen to what large extent the reactor input data lead to rather different results for the same reactor type. However, it is important to note that the ideas of the AEG concerning a light water reactor are in good agreement with the data of the LWR-ORNL reactor.

Next, a *gas graphite* (Magnox) *reactor* (GG), as advocated by the French (CEA), was included in the list of reactors to be evaluated [12]. Here it is worthwhile to mention that our cost estimates are more optimistic than those obtained on the basis of an English type reactor. It is not the purpose of this study to find out, which input data blocks are the more realistic ones. It was more important to be in a position to compare the results of this study with French results.

A *natural uranium D_2O reactor* (D_2O) has been suggested by the Siemens--Schuckertwerke. This company also provided the data block. This reactor type also should be rather typical for the Canadian line of development, as advocated by W. LEWIS in particular. Insofar the results of this study may turn out to be helpful for the persistent discussion on natural uranium D_2O reactors and fast breeders.

After the British recently decided to go in for their own *Advanced Gas-cooled Reactor* line (AGR) instead of the American type light water reactors it was interesting to consider this type as well. The AGR data block was kindly provided by UKAEA through the company Nukleardienst.

The Thorium-High Temperature Reactor (THTR) corresponds to the data block given in the ORNL-study [11] mentioned before. These data are advocated by General Atomics (GA). They also agree rather well with the ideas advocated by BBC-Krupp and Kernforschungsanlage Jülich.

We now turn to sodium-cooled fast breeders (Na-BR). In 1964 General Electric (GE) published an extensive study of a reactor of this type [13]. Kernforschungszentrum Karlsruhe (KFK) has published the study Na-1 in 1964 [14]. The most important difference between these two breeder studies perhaps is given by the magnitude of the breeding ratio. The treatment of these two fast breeders in this study is justified by the problem of what breeding ratio is desirable.

We want to re-emphasize that the Studienkreis Kernenergiereserven has checked the internal consistency of all reactor data blocks and compared them to other information available but has not considered it to be its objective to rate these reactors and in particular the respective cost data.

If the demand for nuclear energy is postulated and if the reactor and cost data (these are assumed to be constant with time, i.e. a conservative estimate) are given, it is possible to evaluate the demand for thorium and uranium resources as well as the cost of energy production. This has been done by means of either one or two type strategies.

In the one type treatment (cf. chapter 5) only a single reactor type was assumed to meet the entire nuclear energy demand. Admittedly, the one type strategy in connection with GE or KFK breeders leads to an unrealistic start-up situation, as there is no plutonium available in nature. This logical gap can be closed by the two type strategy (cf. chapter 6). There we assume that a breeder is built if and only if there is enough plutonium available within the limits of these strategies, i.e. without any external purchase. This establishes a connection between the installation of converters and the installation of breeders. Starting from that moment, when the doubling time of the population of fast breeders agrees with the doubling time of the nuclear demand for nuclear energy which increases with time, one will install breeders only. After this time the converter reactors will die out because of their limited plant life.

In evaluating cost the annual cost for energy production as well as the cumulative cost until the year 2ooo have been calculated. These cost have been calculated as present worth at a discount rate of 7 $^{o}/o$ referring to 197o (cf. chapter 7). This method for instance permits a comparison of the development cost as planned for 197o to the total resulting cost up to the year 2ooo.

Some of the input parameters were varied within certain limits. This applies in particular to the price trends of uranium and thorium ores (cf. chapter 3). Similarly, a lower and an upper estimate of the demand for nuclear energy was considered (cf. chapter 2.2). The various reactor types as such represent a variation of reactor parameters, in particular the pairs: LWR (SSW)/LWR (ORNL) and Na-BR (GE)/Na-1 BR (KFK). This makes it possible to estimate conclusions that could be gained properly only by means of the strategic games of the total interaction between prices for fossil fuels and uranium, data for power stations, prices for energy and demands for nuclear energy. We want to re-emphasize that the study submitted here follows the "if-then" scheme: if we have this demand for nuclear energy these cost for uranium and these particular reactor data, then we arrive at those cost and at a certain demand for uranium and thorium ores.

The subsequent chapter will deal in more detail with the methods of computation and the data that have been applied. For lack of space it was not possible to include in this condensed survey an extensive description of the mathematical models involved or in particular a record of the very extensive data material (5o figures for 2o reactors each). As was mentioned before, this information will be provided in a detailed publication /15/.

2.2 Nuclear Energy Demand in Germany

As was stated before, M. RECKER [16] has worked out the postulates for demand that form the basis of this study. First the total expected demand for electrical energy was estimated. As a starting point the respective postulates for the common market countries up to 1975 [17] were used. The extrapolation up to the year 2040 was guided by American estimates [18] and started with the following assumptions: Doubling of the population up to 2040, increase of the annual per capita consumption to 40,000 kWh, average load factor of 0.48. The corresponding data are shown in the graph on page 10.

On the basis of the known development programs it was possible to estimate the demand for nuclear energy up to 1970. While there are no quantitative data available for the further development, the cost trends seem to indicate a steadily growing share of the newly installed power increment for nuclear energy. Here we have to accept some reasonably plausible working hypothesis. To account for the uncertainty of the prediction which is unavoidable as well as to stress the dependence of the demand for nuclear fuel on the rate of development, we considered it useful to use two different models. One model assumes the nuclear share of new installed power to increase from 15 °/o to 50 °/o between 1970 and 1980 and then to remain constant at 50 °/o up to the year 2000 (lower estimate). The other model assumes this share to reach 80 °/o in 1980 and to increase to 90 °/o in 2000 (upper estimate).

The average load factor for nuclear power stations was chosen to be 0.8 up to 2000 in [16]. Supposing that nuclear energy will be used to meet the peak demand on an increasing scale the load factor then will decrease to 0.48 by 2040. In working out the strategies (chapter 5 and 6 or data block, chapter 4) we have conservatively assumed a load factor of 0.70 for reactor use for the whole period.

This difference represents a small change of the per capita consumption only as estimated by M. RECKER. Table 1 and the graphs on page 1o display the upper and lower curves of the demand for nuclear energy in Germany as used in this study in addition to the last EURATOM prognoses for the Common Market countries [9].

Table 1 Nuclear Power Installed in Germany

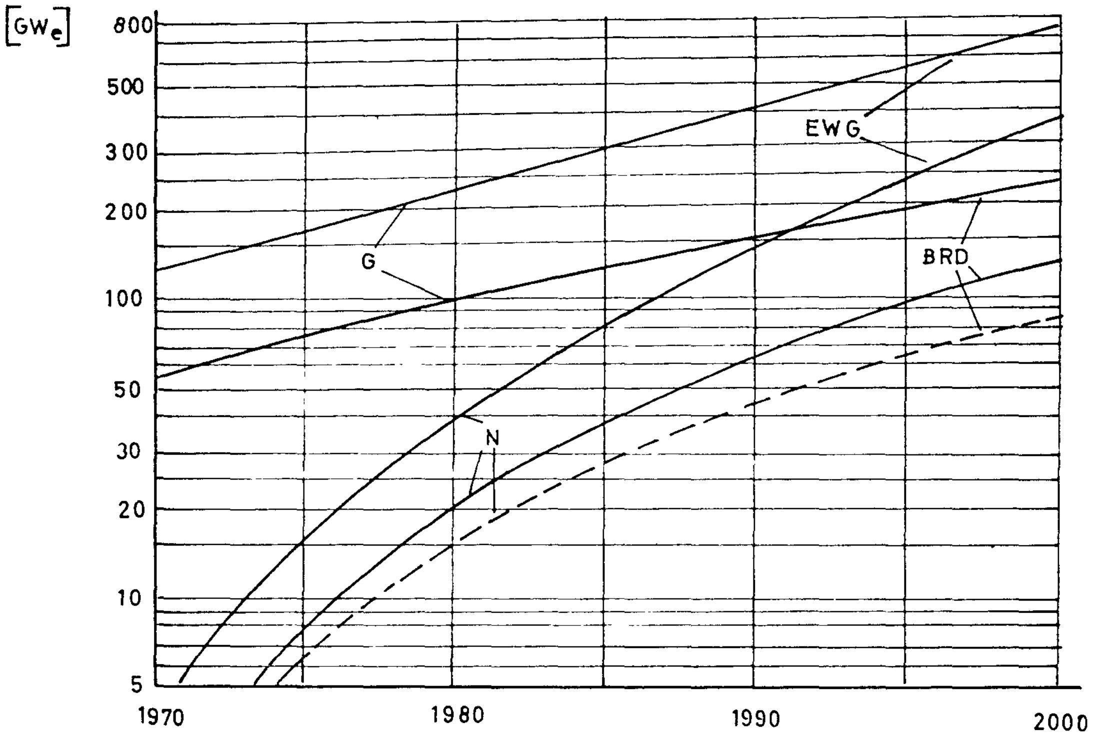
Year	Nuclear power installed in GW_e lower (P_u) estimate	upper (P_o) estimate	Share of total power installed °/o lower (P_u) estimate	upper (P_o) estimate
1965	-	-	-	-
197o	2	2	3.6	3.6
1975	7	8	9.3	1o.6
198o	16	2o	16.3	2o.4
199o	43	62	28.6	41.3
2ooo	85	132	37	57
2o2o	213	31o	47	69
2o4o	4o5	76o	53	1oo

The estimates of nuclear power P [GW_e] installed may be expressed analytically as

$$\begin{aligned} &\text{lower estimate} \qquad P_u = 0.0473 \cdot t^{2.09} \\ &\text{upper estimate} \qquad P_o = 0.0302 \cdot t^{2.34} \end{aligned} \qquad (1)$$

The time t has to be counted starting from 1964, but the curves are valid for years starting from 197o.

ESTIMATE OF THE DEMAND OF POWER INSTALLED

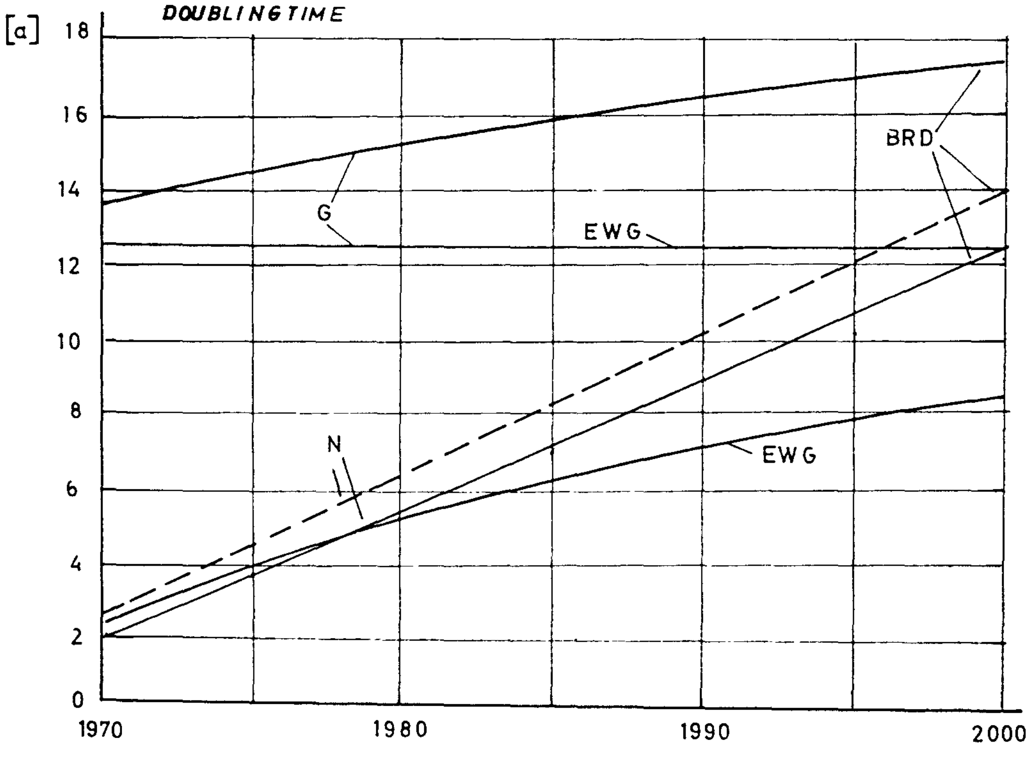


G TOTAL POWER INSTALLED

N NUKLEAR SHARE OF POWER INSTALLED

— UPPER ESTIMATE OF DEMAND

--- LOWER " " "



There is a linear increase of the doubling time T related to the growth formulas, as can be seen in the graph on page 10 as well:

$$\begin{aligned} T_u &= (2^{1/2.09} - 1) \cdot t \\ T_o &= (2^{1/2.34} - 1) \cdot t \end{aligned} \qquad (2)$$

The exponential increase with constant doubling time that is often used does not express the gradual saturation of the demand.

2.3 Nuclear Fuels - Demand and Supply

If the power installed with a certain reactor type is known as a function of time, following 2.2, the respective mass-flow of fissile and fertile materials become of interest. In addition to burnup and conversion the inventories, tied up in the reactors as well as in fuel cycle, are of great importance and are strongly influenced by the rate of annual increase in the number of reactors.

To cover these dynamic effects, detailed balance equations based on the work of R. GIBRAT [19] were elaborated [20]. Their structure can be discussed only shortly. They start with relations for the flowrate of a substance measured in units of t/a . The initial flow rate D_F^s at the start of the fuel production line is given as

$$\begin{aligned} D_F^s(t) &= \kappa\, d_o^s \cdot P(t - \delta_B + \delta_F) + \vartheta_o^s \cdot \frac{d}{dt} P(t + \delta_F) && \text{for } \frac{dP}{dt} > 0 \\ &= \kappa\, d_o^s \cdot P(t + \delta_F) && \text{for } \frac{dP}{dt} \leqslant 0 \end{aligned} \qquad (3)$$

The output D_W^s of the reprocessing plant is given as

$$\begin{aligned} D_W^s(t) &= \kappa\, d_1^s \cdot P(t - \delta_B - \delta_W) && \text{for } \frac{dP}{dt} > 0 \\ &= \kappa\, d_1^s \cdot P(t - \delta_W) - \vartheta_1^s \cdot \frac{d}{dt} P(t - \delta_W) && \text{for } \frac{dP}{dt} \leqslant 0 \end{aligned} \qquad (4)$$

where P(t) is the power of all reactors of type i in units GW_e and γ is the average load factor.

The other symbols have the following meaning

d^s_{oi} $[t/GW_e \cdot a]$	Recharge factor; measures the throughput of substance s as necessitated by burn-up and fabrication losses for one Gigawatt-year
d^s_{li} $[t/GW_e \cdot a]$	Discharge-factor; measures the amount of substance s recovered from the reprocessing plant (allows for losses) for one Gigawattyear
ϑ^s_{oi} $[t/GW_e]$	Inventory-buildup factor; gives the amount of substance s necessary to install one Gigawatt electrical power (including spare elements)
ϑ^s_{li} $[t/GW_e]$	Discharge inventory factor; gives the amount of substance s available after shut down of one Gigawatt electrical power and after reprocessing
δ_{Fi} $[a]$	Fabrication time; covers the period between delivery of fissionable material and charging of the reactor
δ_{Wi} $[a]$	Reprocessing time; covers the period from discharging of the reactor until arrival of the fissionable material in store
δ_{Bi} $[a]$	Load delay; accounts for the fact that the first refill will take place a certain time after start-up of the power station.

The index s generally refers to the different fissile and fertile nuclides. Subsequently, we shall consider natural uranium (s = n), fissionable plutonium (s = p) and thorium (s = t).

The net annual demand $Z^s(t)$ of substance s needed for the reactor population in question in a one type strategy is obtained by properly coupling equations of forms (3) and (4) and allowing for the materials balance of a diffusion plant, if applicable. If multitype strategies are concerned, the Z^s_i of different populations i may be easily combined.

The most important example is the two type strategy of our study (chapter 6) based on a common plutonium stock for breeders (B) and converters (K). This strategy is governed by the difference-differential equation

$$Z^{p}(t) = \sum_{i=B,K} \left[D_{F}^{p}(t) - D_{W}^{p}(t) \right] \qquad (5)$$

Here $Z^{p}(t)$ means an external Pu-source, that will be set equal to zero in our examples.

A detailed presentation of this method is given in [20] and [15].

2.4 Cost Evaluation

Concerning the cost evaluation we have tried to go into details as far as possible, as we have done before with regard to the mass flow rate model. The limitation is set by the data available. The cost evaluation is based on the present worth method throughout.

The specific cost of investment k_I in units of Dpf/kWh were calculated by using the formula

$$k_I = \frac{1}{8760 \cdot \kappa} \left\{ K_A \left[\frac{R + S}{1 - \left(1 + \frac{R+S}{100}\right)^{-L}} + (V_S + V_H) \right] + K_D (R + S + V_S + V_H) \right\} \qquad (6)$$

The symbols have the following meaning

K_A [DM/kW$_e$]	Specific investment cost, including the direct and the indirect investment cost plus interest during construction period
K_D = 100 [DM/kW$_e$]	cost of D_2O
R = 7 [°/o / a]	interest factor for foreign and own capital
S = 2.7 [°/o / a]	taxrate
V_S = 0.5 [°/o / a]	capital insurance
V_H = 0.5 [°/o / a]	liability insurance
L = 25 [a]	plant life

It is complicated to evaluate the share of the fuel cost following the present worth method. This problem has been treated in complete generality by H. SCHMALE et al. [21]. Our treatment [22] represents essentially a simplified version of this work and is based on the approximation formula for the average share of the fuel cost k_{Br} in units of Dpf/ kWhe

$$k_{Br} = \frac{R \cdot \delta_R}{E_1 [1-(1+R)^{-L}]} \left\{ \rho [k_o^* - k_1^* (1+R)^{-L}] + \frac{k_o^* - k_1^*}{Z} - \frac{(1+R)^{-\delta_B} - (1+R)^{-L}}{1-(1+R)^{-\delta_R/Z}} \right. \quad (7)$$

The respective symbols have the following meaning

k_o^*	[DM/kg]	present worth of the cost for fresh fuel (incl. taxes), referring to the date of fuel insertion into the reactor
k_1^*	[DM/kg]	present worth of the net-proceeds for used fuel (incl. taxes), referring to the date of fuel discharge from the reactor
E_1	[kWh/kg]	energy extracted from the fuel
ρ	[1]	excess elements on reserve
δ_R	[a]	inpile-time of fuel
Z	[1]	number of subcharges in the reactor

The quantities k_o and k_1 themselves are defined by

$$k_o^* = [1 + \frac{S}{100} (\delta_F + \frac{1}{2} \delta_R)] \cdot (1 + \frac{R}{100})^{\delta_F} \cdot (K_F + \frac{1}{100} \sum_s m^s x_o^s K_o^s) \quad (8)$$

$$k_1^* = [1 - \frac{S}{100} (\delta_W + \frac{1}{2} \delta_R)] \cdot (1 + \frac{R}{100})^{-\delta_W} [\frac{1}{100} \sum_s v_1^s x_1^s K_1^s - (K_A + K_{TR} + K_R)] \quad (9)$$

The symbols have the following meaning

K_F	[DM/kg]	Fabrication cost for fuel, referring to 1 kg of fissile and fertile materials contained therein
K_o^s; K_1^s	[DM/kg]	cost of the components s of the fuel for insertion (o) or discharge (1)

x_o^s; x_1^s	[°/o]	percentage of component s at insertion (o) or discharge (1)
m^s	[1]	fabrication-loss factor
v^s	[1]	reprocessing-loss factor
K_A, K_{TR}, K_R	[DM/kg]	cost for reprocessing, transportation, and reconversion respectively.

3. On Nuclear Fuel Resources

3.1 Preliminary Remarks

In judging the various strategies to the respective amounts of fuels needed, the fuel prices that enter in k_o^* and k_1^* are of major concern. These prices develop by interaction of supply and demand; they were predictable if the supply, i.e. the uranium and thorium resources of the world and the demand, i.e. the plans for nuclear development of all countries, were sufficiently well known. As will be shown below, there are only rather vague statements possible concerning the resources of nuclear fuels as well as the development programs.

Therefore, we have limited ourselves to consider two price trends as a working hypothesis, that seem plausible to us, to estimate the influence of price changes, as we have done already with regard to the power development programs. It may be stated in advance, that the uranium prices have only little effect on the cost of nuclear energy production, because fuel costs do not constitute a major part of those. Therefore it is all the more justified to use price models.

Hypothesis II assumes the cost of nuclear fuels in the "optimistic" limit to remain at the level characteristic for 1970 - 1980, as shown in table 2, which can be reasonably well substantiated.

To cover the influence of possible increases in price hypothesis II, it was confronted with the "pessimistic" hypothesis I, which has also been shown in table 2.

Table 2 Limits for Price Trends of Nuclear Fuels

Substance	II optimistic	I pessimistic		
	1970-2040	1970-1985	1985-2000	2000-2040
U_3O_8 (\$/lb)	8	8	20	30
ThO_2 (\$/lb)	8	8	20	30
Pu (\$/g fiss.)	10	10	27.5	27.5

These guiding values were gained by the following considerations:

3.2 World Reserves of Uranium Ore

The estimate of the world reserves of uranium that have been published between 1959 and 1964 show a considerable fluctuation. In 1959 [23] and in 1960 [24] the reserves of cheap uranium (below 8-10 \$/lb U_3O_8) were estimated at about 1 million tons and it was assumed that up to the year 2000 3 further million tons could be mined at the same price level. In 1962 [25] the reserves of the USA alone was given to be about 0.8 million tons of cheap uranium and further 0.7 million tons in the category of 10-30 \$/lb U_3O_8. The latest estimates in 1964 [26] figured the resources still available after 1980 in the United States to 0.275 to 0.320 million tons in the lowest price category and to 0.63 million tons in the second lowest one.

A comparison of the latest estimates with the known development programs leads one to the conclusion that the known cheap resources would be exhausted in the 80's, resulting in a transition to the next category. The uranium prices, however, are assumed not to increase too heavily in the foreseeable future. First of all, the possibility to gain up to 10^9 tons of uranium out of the seawater [27] would set an upper price limit of about 30 \$/lb U_3O_8. The growing demand for uranium also will presumably lead to the prospection for uranium, reduced for years, to discover new reserves. Finally, the start-up of fast breeder reactors will lead to a pronounced decrease in the demand for uranium.

Extrapolating the US-data as given in [25] to the world as a whole and using the relations valid up to date, one gets the orders of magnitude shown in table 3.

Because Germany produces about 5 % of the world's electric energy, one can assume as a guide line, she also can claim about 5 % of these resources. If the demand for natural uranium in Germany will stay within these limits - and we will show on the basis of the two type strategies that this is very well possible - one comes to the conclusion that German decisions in the field of nuclear energy will rarely have any influence on the market for uranium. This is an argument to consider very reservedly the results of optimizing strategic games that are merely proceeding from the German situation.

Taking as a basis the curve for average uranium consumption for the strategies here investigated, one obtains periods (right-most column of table 3) that are characterized by a certain price category (left-most column of table 3).

Table 3 Uranium Resources and Price Trends

Price category \$/lb U_3O_8	world resources 10^6 t U_3O_8	share available for Germany 10^3 t U_3O_8	sufficient for
8	1	50	1970 - 1985
20	1	50	1985 - 2000
30	2,4	120	2000 - 2040

Our calculations, based on table 2, also did consider the dependence of the cost of enriched uranium on the optimized waste-concentration of the diffusion plants assuming the separation cost to remain constant at 30 \$/kg.

3.3 Plutonium Prices

The problem of the plutonium price embraces a number of assumptions regarding the ratio of converter - to breeder power on a world basis. Inspite of extensive theoretical work, e.g. /‾26_7, no conclusive results have yet been obtained. Therefore, we have based our price models on plausibility assumptions, as we have done before in chapter 3.2 (cf. table 2). It has been shown in /‾3, 29, 3o_7 that the value of plutonium as a substitute for U-235 in a thermal reactor amounts to about 4o DM/g of fissionable material, based on the cost of U-235 supposed to be in effect in 197o - 198o.

Higher plutonium prices would render recycling of plutonium to thermal reactors unprofitable. Because the period from 197o to 198o is characterized by the predominance of thermal reactors the plutonium price will stay within the order of magnitude just mentioned. Hypothesis II assumes this price level to remain constant until the year 2o4o.

Hypothesis I is arrived at by the following argumentation. Starting in the mid-eighties the installation of breeders may increase the demand for plutonium. This would result in an increase of the price for plutonium. As was mentioned before, criticality calculations show 1 g of fissionable plutonium to be equivalent on the reactivity scale to 1.5 g of U-235 in a fast breeder. Using the factor 1.5 results in a value of 11o DM/g of fissionable plutonium. Higher plutonium prices would render it profitable to use U-235 in fast breeders. This couples the price of plutonium for the period in question to the price of uranium in 1985 to 2ooo. After the year 2ooo the breeder will produce enough plutonium to become independent of external sources of fissionable material. Therefore,no change of the price of plutonium is expected after the year 2ooo, one would rather expect a decline of the price level.

3.4 Price Trends for Depleted Uranium, Thorium and U-233

The price of depleted uranium was taken to be equal to the present price of 12 DM/kg for the whole period considered. To assume a price depending on the price of uranium concentrate would contradict the fact that diffusion plants and converters will produce large amounts of depleted uranium from their start-up and the demand of the breeders (being the only users of depleted uranium) will make a small percentage of those only.

At present, the prices for thorium-oxide (ThO_2) tends to follow the prices for uranium concentrate. Therefore in a first approximation, we assumed the price trends to be the same as those of uranium concentrate.

Concerning the reactor type THTR, U-233 is recycled to the reactor again and again without resulting in a surplus or needing a supply. So we have not established any price, following the arguments of [28].

4. Explanations Concerning the Reactor Data

The references for the sources of the reactor data have been mentioned already in chapter 2.1 (tables 4 and 5).

The net electric output P was normalized to 1000 MWe, to obtain numbers comparable to each other; this was necessary in particular with respect to the reactors LWR (ORNL), GG (CEA), and Na-BR (GE).

Concerning the average specific power "r" and the average burn-up "a" one has to note that core and blanket as a whole were counted as fuel. This definition leads to unusually small figures.

The load-delays δ_B for reactors employing batch charges were gained by dividing in-pile time by the number of batches and were taken as 0.5 [a] for continuous charging.

The reprocessing time δ_W and the refabrication time δ_F if not given by the out of pile cycle as in the case for breeders were rather optimistically taken to be 0.6 or 0.5 years respectively, taking future development into account. The shorter cycle times for breeder reactors arise from the argument that one should permit little fuel only to be tied up in the out of pile cycle, otherwise high unproductive capital ties would result. The total out of pile time turns out to be 3 subcharges of 1/3 in-pile time each for the Na-1 BR (KFK) and 5 subcharges with 2/5 in-pile time each for the Na-BR (GE).

The factors concerning recharge, inventory, and discharge have been explained already in chapter 2.3.

The waste concentrations of the diffusion plant with respect to hypothesis II for the case of fixed separation cost are given at the bottom of the table 2 (cf. chapter 3.4).

The specific plant cost K_A contain the direct plant cost as well as the indirect plant cost appearing as owner expenses, interest during construction and contingencies. To obtain a common basis for comparison, the indirect cost were calculated for all reactors in the same way by adding to the direct cost 3o °/o owner expenses and contingencies and further adding 11 °/o interest during construction on these total investment cost for the whole construction period. For the D_2O reactor the plant cost also includes the cost for the D_2O without depreciation (interest and taxes and insurance).

To have a common base, the annual operation cost K_B were taken to be the same for all reactors only in the case of the D_2O reactor the cost for D_2O losses were added.

The information concerning cost of fuel fabrication K_F were taken from the respective references. With regard to the cost of reprocessing K_A, transport K_T, and reconversion K_R we refer to the detailed report [15].

The specific cost of investment K_I and fuel k_{Br} per kWh are obtained by applying equations (6) and (7) for a load factor of 0.7 ≙ 6ooo h/a and using the cost data from above.

The prices for U_3O_8-concentrate and the prices for plutonium of hypothesis I coupled herewith (cf. chapter 3) have been repeated.

Tabelle 4

TECHNICAL REACTOR DATA

QUANTITY	SYMB	DIM.	LWR(ORNL)			LWR(SSW)			GG(CEA)			D_2O(SSW)			AGR(UKAEA)			THTR(GA)			Na-BR (GE)			Na1-BR(KFK)		
NET ELECTRIC POWER	P	MW_e	1000			1000			1000			1000			1000			1000			1000			1000		
PLANT EFFICIENCY	η	1	0.31			0.32			0.32			0.33			0.41			0.44			0.44			0.40		
AVERAGE SPEC. POWER	r	$\frac{MW}{kgBr}$	0 031			0.027			0.0062			0.020			0.018			0,024			0.0614			0,0415		
AVERAGE BURNUP	a	$\frac{MWd}{kgBr}$	21.0			24.0			5.0			9.0			20.0			57.1			39.0			22,86		
LOAD DELAY	δ_B	a	0.88			0.87			0.50			0.50			0.50			0.78			0.50			0,72		
REPROCESSING TIME	δ_W	a	0.60			0.60			0.60			0.60			0.60			0.60			0.50			0.50		
FABRICATION TIME	δ_F	a	0.50			0.50			0.50			0.50			0.50			0,50			0.25			0,22		
DEPLETION LEVEL			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
REFILLFACTOR U_{nat}	d_0^n	$\frac{t}{GW_e a}$	241.3	212.0	202.9	288 5	250.4	238.5	230.4	230.4	230.4	124 1	124 1	124.1	196.5	172 5	164.9	73.36	61.81	58.19	19.69	19.69	19 69	38.33	38.33	38.33
REFILLFACTOR Pu	d_0^p	$\frac{t}{GW_e a}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	–	–	1.205	1.205	1.205	1.347	1.347	1.347
REFILLFACTOR Th	d_0^t	$\frac{t}{GW_e a}$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	13.73	13.73	13.73	–	–	–	–	–	–
INVENTORY BUILDFACTOR U_{nat}	ϑ_0^n	$\frac{t}{GW_e}$	470.2	413.2	395.3	737.8	640.4	609.9	514.2	514.2	514.2	154.6	154.6	154.6	604.0	530.2	507.1	502.1	423.0	398.2	35.98	35.98	35.98	60.74	60.74	60.74
INVENTORY BUILDFACTOR Pu	ϑ_0^p	$\frac{t}{GW_e}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	–	–	2.202	2.202	2.202	2.134	2.134	2.134
INVENTORY BUILDFACTOR Th	ϑ_0^t	$\frac{t}{GW_e}$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	93.96	93.96	93.96		–	–	–	–	–
DISCHANGE FACTOR U_{nat}	d_1^n	$\frac{t}{GW_e a}$	44.96	46.38	46.83	87.25	80.63	78 55	0	0	0	0	0	0	42.33	42.42	42 45	22 35	18 85	17 75	18.18	18.18	18.18	36.29	36.29	36.29
DISCHANGE FACTOR Pu	d_1^p	$\frac{t}{GW_e a}$	0.2388	0 2388	0 2388	0.3119	0 3119	0.3119	0.3819	0 3819	0.3819	0.3133	0.3133	0.3133	0.1337	0.1337	0 1337	–	–	–	1.414	1.414	1.414	1.712	1.712	1.712
DISCHANGE FACTOR Th	d_1^t	$\frac{t}{GW_e a}$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	12.80	12 80	12.80	–	–	–	–	–	–

PERIOD		1970 - 1985	1986 - 2000	2001 - 2050
DEPLETION LEVEL		a	b	c
U-235 CONTAINED IN WASTE OF DIFFUSION PLANT	%	0.2531	0.1668	0.1329

QUANTITY	SYMB	DIM	LWR (ORNL)			LWR (SSW)			GG (CEA)			D_2O (SSW)			AGR (UKAEA)			THTR (GA)			Na-BR (GE)			NaI-BR (KFK)		
SPEC.INVESTMENT C.	K_I	$\frac{DM}{kWe}$	532.8			577.2			692.6			634.9			606.0			467.3			634 9			599 4		
ANNUAL OPERATING C.	K_B	$\frac{DM}{a}$	7.3 · 10^6			7.3 10^6			7 3 · 10^6			8.3 · 10^6			7.3 · 10^6			7.3 10^6			7 3 · 10^6			7.3 10^6		
FABRICATION COST	K_F	$\frac{DM}{kgBr}$	250			300			71			200			300			1000			476			300		
REPROCESSING COST	K_A	$\frac{DM}{kgBr}$	100			100			80			90			100			200			120			260		
TRANSPORTATIONCOST	K_{TR}	$\frac{DM}{kgBr}$	40			40			30			30			40			40			40			100		
RECONVERSION COST U,Th	$K_R^u K_R^t$	$\frac{DM}{kg}$	22.4			22.4			-			-			22 4			22 4			-			-		
Pu	K_R^p	$\frac{DM}{g}$	6			6			6			6			6			–			6			6		
PRICE LEVEL			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
SPEC.INVESTMENTCOST	k_I	$\frac{Dpf}{kWh}$	1.022	1.022	1.022	1 107	1.107	1.107	1.329	1.329	1.329	1.218	1.218	1 218	1136	1.136	1136	0.915	0 915	0.915	1.218	1.218	1.218	1150	1.150	1.150
SPEC.OPERATING COST	k_B	$\frac{Dpf}{kWh}$	0.119	0 119	0 119	0.119	0.119	0 119	0.119	0.119	0.119	0.135	0.135	0.135	0.119	0 119	0 119	0 119	0.119	0.119	0.119	0 119	0.119	0.119	0 119	0 119
SPECIFIC FUEL COST	k_{Br}	$\frac{Dpf}{kWh}$	0766	0.945	1 225	0.891	1.087	1.415	0.741	0.861	1.155	0.564	0.547	0 724	0.733	0.966	1 213	0.763	0 964	1117	0 278	0 425	0.425	0.349	0 380	0 380
SPEC. ENERGY COST	k_E	$\frac{Dpf}{kWh}$	1.907	2 090	2.306	2 117	2,313	2 641	2.189	2 309	2 603	2.092	2 075	2 252	2 015	2 248	2495	1797	1.998	2151	1.615	1.762	1.762	1618	1.649	1649

PERIOD		1970 - 1985	1986 - 2000	2001 - 2050
PRICE LEVEL		a	b	c
PRICE OF URANIUM CONCENTR.	$\frac{\$}{lb\ U_3O_8}$	8	20	30
	$\frac{DM}{kg\ U_3O_8}$	70 48	176 21	264.31
PLUTONIUM PRICE	$\frac{DM}{g\ spaltb\ Pu}$	40	108.8	108 8

5. Explanations Concerning the One Type Strategies

In the one type strategy the demand for nuclear energy will be satisfied exclusively by additional installation of reactors of one type. The graphs on pages 24 to 31 show the results for each one of the reactors characterized in tables 4 and 5.

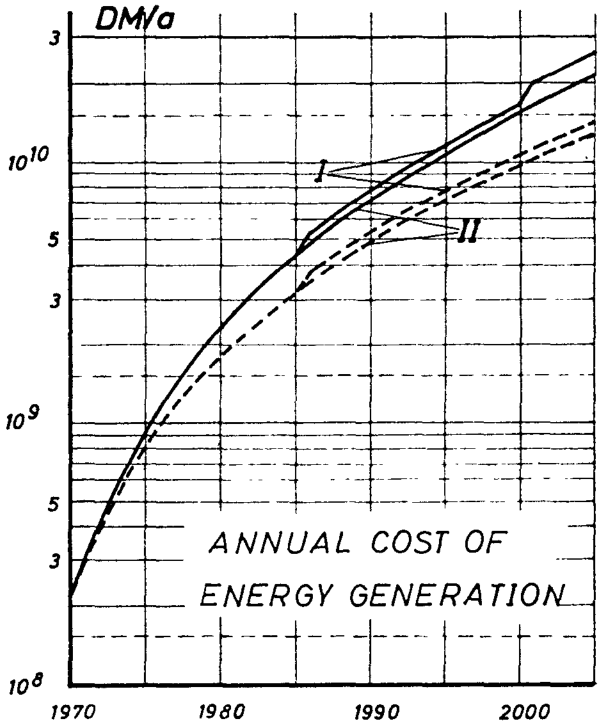
In all graphs the results for the upper estimate of the demand are shown by a full line while those for the lower estimate are shown by a dotted line. On the top left the graphs show the annual cost of energy production, while on the top right they show the cumulative demand for natural uranium or for plutonium in the case of breeders. On the bottom left the cumulative output or demand for depleted uranium from the diffusion plants respectively is given. On the bottom right the cumulative output of fissionable plutonium is shown with exception of the graph on page 29 which displays the demand for thorium.

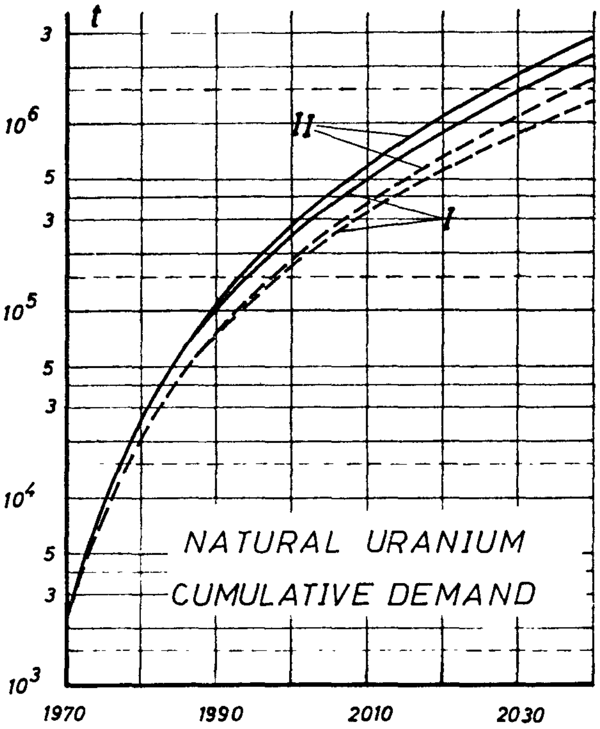
Some of the curves branch starting in 1985 depending on what hypothesis of the further price development for uranium and plutonium (I or II) is applied (cf. table 2). This is obvious for the annual cost. Concerning the cumulative amounts of natural and depleted uranium the price increases of hypothesis I will result in decreases because of a reduction in the waste concentration of the diffusion plants (tables 4 and 5).

For fast breeders the cumulative output of plutonium will not become positive before the annual output exceeds the annual consumption and before the accumulated demand for plutonium has been satisfied. The initial demand is displayed cumulatively on the top right of the graph for the fast breeders. The maximum corresponds to that year, starting from which no plutonium has to be added.

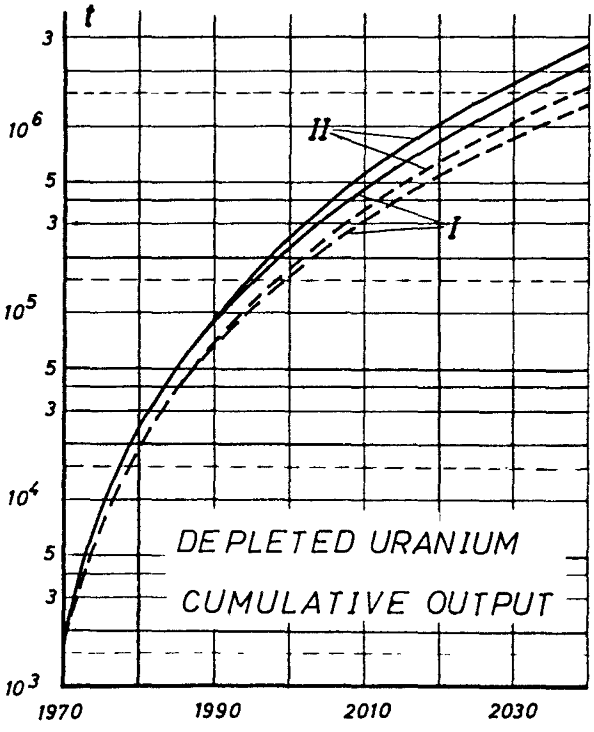
ONETYPE STRATEGY

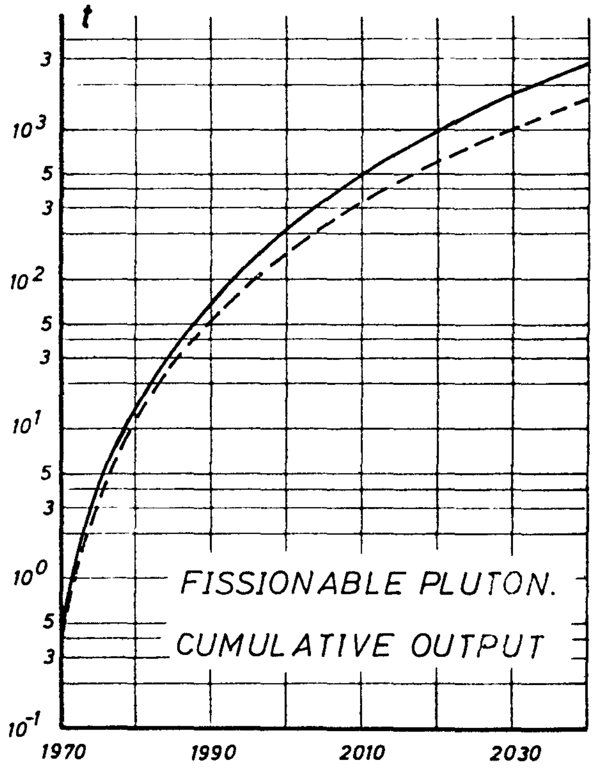
LWR (ORNL)





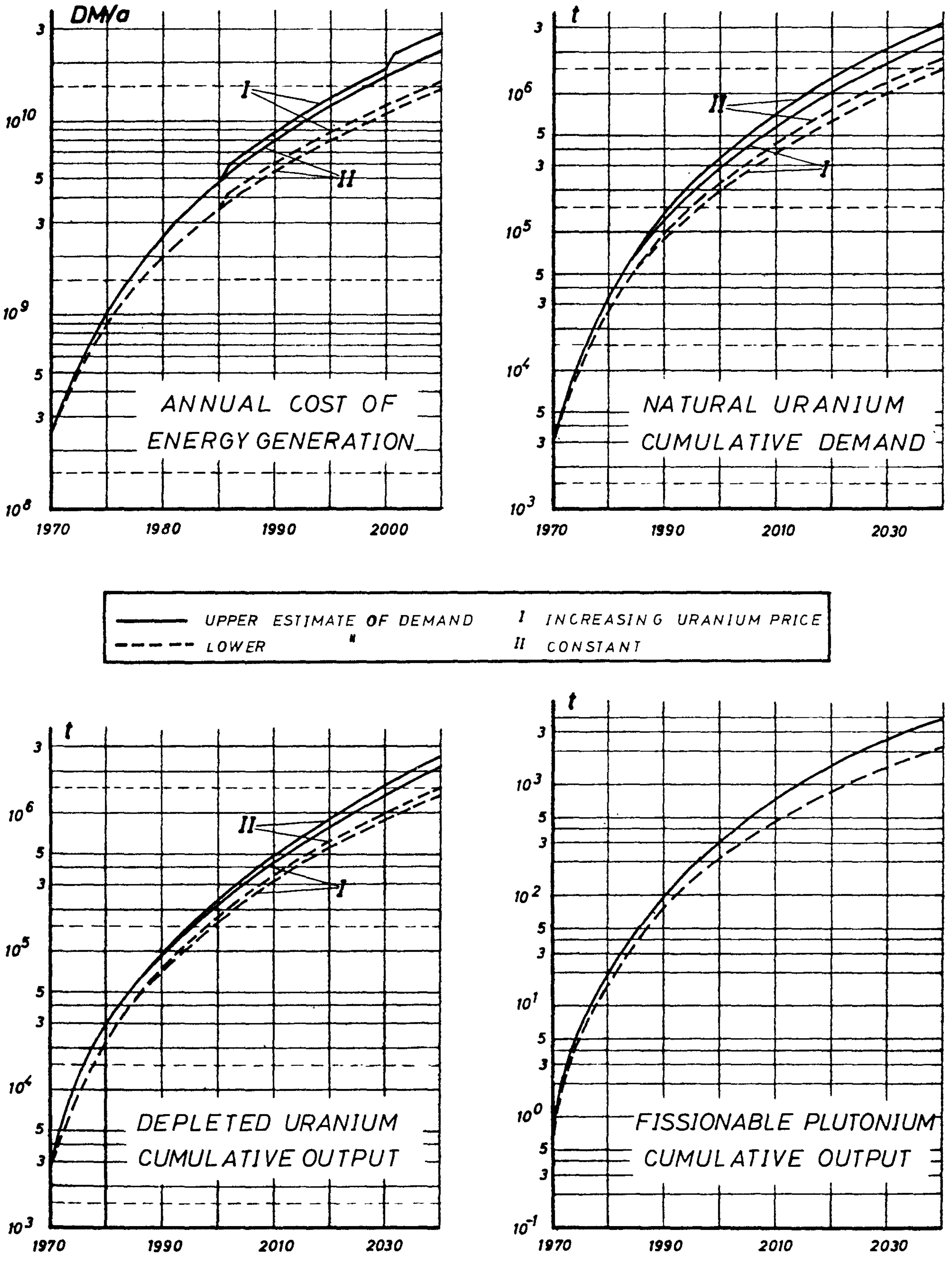
——— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE
– – – – LOWER " II CONSTANT "





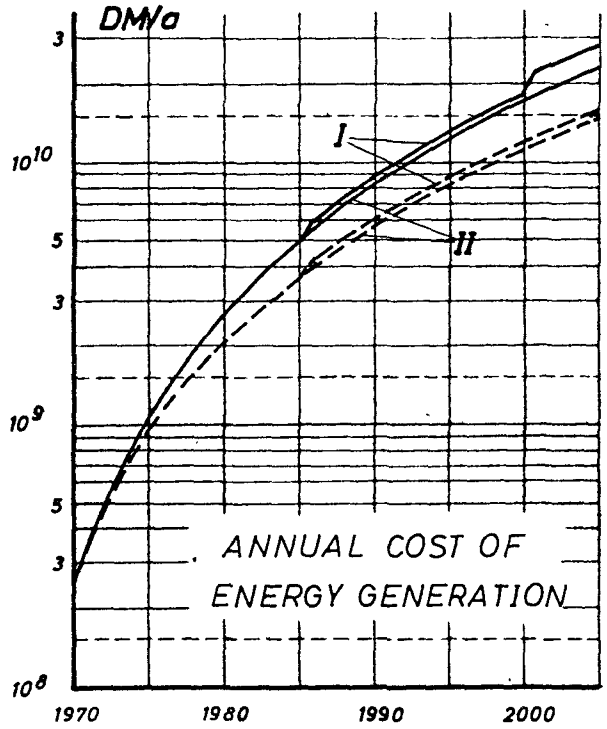
ONETYPE STRATEGY

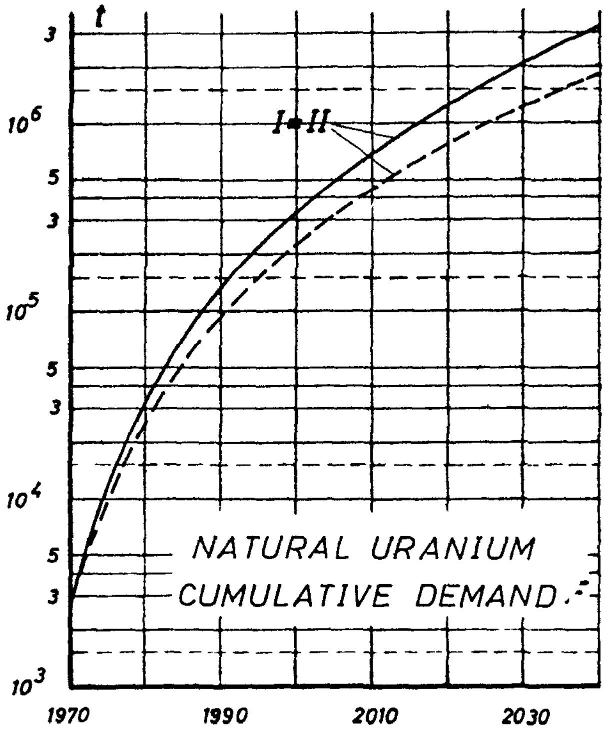
LWR (SSW)



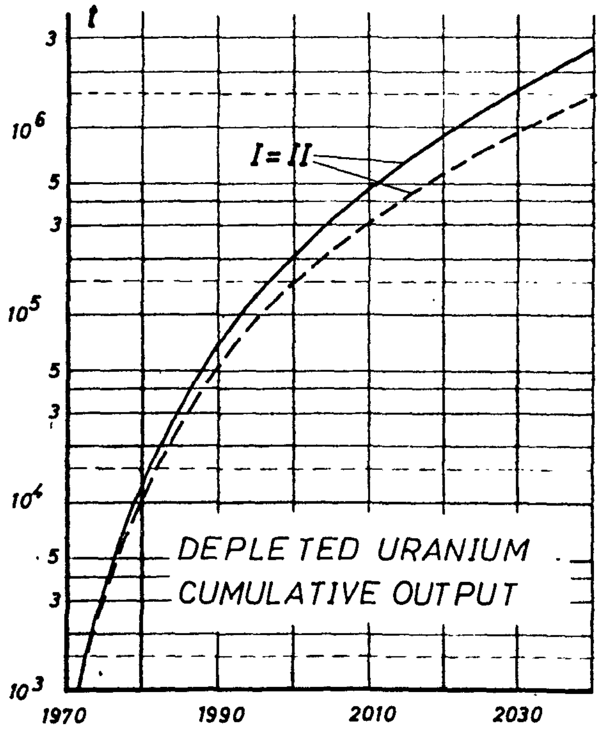
ONETYPE STRATEGY

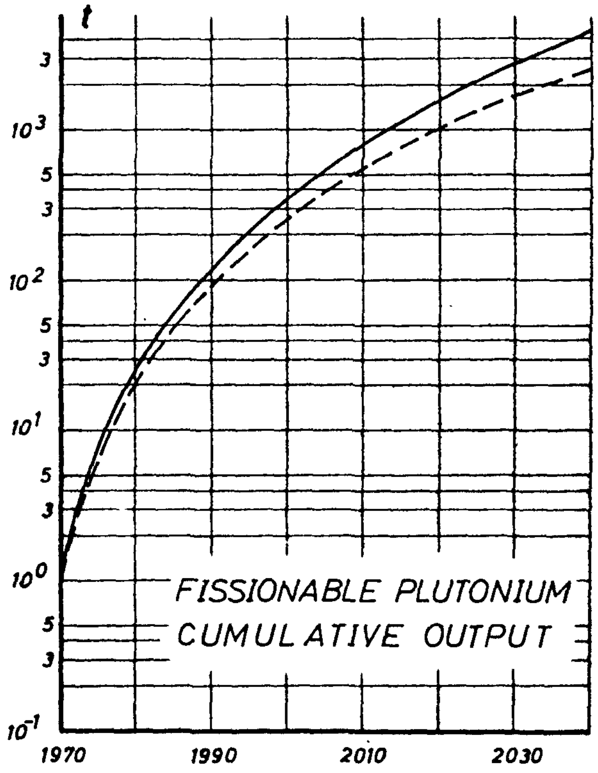
GG (CEA)





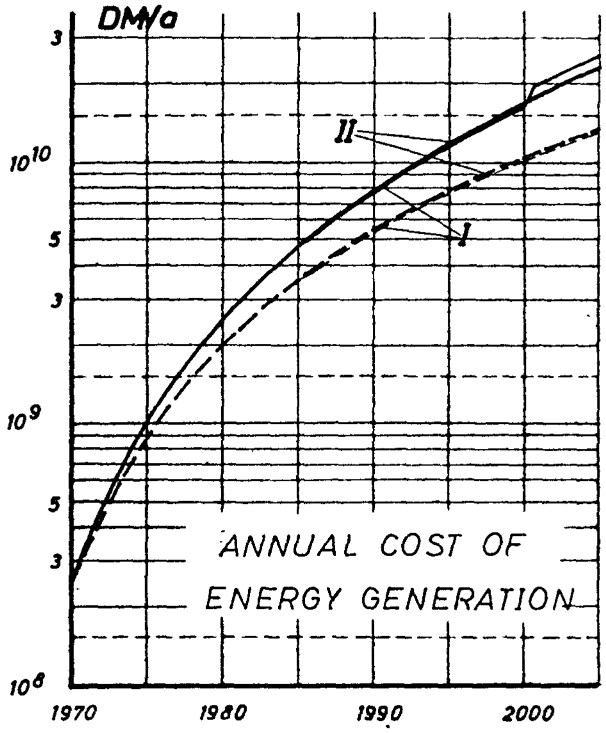
——— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE
– – – – LOWER " II CONSTANT "

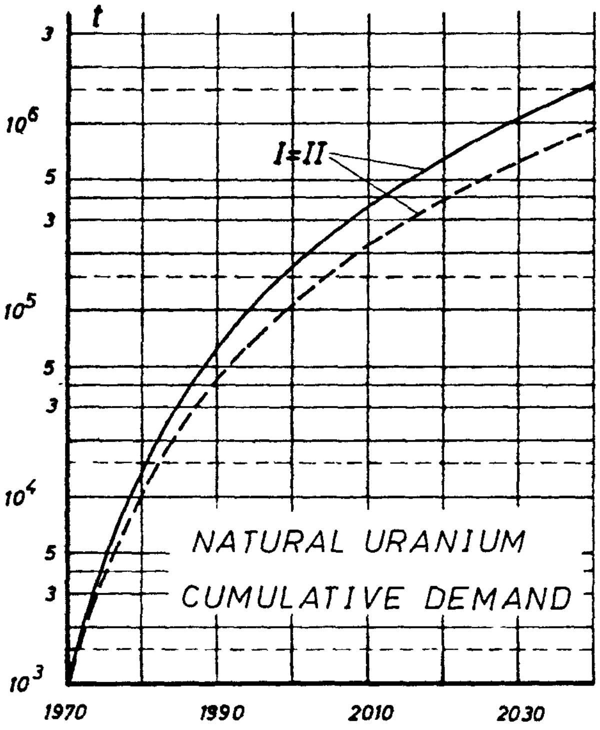




ONETYPE STRATEGY

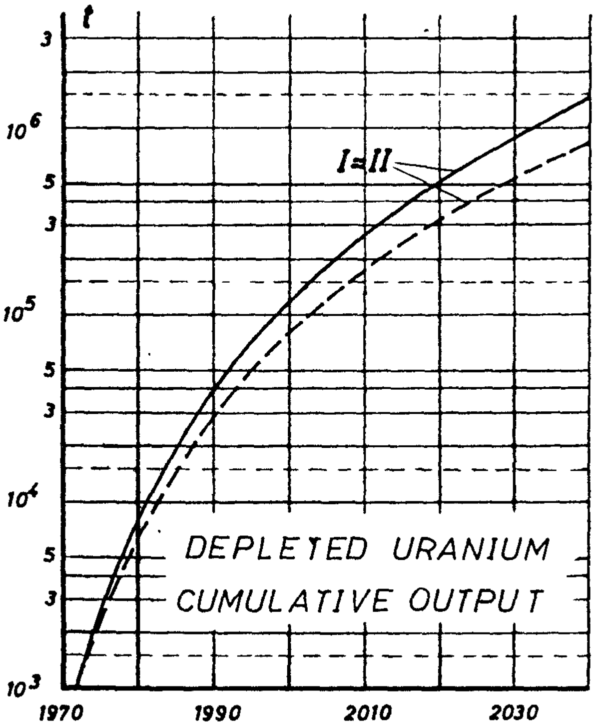
D_2O (SSW)

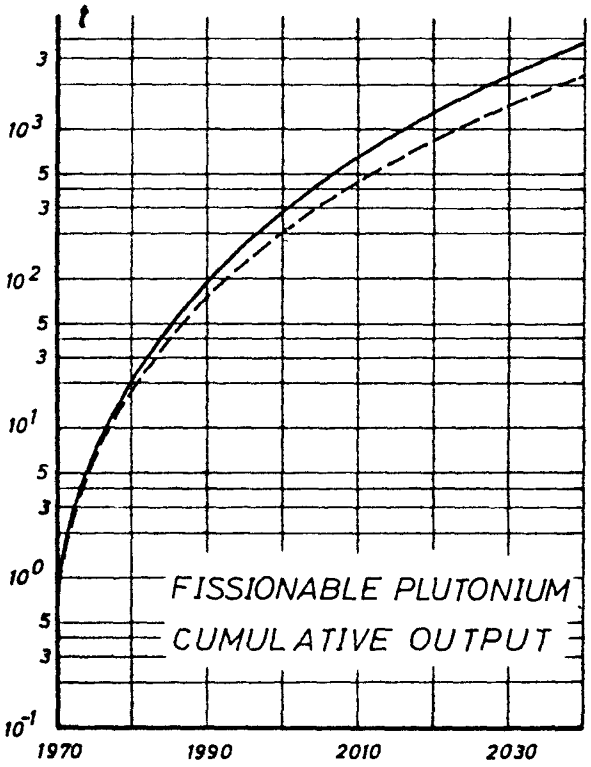

ANNUAL COST OF ENERGY GENERATION


NATURAL URANIUM CUMULATIVE DEMAND

——— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE

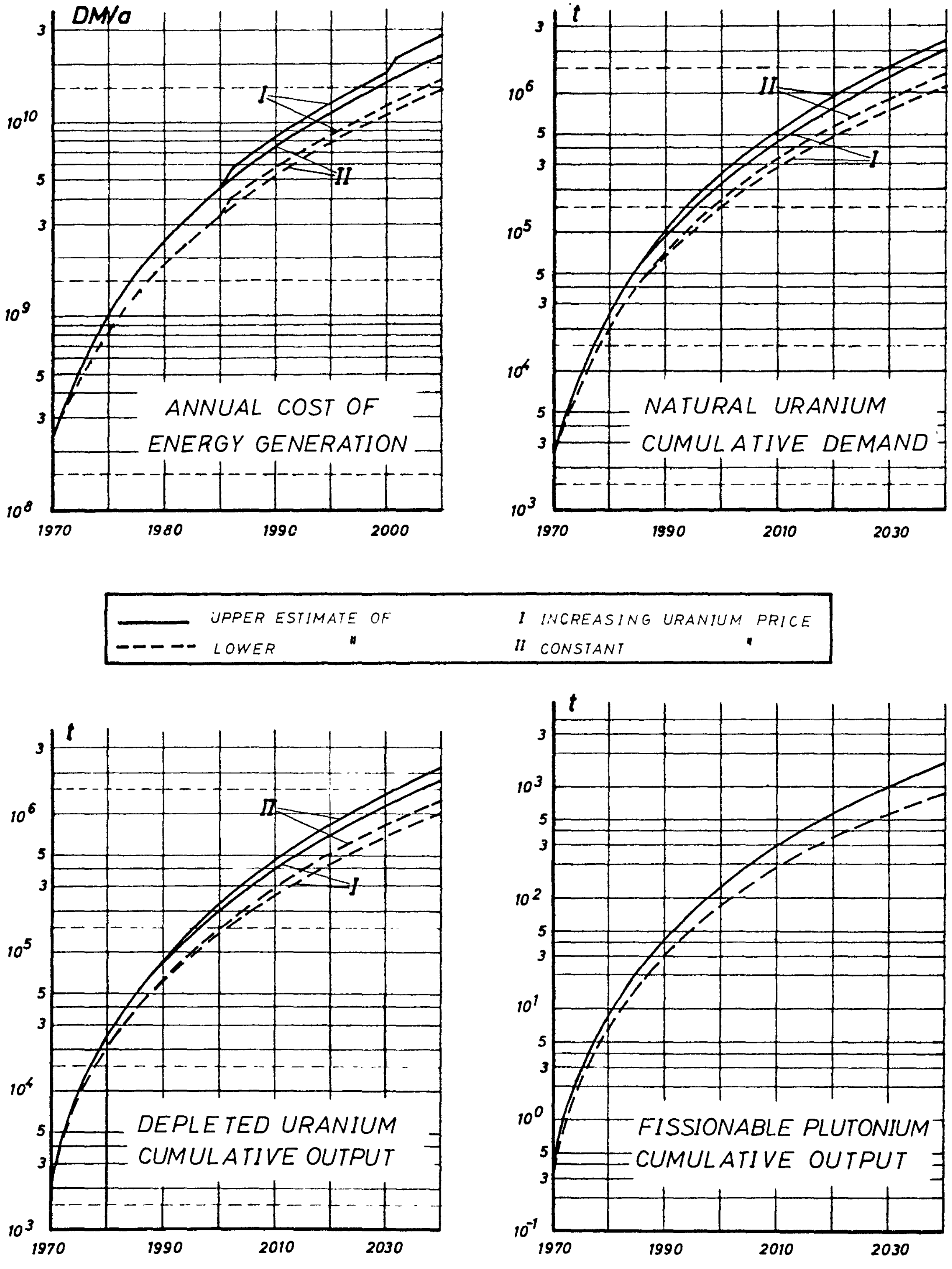
– – – LOWER " II CONSTANT "


DEPLETED URANIUM CUMULATIVE OUTPUT

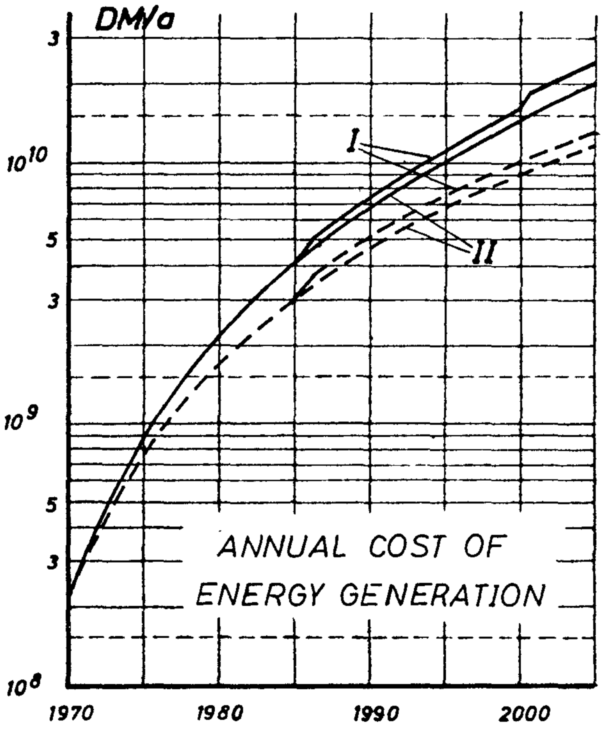

FISSIONABLE PLUTONIUM CUMULATIVE OUTPUT

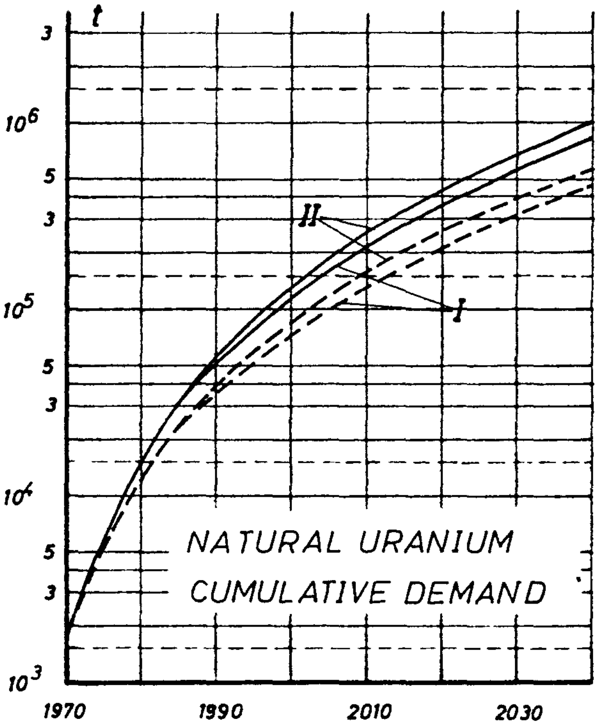
ONETYPE STRATEGY

AGR (UKAEA)

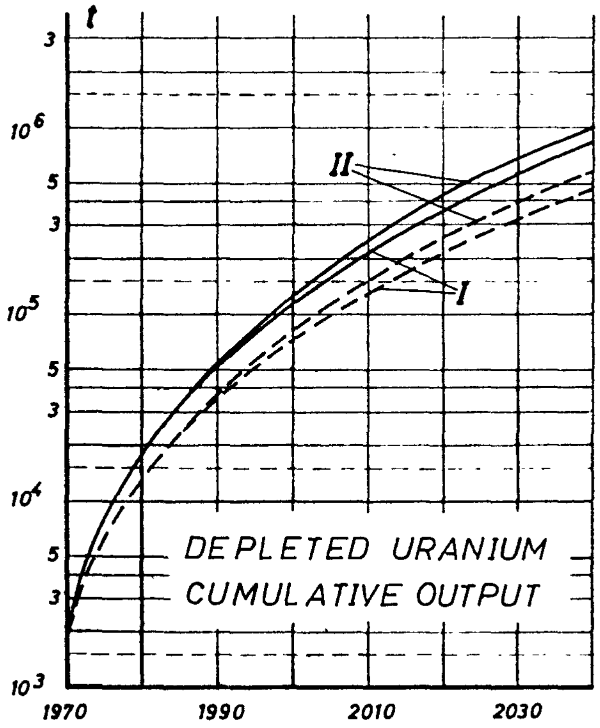


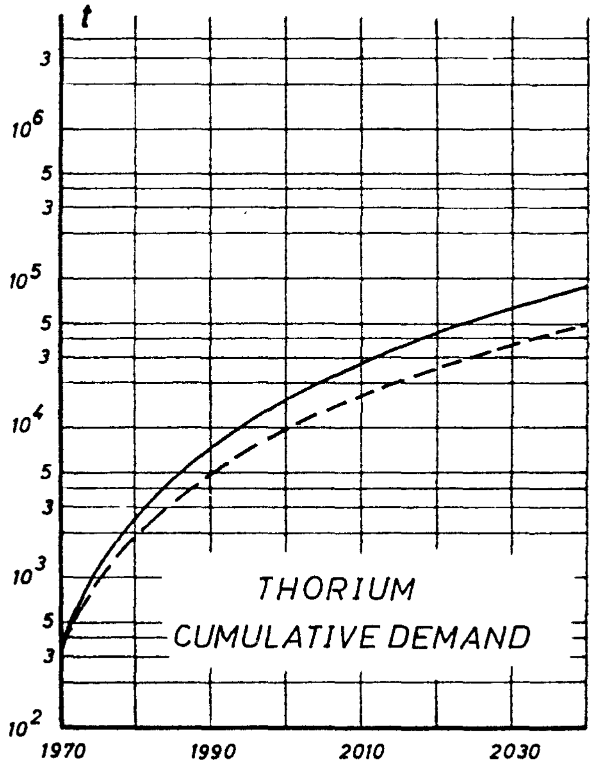
ONE TYPE STRATEGY **THTR(GA)**





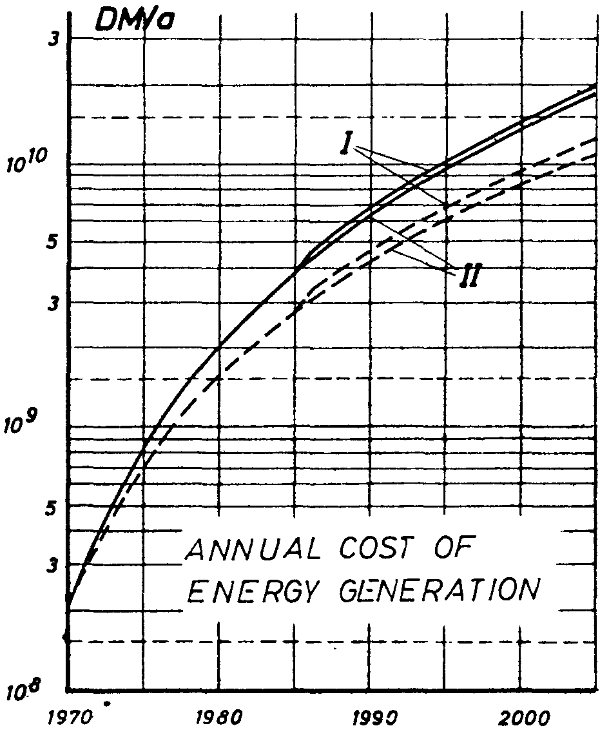
——— UPPER ESTIMATE OF DEMAND
– – – – LOWER "
I INCREASING URANIUM PRICE
II CONSTANT "

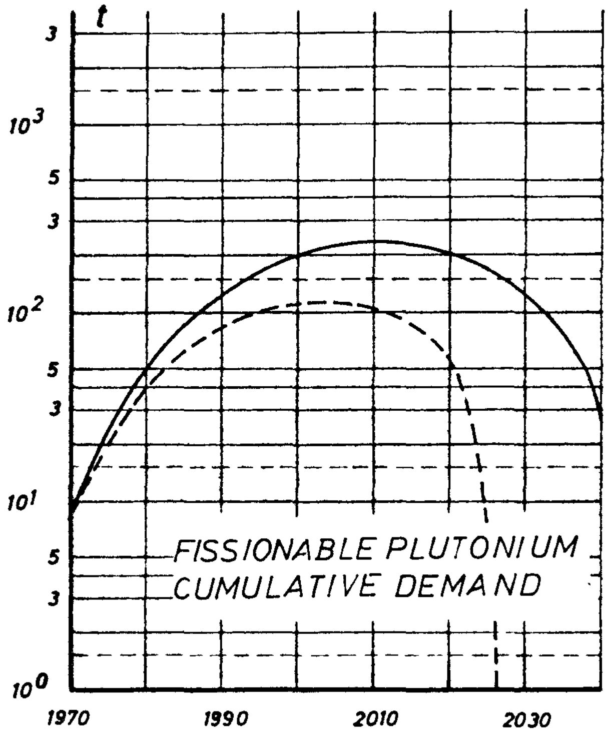




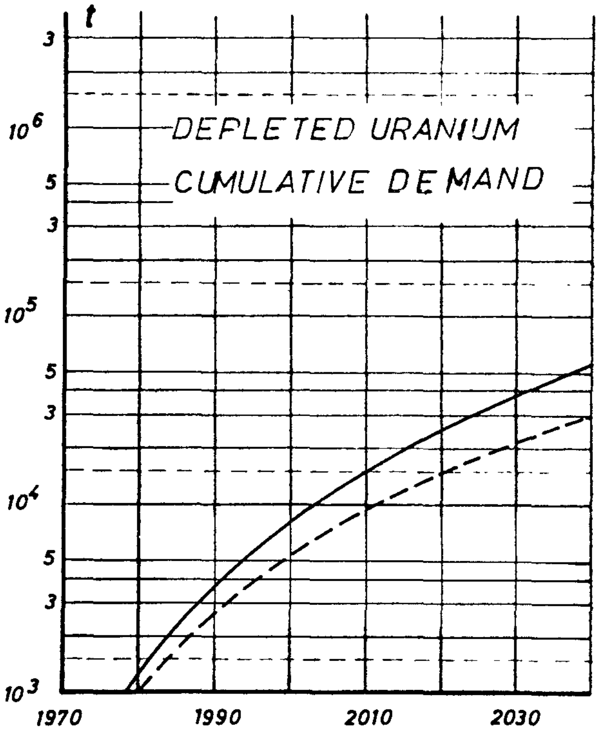
ONE TYPE STRATEGY

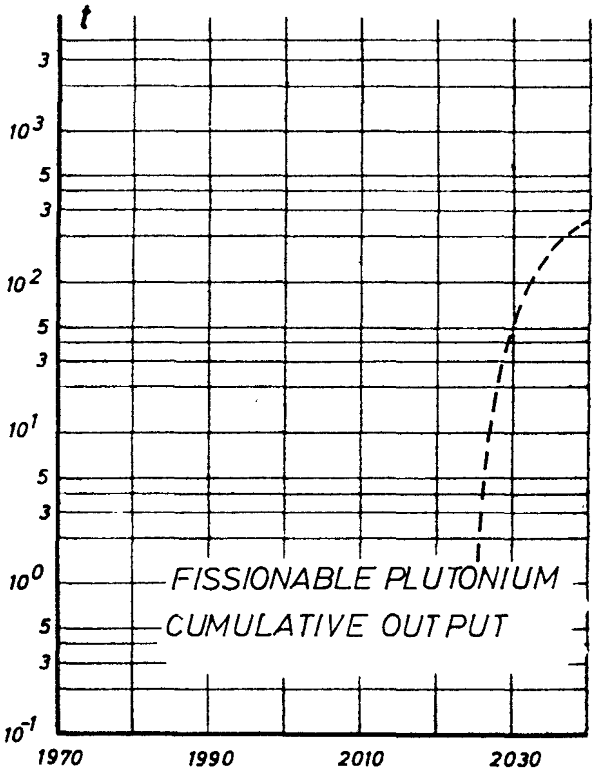
Na-BR (GE)





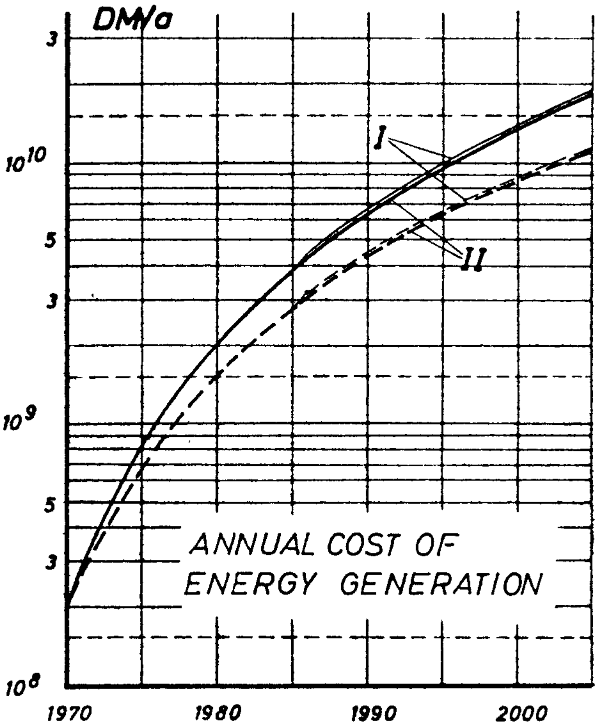
——	UPPER ESTIMATE OF DEMAND	I	INCREASING URANIUM PRICE
– – – –	LOWER "	II	CONSTANT "



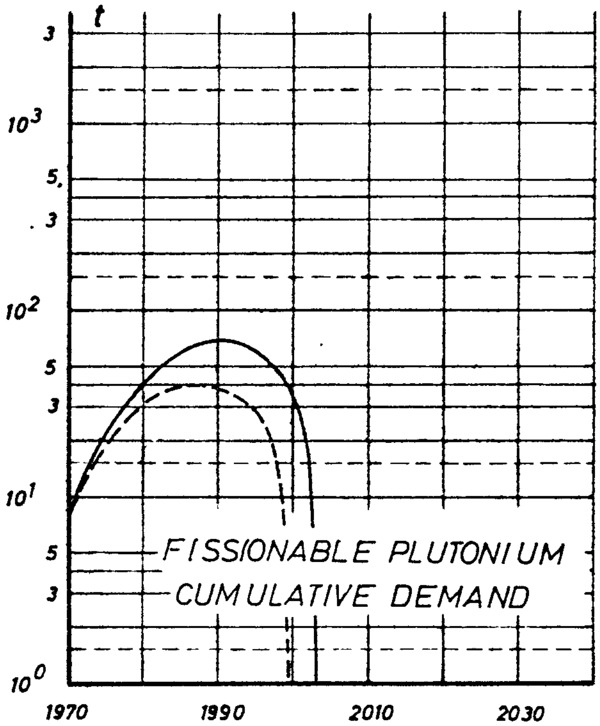


Na1-BR(KFK)

ONE TYPE STRATEGY

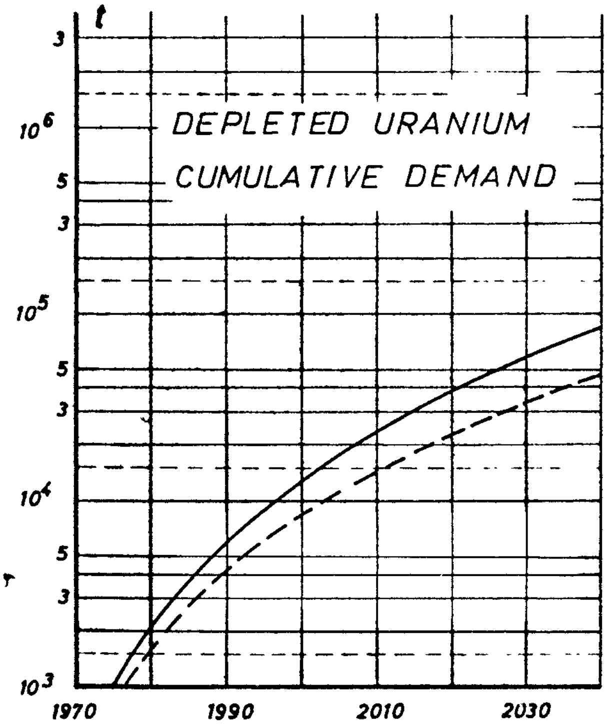


ANNUAL COST OF ENERGY GENERATION

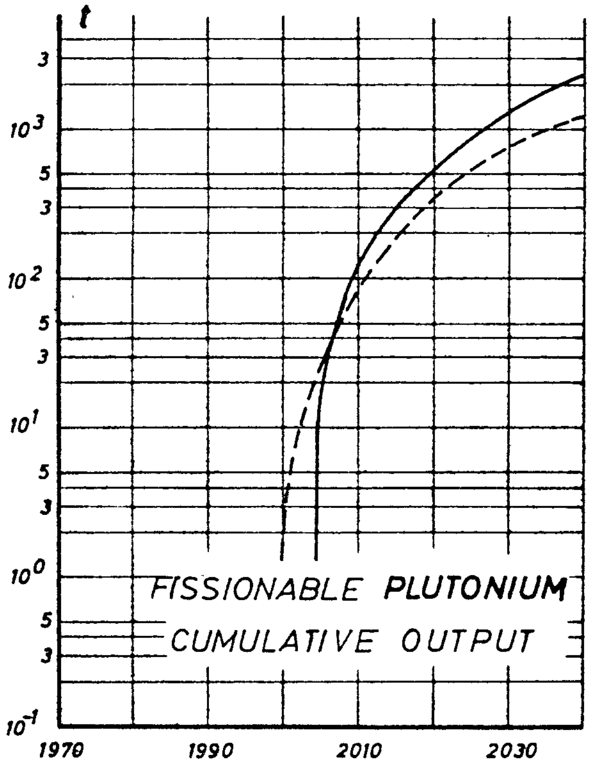


FISSIONABLE PLUTONIUM CUMULATIVE DEMAND

——— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE
– – – – LOWER " II CONSTANT "



DEPLETED URANIUM CUMULATIVE DEMAND



FISSIONABLE PLUTONIUM CUMULATIVE OUTPUT

6. Explanations Concerning the Two Type Strategies

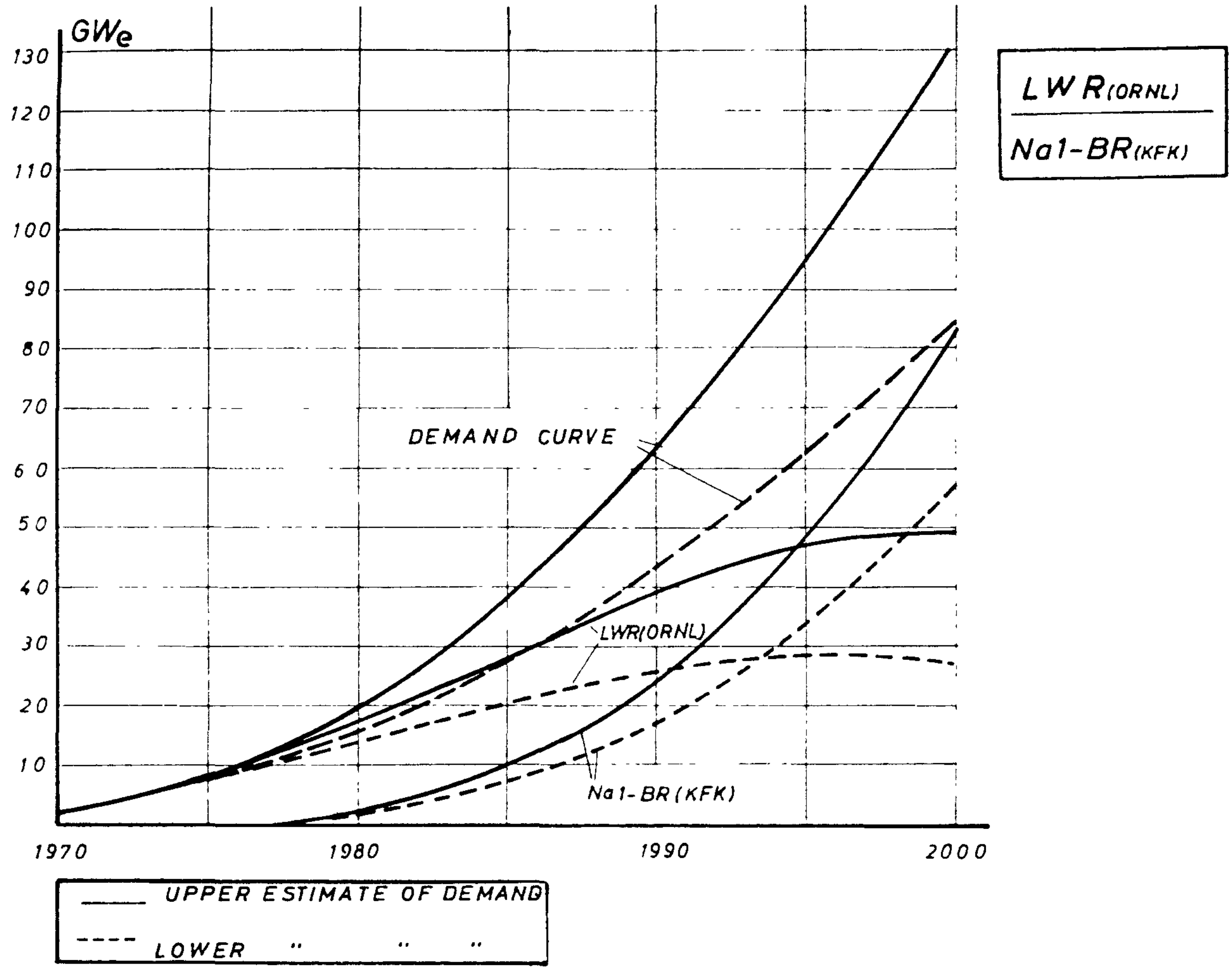
As was mentioned before, the growth of a breeder population may be coupled to a converter population. This is achieved by two conditions within the framework of the two type strategy. First new reactors will be added only according to the energy demand-curve. Secondly the newly added reactor will be a fast breeder, if enough plutonium from converters and fast breeders already in existence has accumulated. Here it has to be mentioned that to begin with 2 t of plutonium will be withdrawn from the system for experimental purposes. Using this method, the results for the four converters LWR (ORNL), LWR (SSW), D_2O (SSW), GG (CEA) combined each with the breeders Na-BR (GE) and Na-1 BR (KFK) were obtained. The curves show the respective shares of the nuclear power production. These allow one to compute the cost of power production as well as the demand for nuclear fuel.

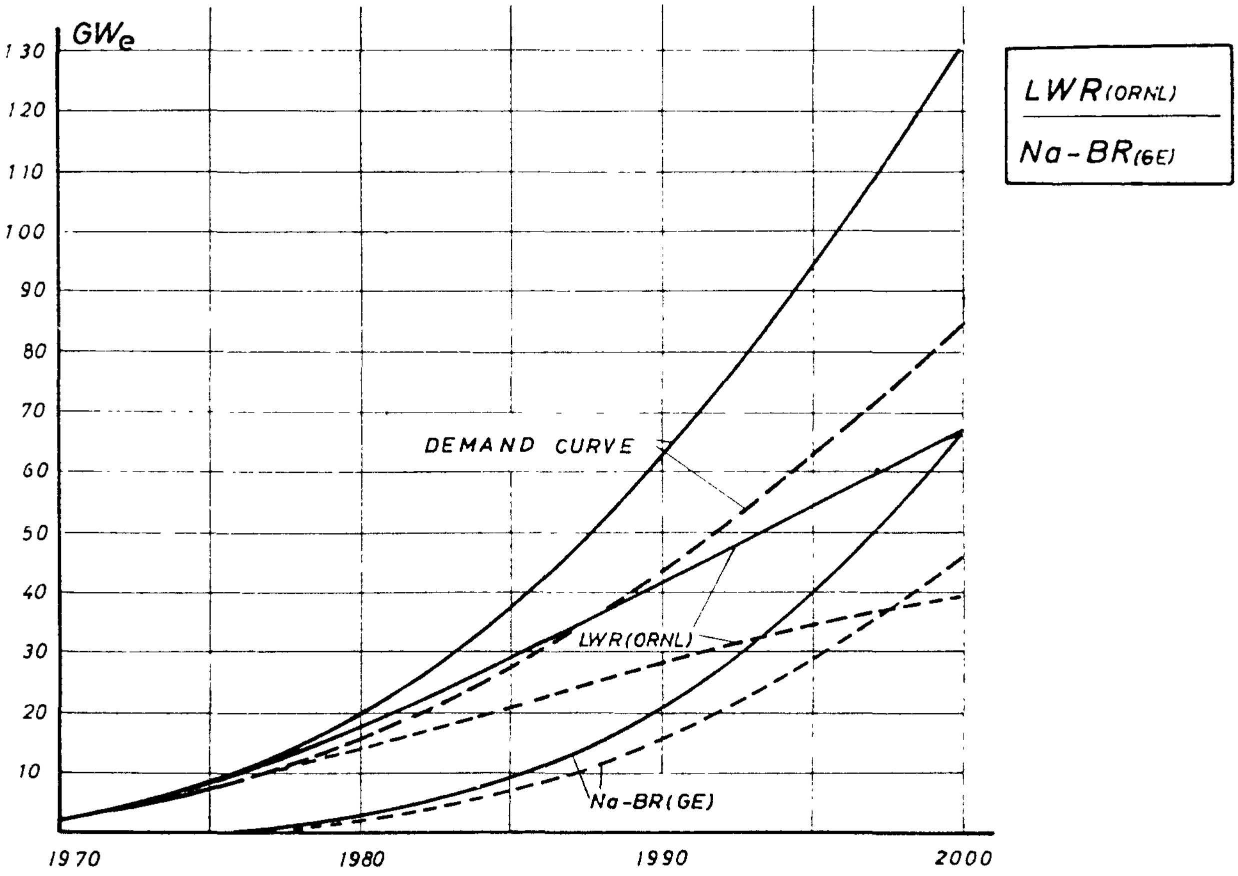
The results for each converter type are displayed in three consecutive graphs. The first one shows on top the combination with Na-1 BR (KFK), having a high breeding ratio (1.38) and for comparison on the bottom the combination with Na-BR (GE), having a lower breeding ratio (1.25). The dotted and full lines refer to the lower and upper estimates of the demand respectively. Because only 1ooo MWe plants are considered, the number of power stations in operation at a certain time may be found immediately. One curve refers to the breeder while the other refers to the converter. Both combined will result in the demand curve.

Each of the second graphs presents the annual cost of energy production for the two demand curves and the respective reactor combinations. These costs start branching from 1985 onwards and become higher for increasing uranium prices.

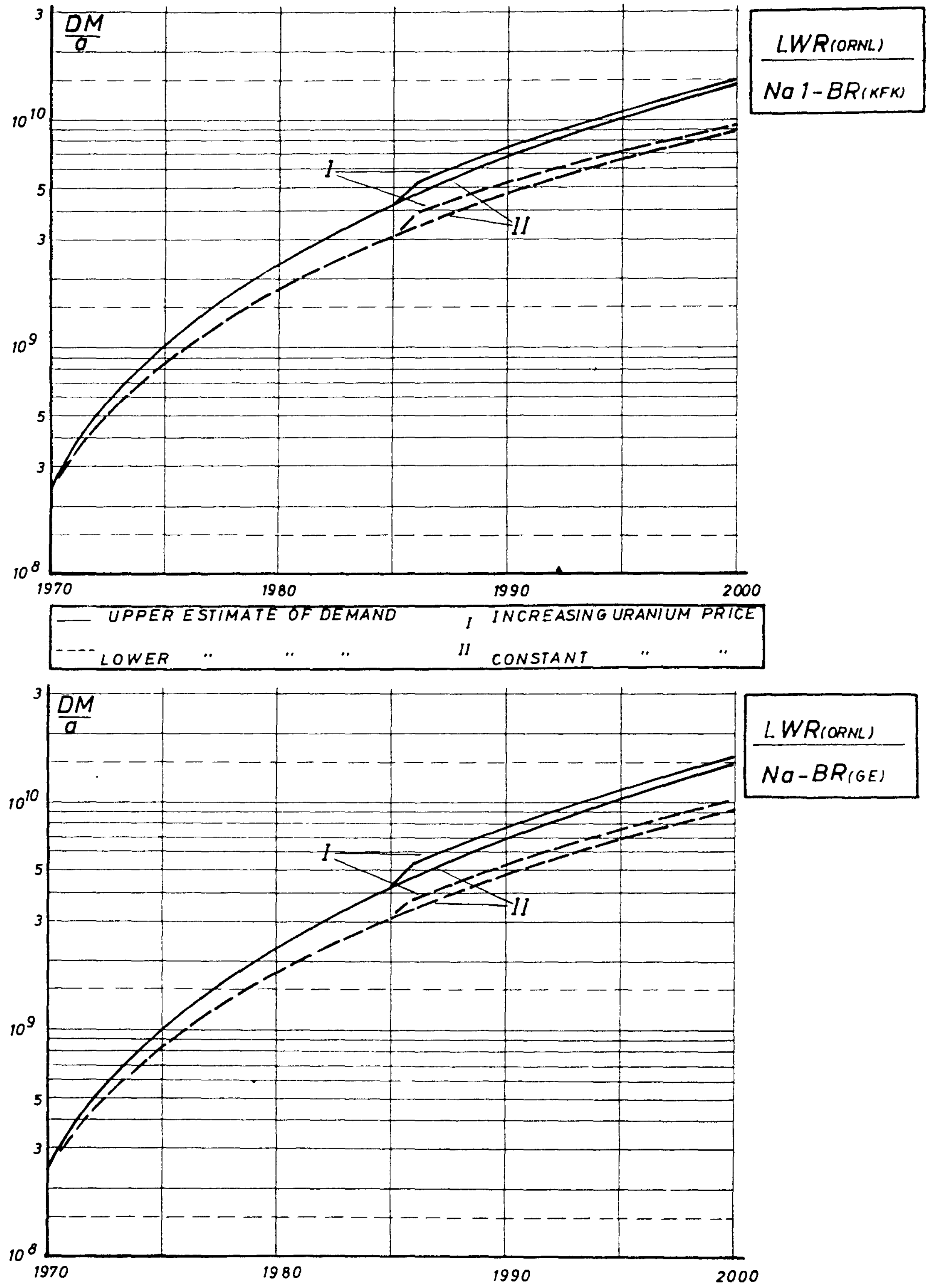
Each of the third graphs shows the consumption of natural uranium for a two type strategy as well as the amount of depleted uranium, taking the combination with Na-1-BR (KFK) as an example. The fact that the fast breeder will use some depleted uranium has been taken into account. In the case of combinations with the two light water reactors the demand curves branch, the lower one having resulted on account of the decreasing depletion level in the diffusion plant for increasing uranium prices.

SHARES OF NUKLEAR POWER INSTALLED FOR A COUPLED TWO TYPE STRATEGY





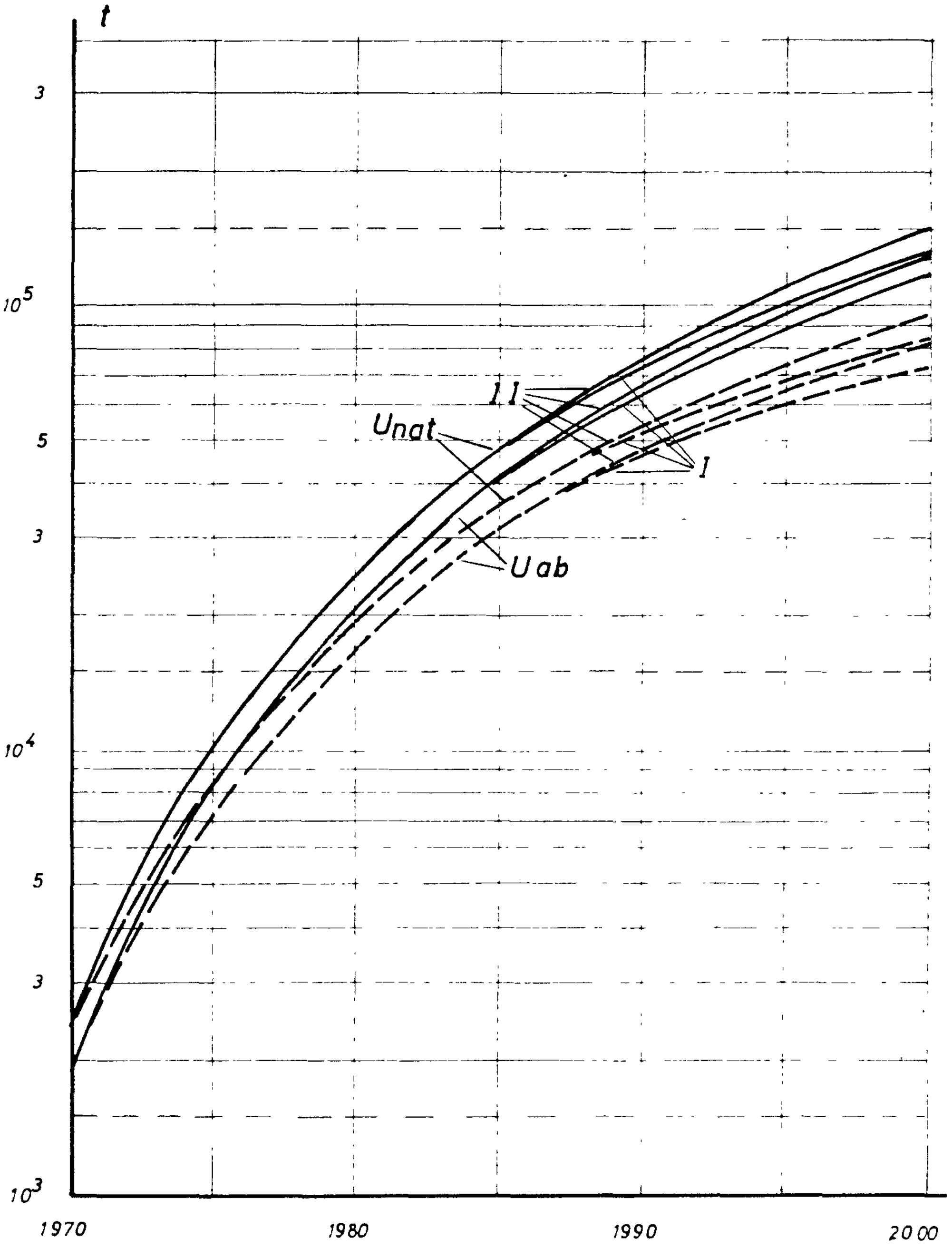
ANNUAL COST OF ENERGY GENERATION



NATURAL URANIUM, CUMULATIVE DEMAND
DEPLETED URANIUM, CUMULATIVE OUTPUT

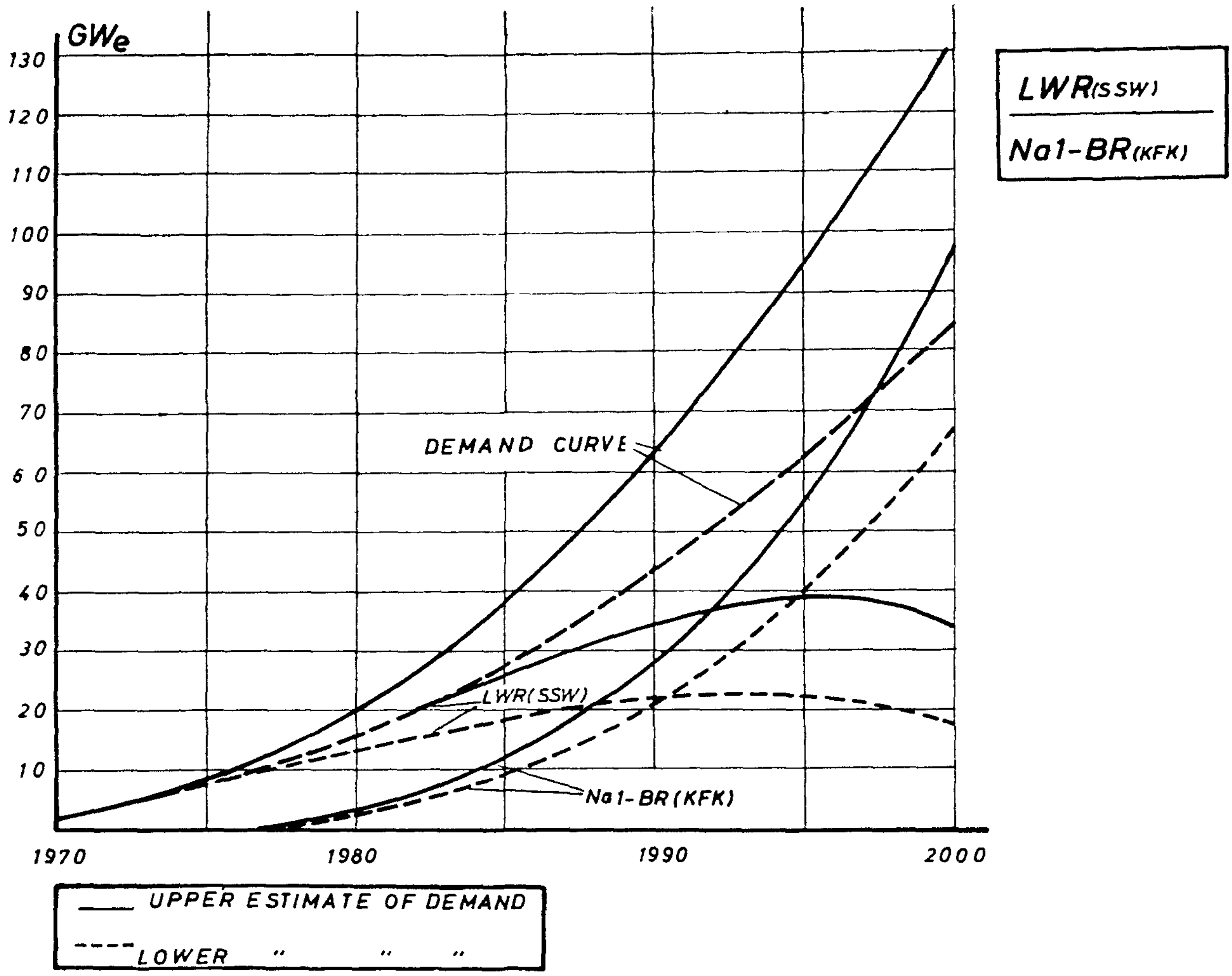
LWR(ORNL)

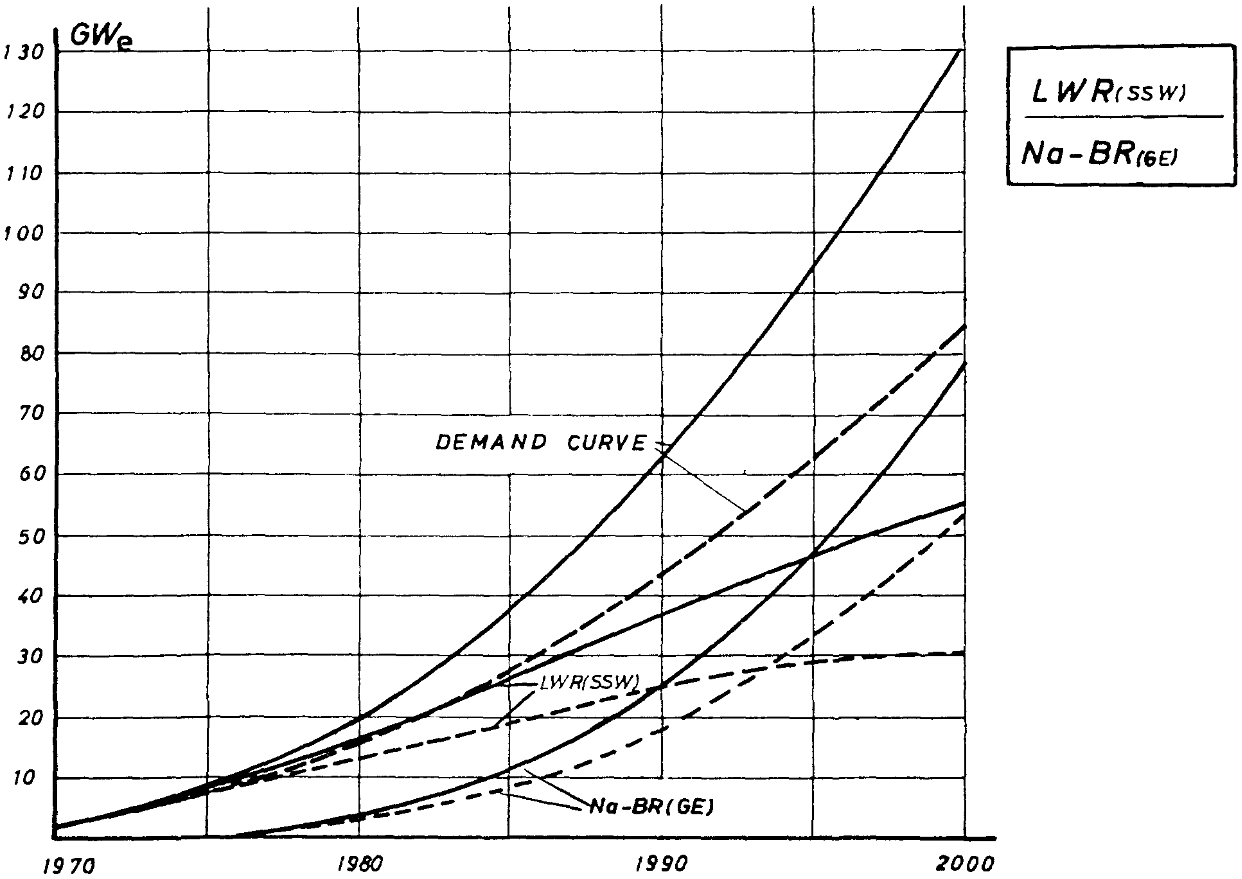
Na1-BR(KFK)



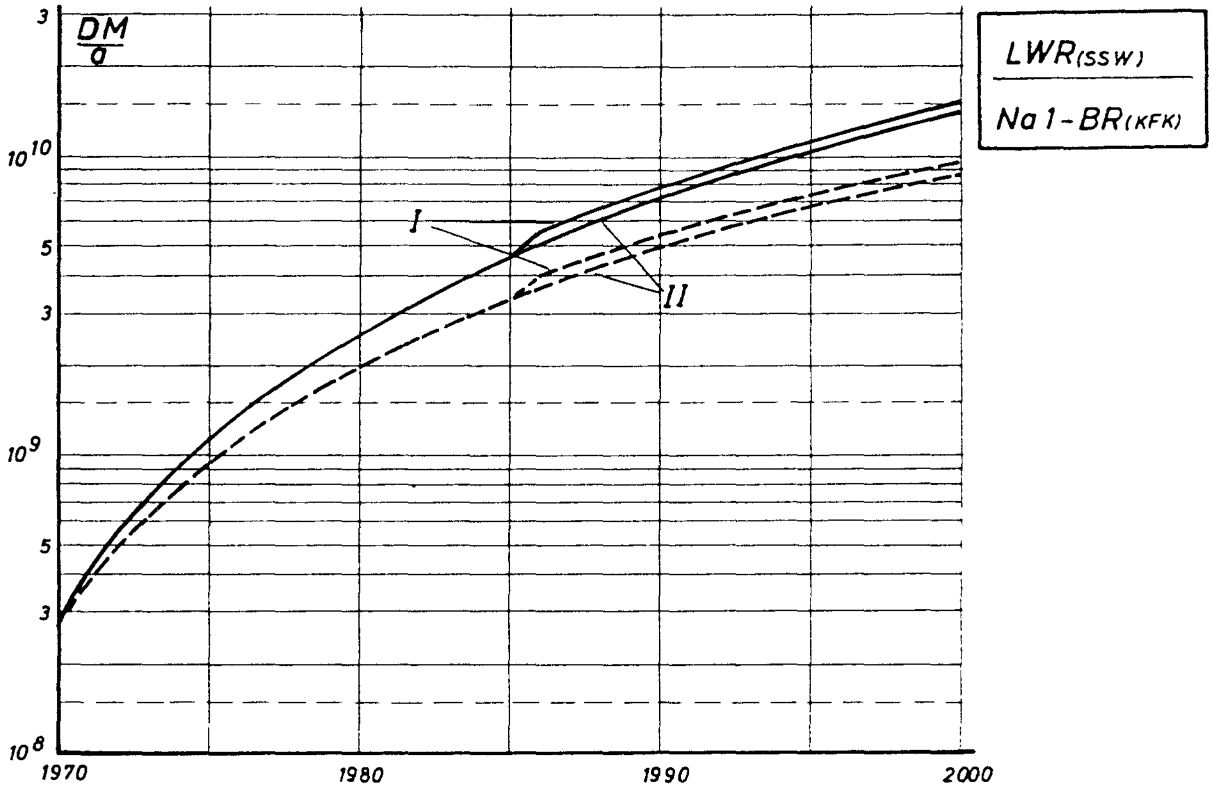
————	UPPER ESTIMATE OF DEMAND	I	INCREASING URANIUM PRICE
– – – – –	LOWER " " "	II	CONSTANT " "

SHARES OF NUKLEAR POWER INSTALLED FOR A COUPLED TWO TYPE STRATEGY



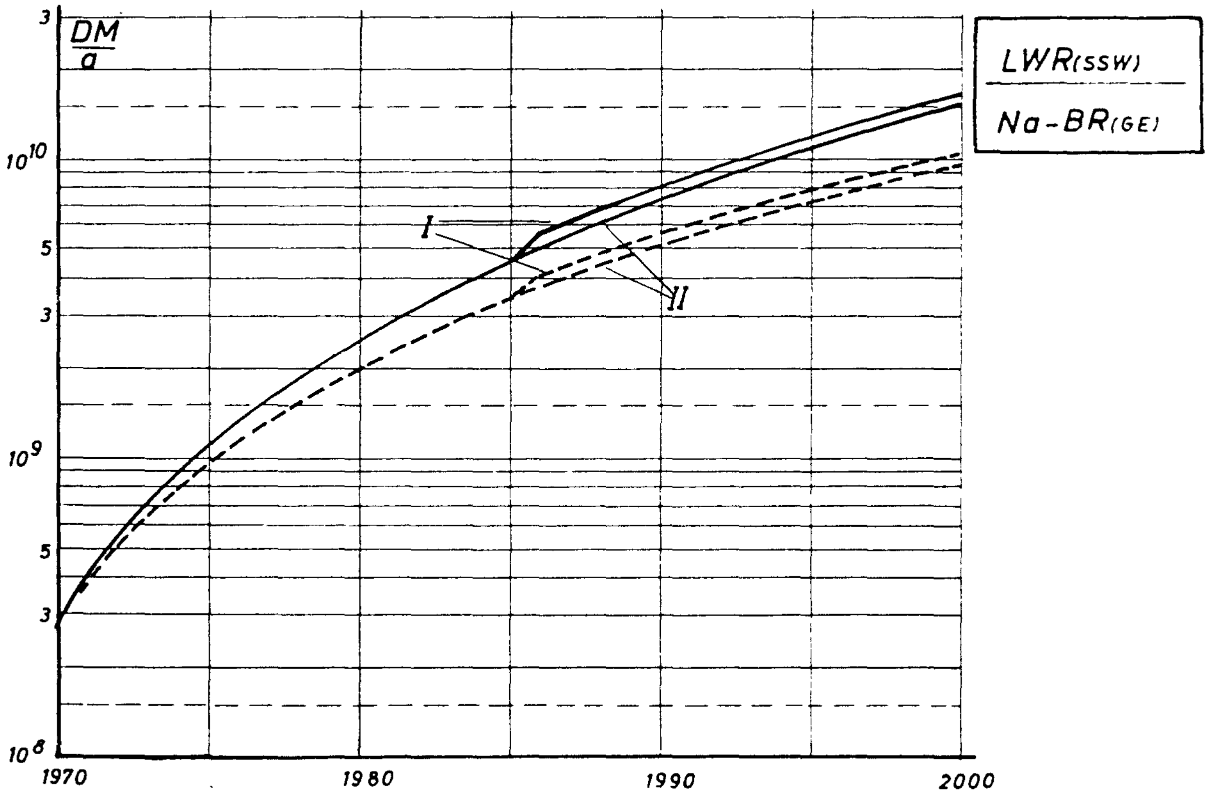


ANNUAL COST OF ENERGY GENERATION



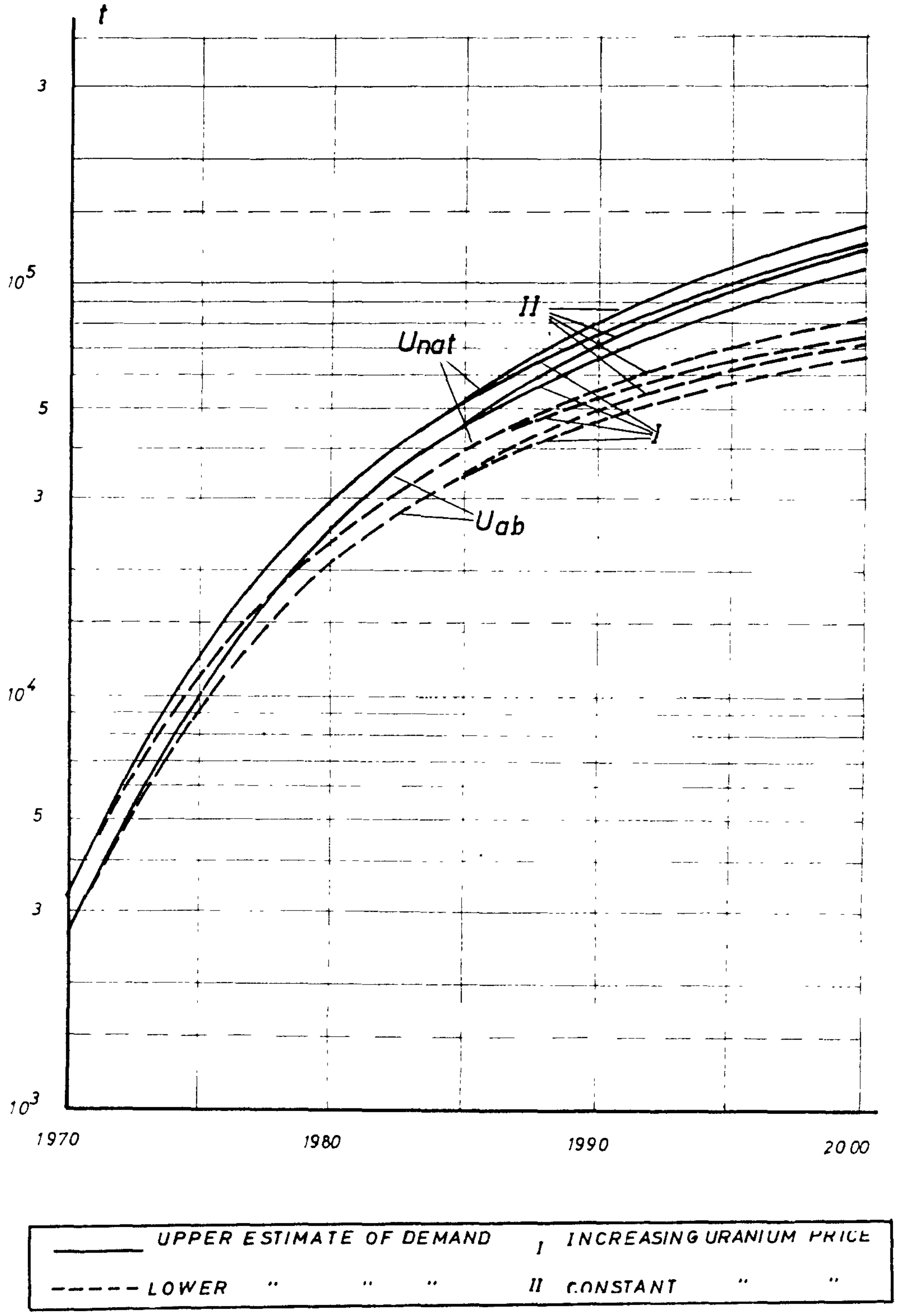
—— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE

---- LOWER " " " II CONSTANT " "

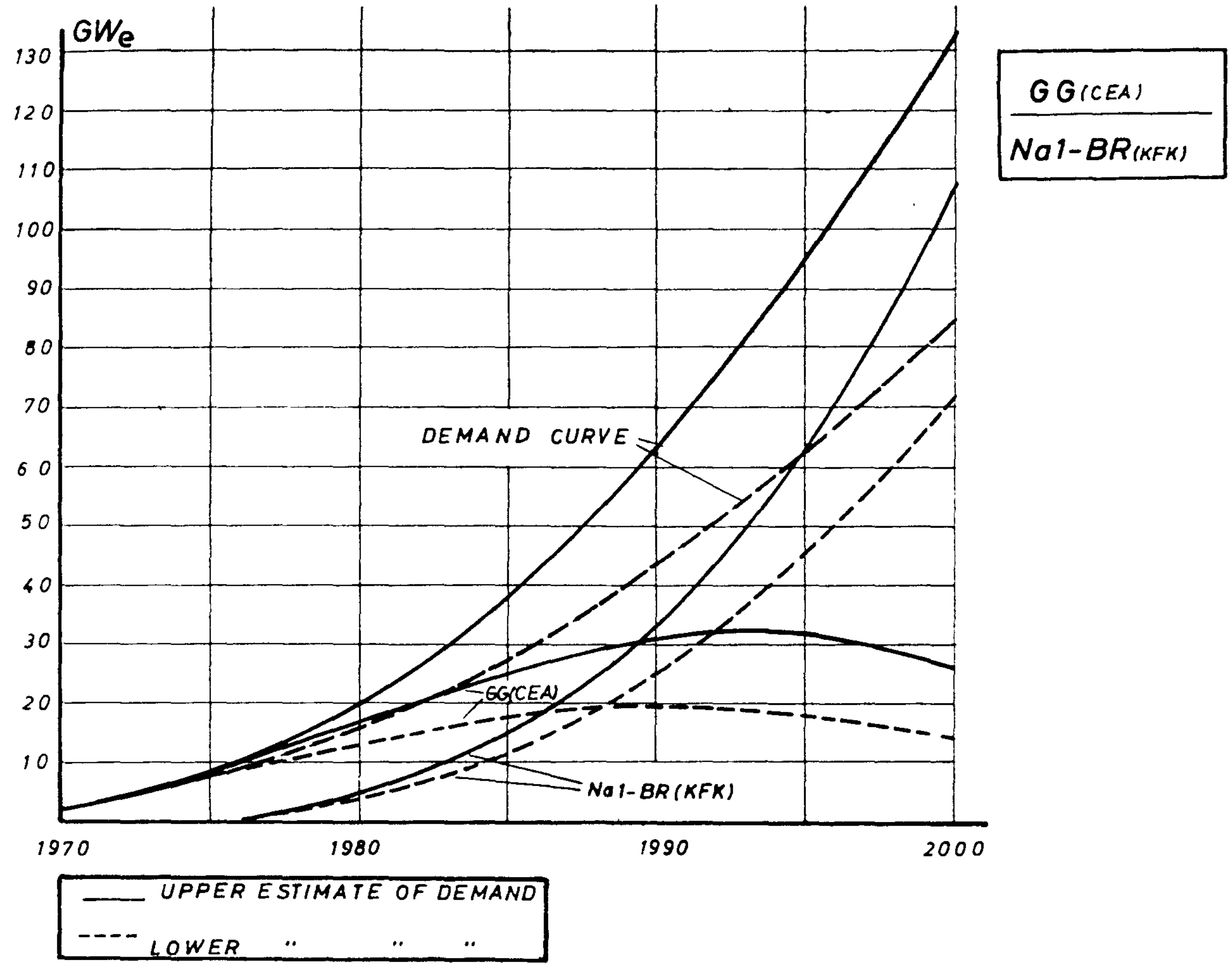


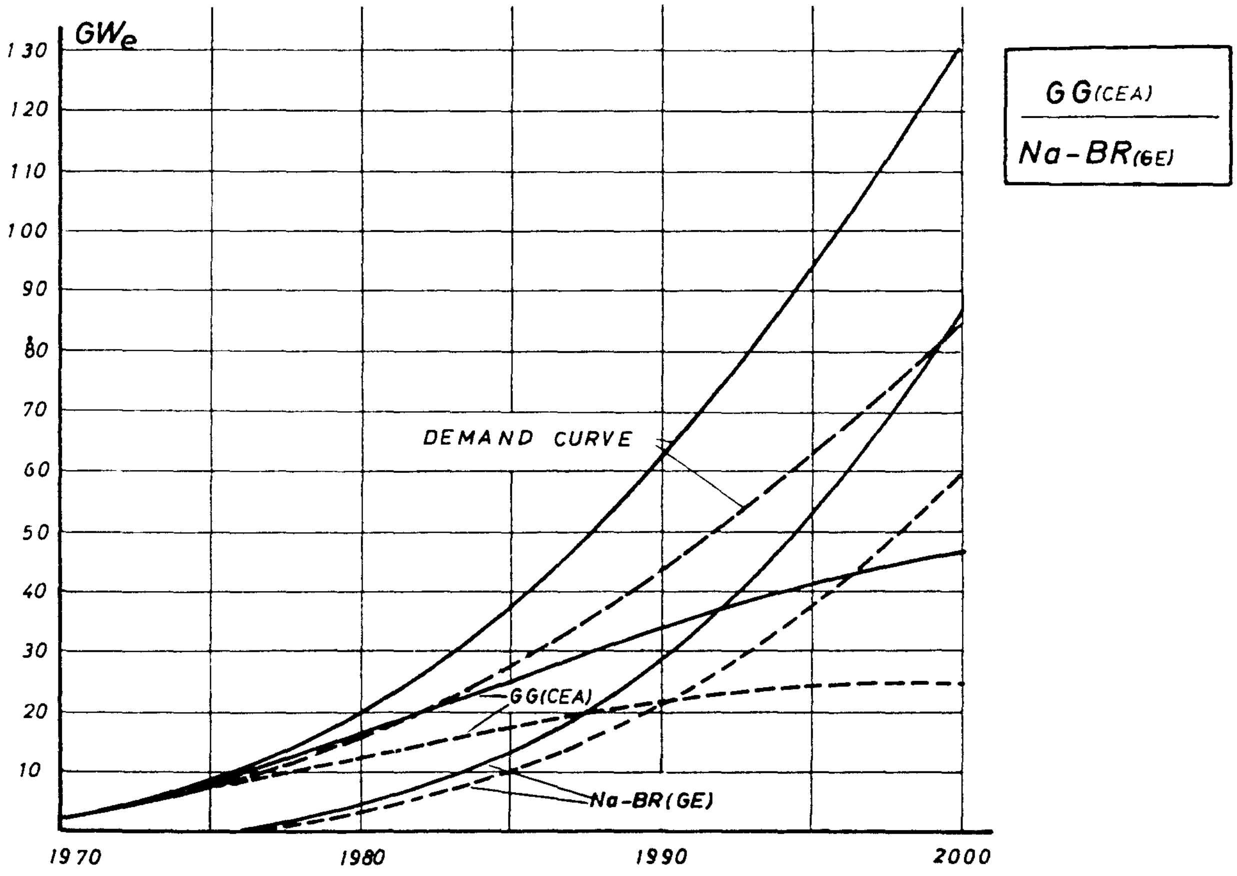
NATURAL URANIUM, CUMULATIVE DEMAND
DEPLETED URANIUM, CUMULATIVE OUTPUT

LWR(SSW)
Na1-BR(KFK)

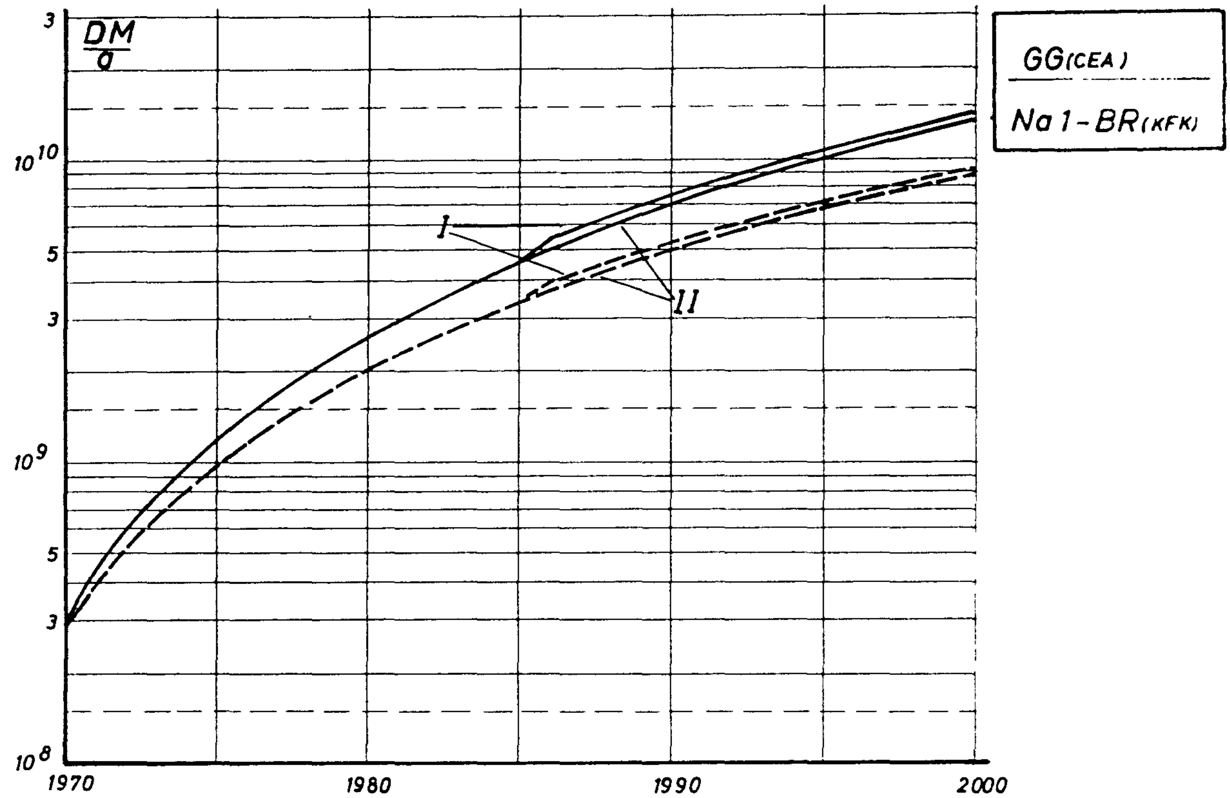


SHARES OF NUKLEAR POWER INSTALLED FOR A COUPLED TWO TYPE STRATEGY



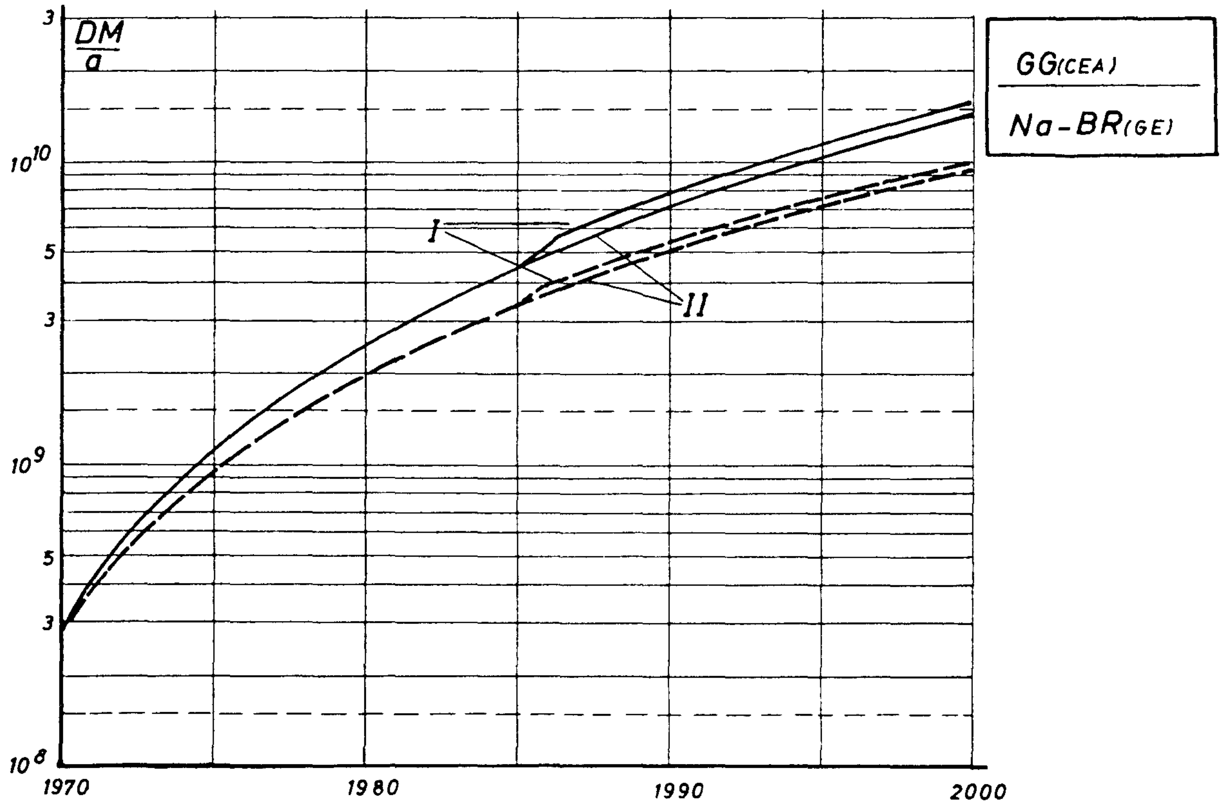


ANNUAL COST OF ENERGY GENERATION



—— UPPER ESTIMATE OF DEMAND I INCREASING URANIUM PRICE

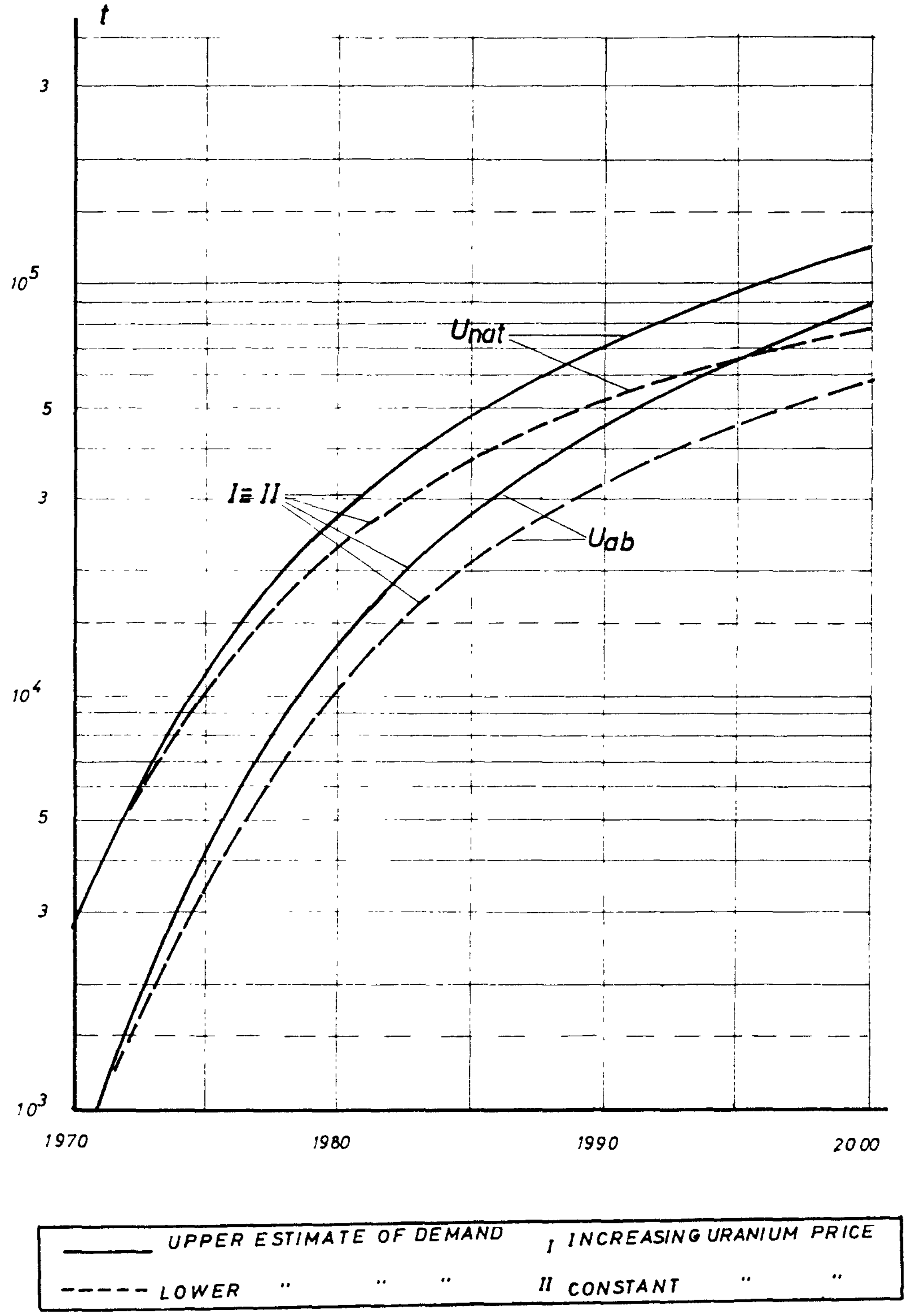
---- LOWER " " " II CONSTANT " "



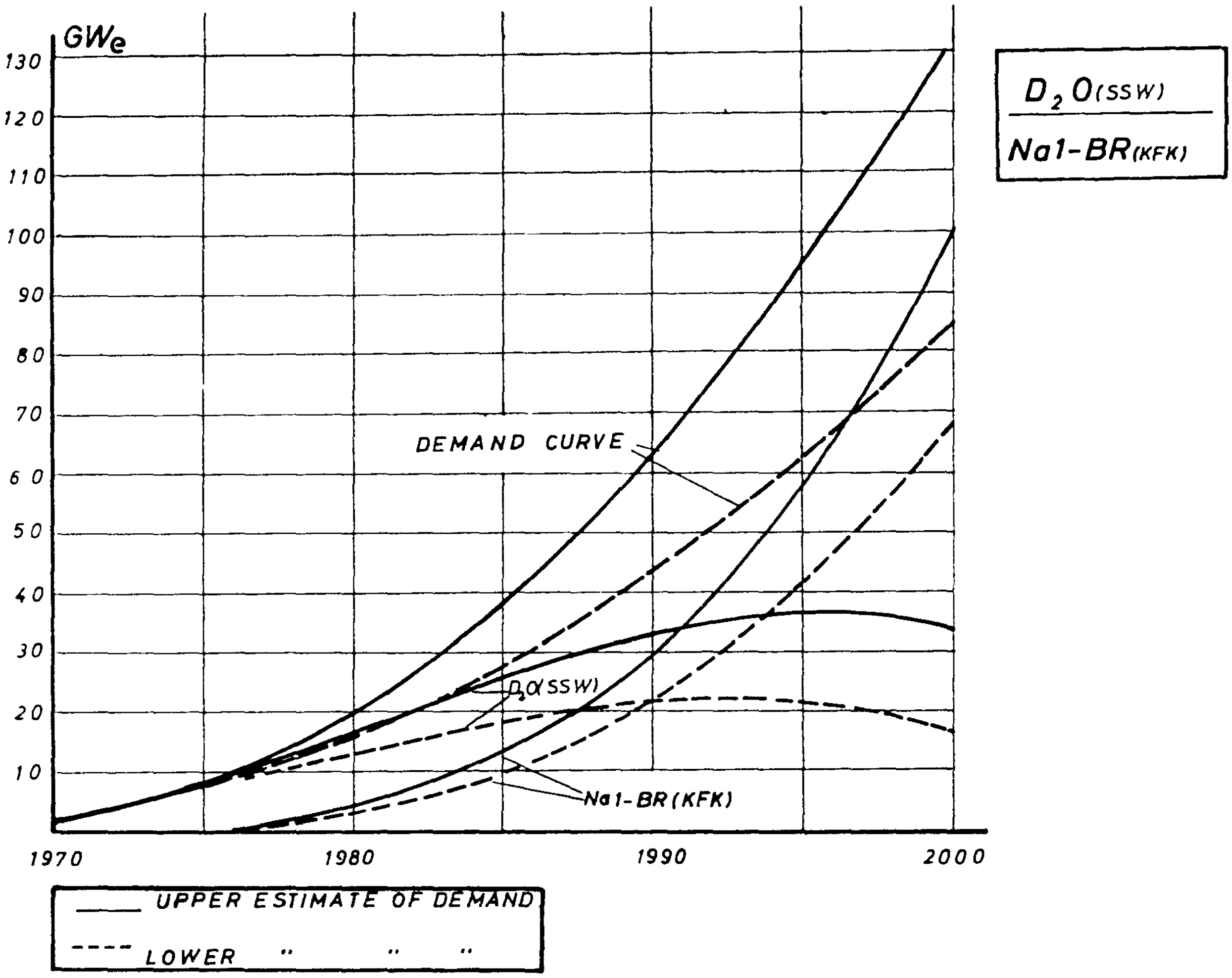
NATURAL URANIUM, CUMULATIVE DEMAND
DEPLETED URANIUM, CUMULATIVE OUTPUT

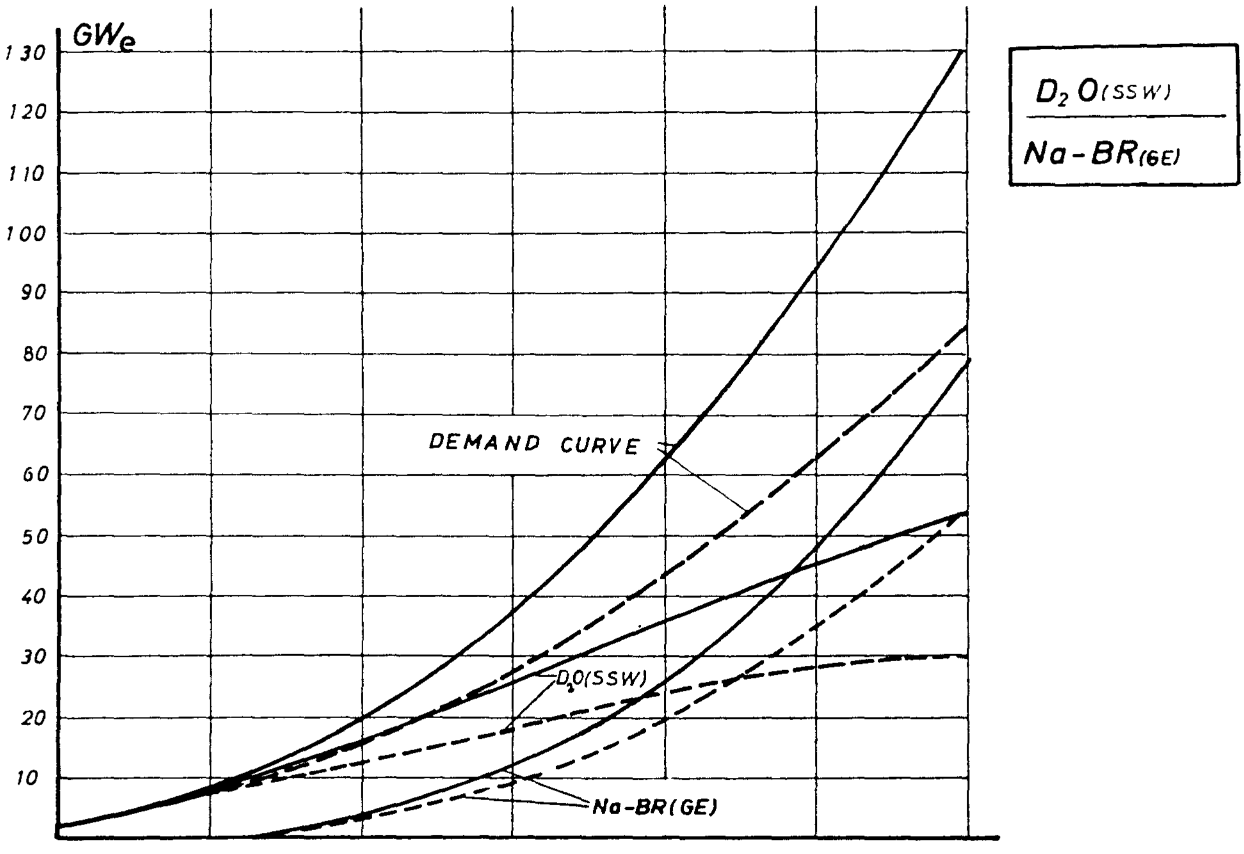
GG(CEA)

Na1-BR(KFK)

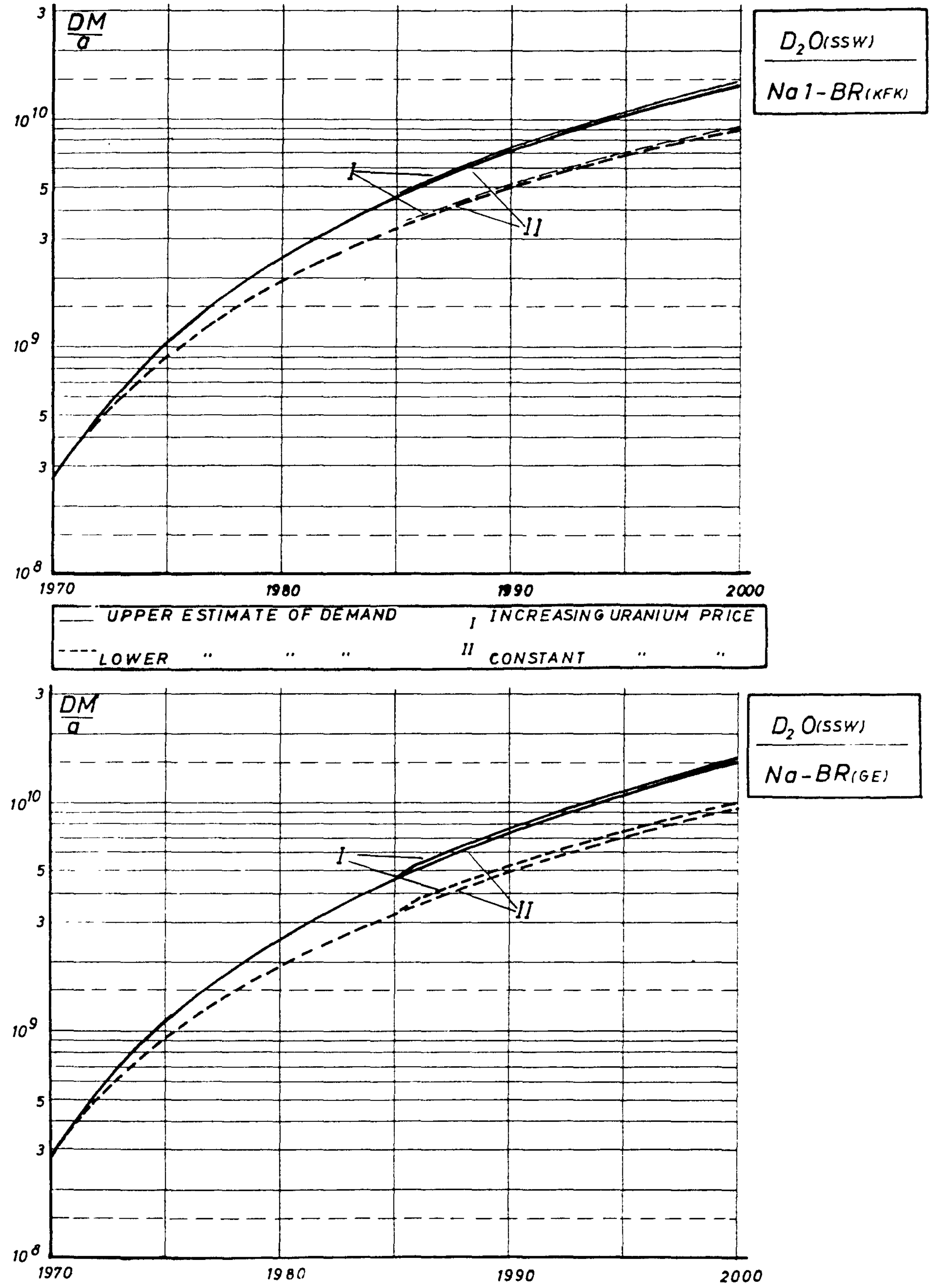


SHARES OF NUKLEAR POWER INSTALLED FOR A COUPLED TWO TYPE STRATEGY





ANNUAL COST OF ENERGY GENERATION

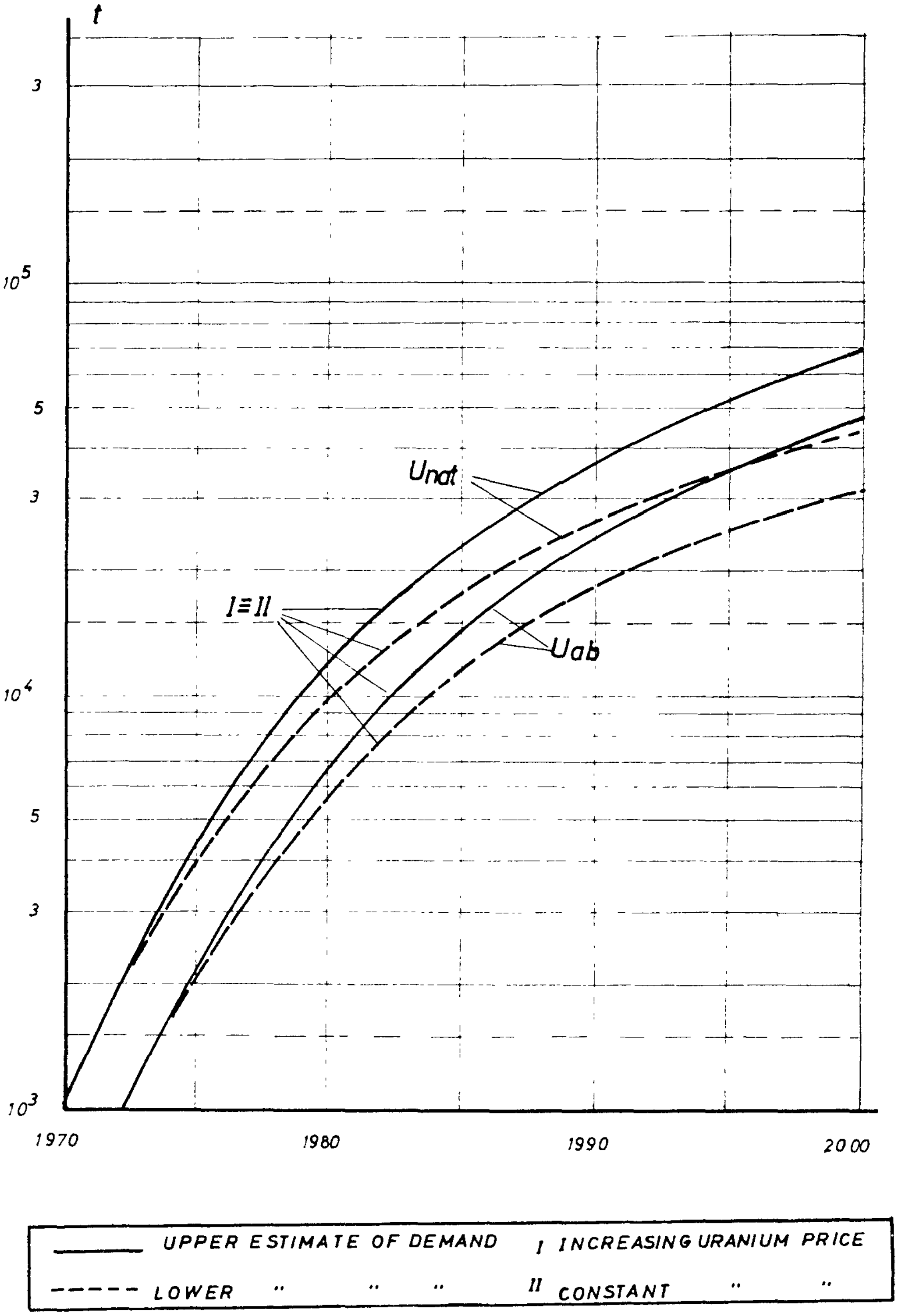


NATURAL URANIUM, CUMULATIVE DEMAND

DEPLETED URANIUM, CUMULATIVE OUTPUT

D_2O(SSW)

Na1-BR(KFK)



7. Explanations on Summarized Results

The subsequent pages and tables present important characteristic numbers that have been taken from the numerical evaluation of the one and two type strategies. Considering the limited resources of cheap natural uranium, the cumulative uranium consumption turns out to be the crucial quantity of a certain strategy. This consumption until the year 2000 is shown by the figures on page 46 for the one as well as the two type strategies, for the lower as well as the higher demand curves, and for the hypothesis I and II (concerning fuel cost). The figures on page 46 emphasizes the strongly reduced uranium consumption of the two type strategies by comparing the consumption of a converter generation with that of a combination of the same converters with Na-1 breeder, all data referring to the year 2040.

The annual cost of energy generation in the year 2000 form the second characteristic number for the different strategies and are presented on page 48.

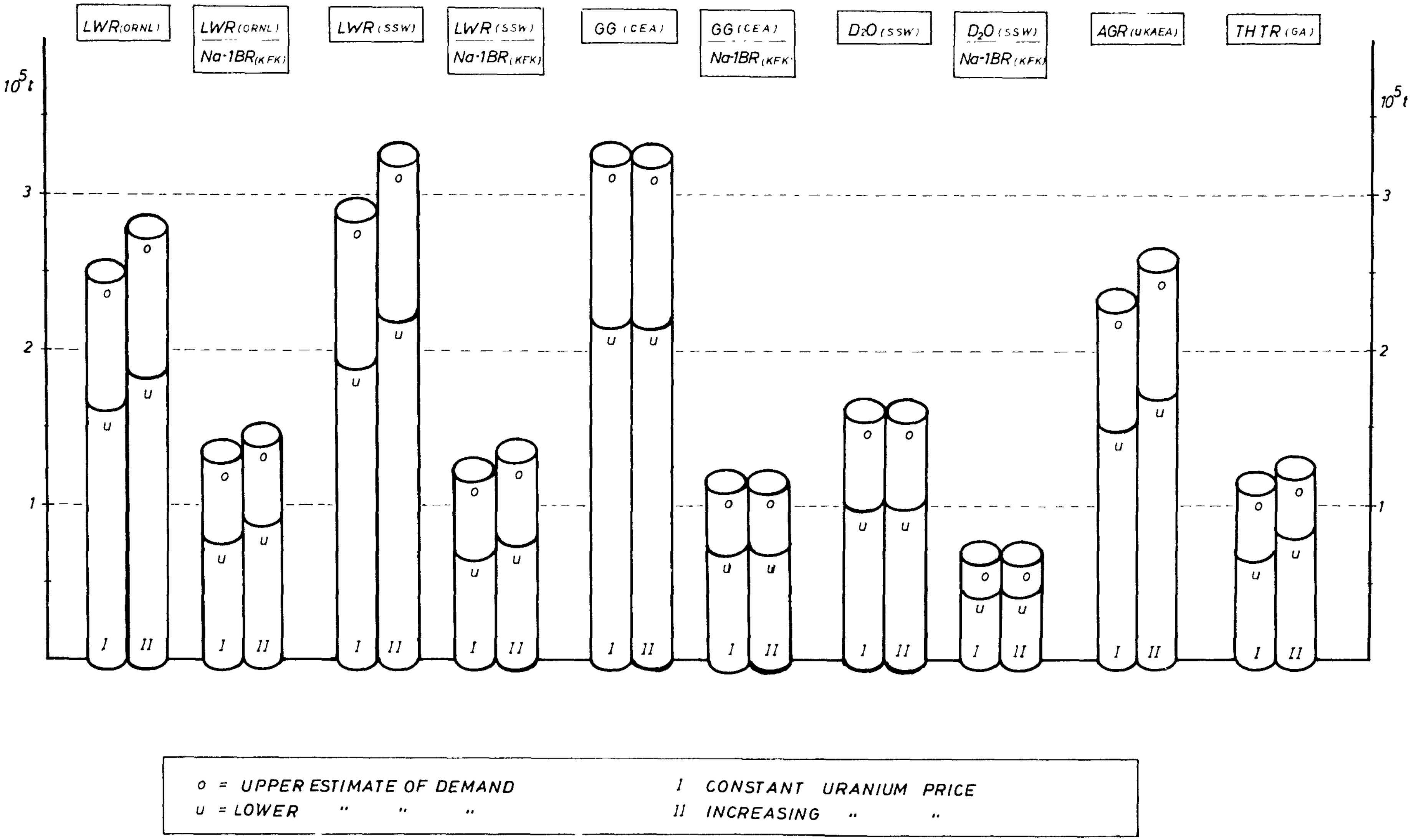
Finally, the present worth of the cost of the total energy generated from 1970 to 2000 constitutes a particularly characteristic number. It is presented in table 6 for different strategies in addition to the cumulative fuel demands and the annual cost.

Table 7 gives the annual cost of energy generation, investment cost, capital cost, operating cost, and fuel cost for different years referring to the examples LWR (ORNL) and LWR (ORNL)/Na-1 BR (KFK).

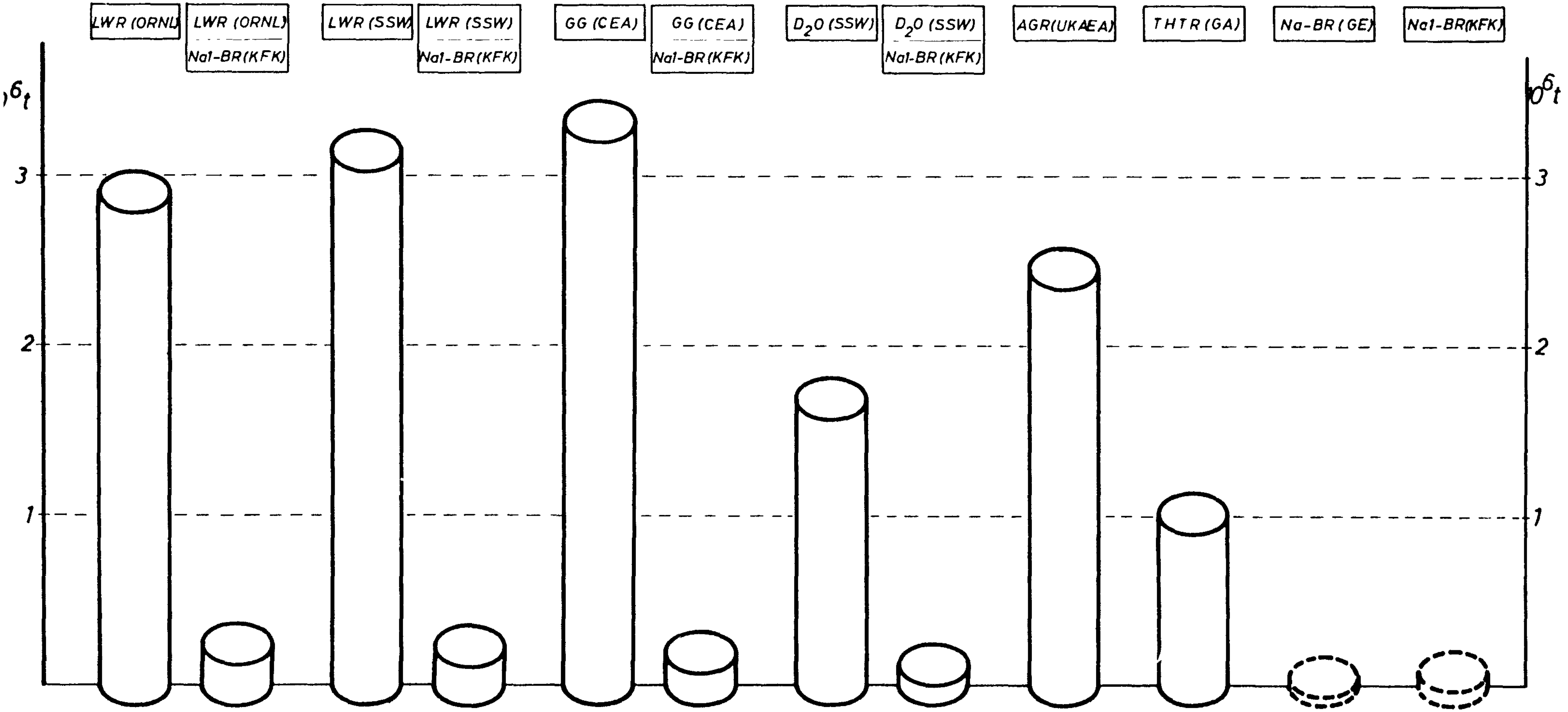
Table 8 repeats numerically the cumulative demand for natural uranium that has been presented already in the graphs on pages 46 and 47.

Table 9 gives an estimate of the annual flow rate through the reprocessing plants. This enables one to recognize the dependence of the amount to be reprocessed on the different one and two type strategies for the years 1975, 1980, 1990, and 2000.

CUMULATIVE DEMAND FOR NATURAL URANIUM FOR A ONE AND TWO TYPE STRATEGY UNTILL THE YEAR 2000



CUMULATIVE DEMAND FOR NATURAL URANIUM UNTIL 2040 FOR ONE AND TWO TYPE STRATEGIES USING CONSTANT URANIUM COST AND THE UPPER ESTIMATE OF DEMAND



ANNUAL COST OF ENERGYGENERATIONFORTHE YEAR 2000 FOR A ONE AND TWO TYPE STRATEGY

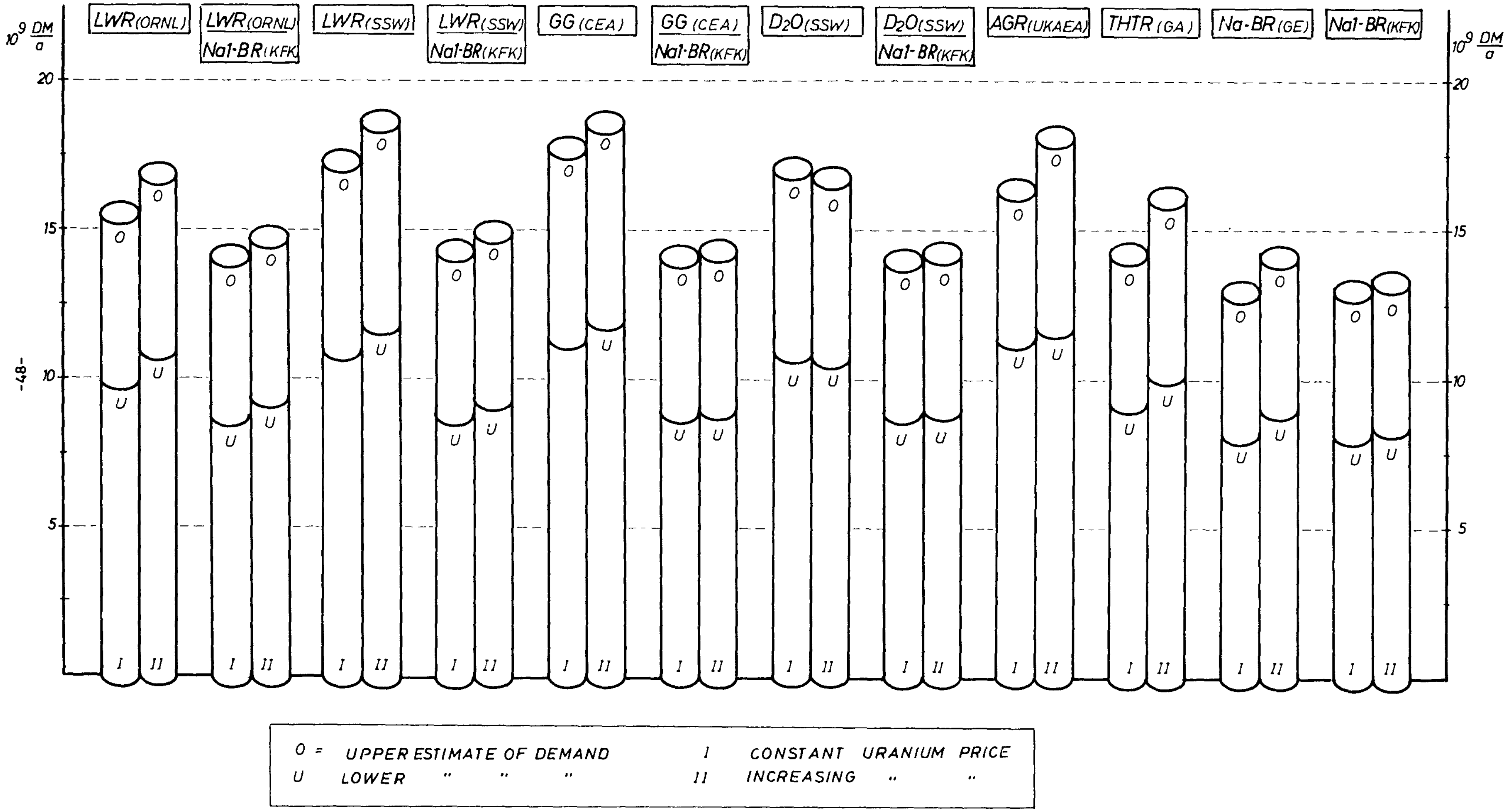


Tabelle 6

COMPARISON OF ONE-AND TWO TYPE STRATEGIES FOR THE YEAR 2000

(INCREASING URANIUM COST, UPPER ESTIMATE OF DEMAND)

			LWR (ORNL)	LWR (SSW)	GG (CEA)	D_2O (SSW)	AGR (UKAEA)	THTR (GA)	Na-BR (GE)	Na1-BR (KFK)
ONE TYPE STRAT	CUM. DEMAND FOR NAT. URANIUM	1000 t	248	290	327	168	232	114	8.1	13.3
	PLUTONIUMPRODUKTION (DEMAND FOR THORIUM)	t	227	298	377	310	132	(14900)	- 193	- 37.5
	ANNUAL COST	$\frac{GDM}{a}$	16.92	18.72	18.68	16.79	18.20	16.15	14.26	13.53
	PRESENT WERTH	GDM	44.09	48.84	49.29	45.20	47.16	41.96	37.22	35.60
TWO TYPE STRATEGIES WITH Na1-BR(KFK)	CUM. DEMAND FOR NAT. URANIUM	1000 t	133	123	117	69				
	ANNUAL COST	$\frac{GDM}{a}$	14.74	14.86	14.43	14.28				
	PRESENT WERTH	GDM	41.01	43.23	42.85	41.25				
TWO TYPE STRATEGIES WITH Na-BR(GE)	CUM. DEMAND FOR NAT. URANIUM	1000 t	146	140	144	76				
	ANNUAL COST	$\frac{GDM}{a}$	15.66	16.18	15.88	15.34				
	PRESENT WERTH	GDM	42.07	44.69	44.52	42.49				

TABLE 7

ANNUAL COST

(IN BILLION DM)

YEAR	TOTAL COST OF ENERGYGENERATION		INVESTMENT COST		CAPITAL COST		OPERATION COST		FUEL COST	
	1	2	1	2	1	2	1	2	1	2
1970	0,24	0.24	–	–	0.13	0.13	0.014	0.014	0.095	0.095
1975	1.0	1.0	0.95	0.95	0.52	0.52	0.063	0.063	0.39	0.39
1980	2.3	2.3	1.55	1.6	1.25	1.28	0.19	0.18	0.90	0.80
1990	8.0	6.4	2.6	2.8	3.9	4.1	0,46	0.47	3.6	1,9
2000	17	15	4.6	4.9	8.3	9.0	0.97	1.0	7.7	5,0

1 FOR THE ONE TYPE STRATEGY WITH LWR (ORNL)

2 FOR THE TWO TYPE STRATEGY WITH LWR (ORNL)/Na1-BR (KFK)

(CAPITAL-, OPERATION- AND FUEL COST SUMMED UP RESULT IN COST OF ENERGYGENERATION SHOWN IN THE 1^{st} COLUMN)

TABLE 8

ESTIMATE OF THE MAXIMUM CUMULATIVE DEMAND FOR NATURAL URANIUM FOR THE FEDERAL REPUBLIC OF GERMANY USING ONE AND TWO TYPE STRATEGIES UNTIL THE YEAR 2000 RESP. 2040.

(IN 1000 t NATURAL URANIUM)

	ALONE		WITH NA-1 BREEDER (KFK) BREEDINGRATIO 1.38		WITH NA-BREEDER(GE BREEDINGRATIO 1.25	
	2000	2040	2000	2040	2000	2040
LWR (ORNL)	248	2200	133	220	146	650
LWR (SSW)	290	2500	123	210	140	470
GG (CEA)	327	3200	117	160	144	375
D_2O (SSW)	168	1700	69	109	76	235
AGR (UKAEA)	232	2050				
THTR (GA)	114	800				
Na-BR (GE)	8.1	57				
Na1-BR (KFK)	13.3	87				

TABLE 9

FLOWRATE THROUGH THE REPROCESSINGPLANTS IN THE FEDERAL REPUBLIC OF GERMANY (t / a)

	1975		1980		1990		2000	
	1	2	1	2	1	2	1	2
LWR (ORNL)	252	252	656	648	2171	1945	4772	4038
LWR (SSW)	212	212	552	521	1828	1664	4017	3724
GG (CEA)	1018	1018	2652	2319	8777	5375	19300	7690
D_2O (SSW)	548	548	1430	1287	4727	3321	10390	5813
Na1-BR (KFK)	176	–	457	–	1512	–	3322	–

1 ONE TYPE STRATEGIES

2 TWO TYPE STRATEGIES WITH FAST BREEDER Na-1BR (KFK)

8. Discussion of Results

The results as given in the last three chapters represent the actual outcome of the studies of the "Studienkreis Kernenergiereserven". A discussion of this wealth of results some of which are rather complex in nature may contribute a certain amount of subjective bias to the interpretations. Accordingly, the discussion of the results merely represents the opinion of the authors of this study who have been mentioned by name.

It will be useful first to consider the demand for nuclear energy (equation 1). The curve referring to the maximum demand is increasing with the 2.34th power of the time, i.e. does not increase exponentially. One rather finds a linear increase with time of the doubling time for nuclear energy (equation 2). In 1986 already, this doubling time reaches the value of 7.5 years. Following the maximum estimate, in 1980 one expects a demand for 20 GW_e and in 2000 for 132 GW_e of nuclear generation capacity. The respective values for the minimum estimate are 15 GW_e and 85 GW_e. These estimates are in good agreement with corresponding one done for instance by EURATOM and France. The graph on page 10 shows a comparison of this information from different sources. In addition, the doubling time of the curve for the German energy demand has also been given.

Now turning to the results of the one and two type strategies, one has to point to a remarkable fact: the original cost data as given in the data blocks for different reactors (cf. table 5) are very close to each other. This implies that the energy costs calculated from these data will also be very similar to each other.

The French gas-graphite reactor, for instance, shows energy cost higher by about 15 $^{o}/o$ and investment cost higher by about 30 $^{o}/o$ only as compared to the LWR (ORNL), while an analoguous comparison with the respective British data leads to a larger difference. As has been mentioned before, however, it was not the task of this study group to evaluate and weigh the input data.

We now turn to the cost of one type strategies. If we limit ourselves to the near future, the results of the one type strategies are characteristic because the two type strategies show that it will be a considerable time before the breeders will take over a larger percentage of nuclear energy generation. Because the cost are rather similar, it is not of much interest to give exact numbers but to indicate the order of magnitude and approximate date, when these costs will occur. In 1975 the annual cost of energy, that are composed of capital charges, operation and fuel costs, will reach the amount of about 1 billion DM annually. In 1977, the investment cost alone will reach 1 billion DM per year, while in 1979 the capital charges related to the investment cost will amount to 1 billion DM (cf. table 7).

Now turning to the cost of two type strategies we find that the difference in annual cost of energy production accumulated until 1984 to amount to 1 billion DM, between the one type strategy LWR (ORNL) and two type strategy LWR (ORNL)/Na-1 BR (KFK). It is useful to keep these figures in mind, as at present the development cost for a line of reactors are occasionally discussed to amount to 1/2 to 1 billion DM.

The question concerning the cumulative amount of fissionable plutonium represents another important point. Up to 197o, one expects about 5oo kg totally. In 198o 1o to 2o t of plutonium will be available in the Federal Republic. This implies that the technology of plutonium and of chemical reprocessing have to be mastered within the next years. It also means that in contrast to the U-233-thorium cycle these amounts of plutonium by means of their mere existence will enforce a continuation of the intensive study of the plutonium-U-238 cycle. This is internally connected to the fact stressed here emphatically that the consumption of natural uranium occurring for one type strategies leads to the build-up of almost equal amounts of depleted uranium.

The LWR (ORNL) strategy for example by the year 2000 will lead to a cumulative demand for natural uranium of about $250 \cdot 10^3$ t while the build-up of depleted uranium will amount to about $230 \cdot 10^3$ t. Both of these substances, the accumulated plutonium as well as the accumulated depleted uranium, enforce a further study of the plutonium-U-238 cycle.

It may be reasonable to add some remarks referring to the THTR reactor in particular. As the mass balances show, by the year 2000 for instance a demand for natural uranium of $114 \cdot 10^3$ t will exist, being accompanied by a demand for thorium of $14.9 \cdot 10^3$ t only, i.e. 13 °/o of the former. So long as the THTR does not breed truly, it rather represents a reactor with uranium-235 cycle, that has a relatively small consumption of natural uranium as compared to one type strategies. The high degree of uranium enrichment in the THTR leads to energy cost higher than those of the fast breeder reactors even though the investment cost in the data block for this study are shown to be smaller as compared to those for fast breeders. In this context we again want to point to the fact that in compiling the data block for the THTR reactor the value of the U-233 circulating in the fuel cycle of the THTR reactor was taken as zero.

Only a short discussion on the time dependence of the uranium price would suffice. If the price of uranium concentrate (and being connected with this, the price of plutonium) will rise from 8 to 30 $/lb the specific energy cost will change by about 3 °/o for the Na- fast breeder, by about 8 °/o for the D_2O reactor, by about 20 °/o for the LWR (ORNL), and by about 25 °/o for the AGR and the LWR (SSW).

Finally we want to discuss the problem concerning the consumption of the uranium resources that forms the basic question of this study. In doing so, we will use the results of one type strategies as well as two type strategies. We have to realize first, that according to the considerations of the third chapter there will be about 10^5 t of uranium ore available until the year 2ooo. If we are willing to consider the third category of ore, being distinctly more expensive, we gain additional 10^5 t, resulting in a total of 2oo,ooo t of ore available. We will call these resources the resources of class 1. Considering the uncertainty of prospection and taking into account the opinion of many experts, one may figure there are possibly 2oo,ooo more tons available on a relatively high price level for Germany (Federal Republic). These resources, only possibly available, shall be called the resources of class 2. The resources of classes 1 and 2 combined therefore amount to about 4oo,ooo t. Let us now consider the magnitude of the cumulative demand for natural uranium first for the one type strategies up to the year 2ooo. The THTR needing $114 \cdot 10^3$ t and the D_2O reactor needing $168 \cdot 10^3$ t stay within the limits of class 1 resources (cf. page 49).

All the other reactor types, however, have to add some of the class 2 resources, beginning with $232 \cdot 10^3$ t needed for the AGR reactor up to $327 \cdot 10^3$ t needed for the gas-graphite reactor. We have not included the breeders in this comparison of one type strategies because they are not able to start on their own. To summarize one may state that until the year 2ooo the uranium consumption of the one type strategies is high for some particular types, but is not prohibitive. The uranium consumption of the two type strategies, on the other hand, amounts to smaller values, but not much smaller ones because up to 1985 to 199o each two type strategy is very similar to the corresponding one type strategy and the same applies to the respective uranium consumptions. The uranium consumption of the two type strategies lies between $69 \cdot 10^3$ t for D_2O/Na-1 and $133 \cdot 10^3$ t for LWR (ORNL)/Na-1, i.e. clearly stays within the limits set by class 1.

The demand in 2o4o (cf. page 51) on the contrary looks qualitatively rather different. Each one type strategy implies a demand for natural uranium ore that clearly exceeds the amounts supplied by classes 1 and 2. The demand amounts to between $17oo \cdot 10^3$ t (D_2O)

and 3200 · 10^3 t (gas-graphite). As far as we can presently judge such a demand for natural uranium is prohibitive, even if one takes into account the uncertainties of the prediction. Thus, it is not possible in the long run to satisfy the demand for nuclear energy using merely a converter reactor type.

There are two solutions to this problem. Either one starts to extract uranium out of the seawater or one introduces breeder reactors.

If we consider the possiblity of breeding, as has been done in this study, we will find it necessary to calculate the cumulative demand for natural uranium at that time, when the last converter reactor of our two type strategy has been shut down.

For the two-type strategies employing Na-1 BR (KFK) this will happen before 2040. After this date in the long run one will need depleted uranium only for newly installed breeder reactors. The total demand up to 2040 may be found on page 51. It is smaller by 1.5 orders of magnitude as compared to the demand of converting reactors for natural uranium. Accordingly, the demand for natural uranium until 2040 will be as follows:

LWR (ORNL) / Na-1 BR (KFK): 220 · 10^3 t
LWR (SSW) / Na-1 BR (KFK): 210 · 10^3 t
GG (CEA) / Na-1 BR (KFK): 160 · 10^3 t
D_2O (SSW) / Na-1 BR (KFK): 109 · 10^3 t

The maximum of the converter power installed will amount to:

LWR (ORNL) / Na-1 BR (KFK): 50 GW_e in the year 1998
LWR (SSW) / Na-1 BR (KFK): 38 GW_e in the year 1993
GG (CEA) / Na-1 BR (KFK): 32 GW_e in the year 1992
D_2O (SSW) / Na-1 BR (KFK): 37 GW_e in the year 1994

The decrease of the power supplied by converters will start to take place five or ten years later. Pursuing the two type strategies of the GE breeders until 2040, when the converters will have been shut down too, results in the subsequent data:

LWR (ORNL) / Na-BR (GE): $650 \cdot 10^3$ t
LWR (SSW) / Na-BR (GE): $470 \cdot 10^3$ t
GG (CEA) / Na-BR (GE): $375 \cdot 10^3$ t
D_2O(SSW) / Na-BR (GE): $235 \cdot 10^3$ t

The maximum of the converter power installed will amount to:

LWR (ORNL) / Na-BR (GE): 80 GW_e in the year 2008
LWR (SSW) / Na-BR (GE): 60 GW_e in the year 2005
GG (CEA) / Na-BR (GE): 48 GW_e in the year 2002
D_2O (SSW) / Na-BR (GE): 58 GW_e in the year 2005

This result is a very remarkable one. The GE breeder, employing a rather low breeding ratio of 1.25, if combined with light water reactors as converters leads to an absolutely inhibitive demand for natural uranium while the KFK breeder, having a breeding ratio of 1.38 even in combination with weak converters will result in a demand that can just be satisfied within the limits set by class 1. Even more: the best converter (D_2O) in combination with the less efficient breeder (GE) leads to a total demand ($235 \cdot 10^3$ t) larger than that for the combination of the least efficient converter (LWR-ORNL) and the more efficient breeder (KFK) ($220 \cdot 10^3$ t).

We further state: In case the fast breeder here considered breeds rather well, i.e. if the breeding ratio is larger than about 1.4, it may be possible for a breeder of this type to be combined with any converter type without exhausting the resources of class 1.

Therefore, judging from these facts, it is not necessary to develop an intermediate generation of highly converting reactors and to install those in 1985 - 1900. If, on the other hand, the fast breeder under consideration has a rather small breeding ratio, the interaction solely with a lightwater reactor is not possible, i.e. there will be a need for an intermediate generation, for instance one of D_2O reactors. The minimum uranium consumption that can be achieved in this way is given by the two type strategy D_2O/GE and, again, may be satisfied by the resources of class 1. These results render it interesting to compare the additional cost of introducing an intermediate generation of highly converting reactors with the cost that may possibly arise in the achievement of a high breeding ratio of a fast breeder.

we state in addition that an intermediate generation of highly converting reactors will become necessary as soon as one considers a cumulative natural uranium consumption of about $22o \cdot 1o^3$ t to be a risk. In this case, however, one also has to build breeders that have higher breeding ratios.

The absolute minimum possible is achieved by means of the two type strategy D_2O/Na-1 BR (KFK) consuming $1o9 \cdot 1o^3$ t only.

The term intermediate generation does not mean this reactor generation should or could be pushed between the converter presently available and the fast breeders. It rather will be necessary in any case to start the installation of a breeder generation as soon as possible, i.e. about 198o. Our two type strategies show that in case breeders will become predominant by the year 2ooo, in 1985 already about 12 GW_e of breeder power have to be installed. This then implies that the intermediate generation will be added to the converters presently available. Accordingly, it is more like a supplemental generation that should gain its maximum installation in the nineties.

Confronting the possibility of breeding just discussed with the possibility of gaining uranium out of the seawater, the statements just made naturally do not apply. Judging from our present knowledge the resources made available by this method are so large as to render any activities unnecessary in this country that concern the economic use of uranium.

The problems concerning the extraction of uranium from seawater, however, have to be considered technically and economically as unsolved, while the possibility of breeding seems to be technically feasible and will most likely provide more favorable prices.

While the installation of fast breeders up to the year 2000 leads to a difference concerning uranium consumption of 1.5 orders of magnitude in the long run, anything similar with regard to costs is impossible. Because in any plant, in which the reactor is used as a heat source with heatexchangers, pipings, pumps, and turbines, the cost difference cannot exceed 15 to 25 °/o. This means that technical details will dictate the differences in cost. Within the framework of the cost data presented here, we obtain the following sequence of the specific cost for the two periods of 1970 to 1985 and 1985 to 2000 respectively:

1970 - 1985			1985 - 2000		
Na-BR (GE)	1.62	[DPf/kWh]	Na-1-BR (KFK)	1.65	[DPf/kWh]
Na-1 BR (KFK)	1.62	"	Na-BR (GE)	1.76	"
THTR (GA)	1.80	"	THTR (GA)	2.00	"
LWR (ORNL)	1.91	"	D_2O (SSW)	2.08	"
AGR (UKAEA)	2.02	"	LWR (ORNL)	2.09	"
D_2O (SSW)	2.09	"	AGR (UKAEA)	2.25	"
LWR (SSW)	2.12	"	GG (CEA)	2.30	"
GG (CEA)	2.19	"	LWR (SSW)	2.31	

The data have to be considered with some reservation, because the cost analysis as has been done here, was necessarily rather summarizing and all estimates were based on 1970 data. Nevertheless, it may be possible to state that the development of fast breeders gets an incentive *merely from the cost point of view* too.

Thus, the advantages related to the conservation of uranium resources, that have been treated before, do *not* imply disadvantages concerning cost. Rather, the contrary is the case.

In this context, it will be necessary, to enter once more in the problem of the supplemental generation, for instance of D_2O reactors. As long as the price for uranium concentrate will remain at 8 $/lb, the LWRs (ORNL) have a price advantage according to our data. However, as soon as natural uranium resources with a price of 3o $/lb of concentrate have to be used, even the price advantage of the LWRs (ORNL) as compared to the D_2O reactor of our data block is lost. Both then are characterized by specific energy cost of 2.25 or 2.3o DPf/kWh, respectively. As compared to the LWR (SSW), the D_2O (SSW) reactor has a price advantage anyhow.

Further, one has to consider, that the American diffusion plants presently in existence are able to satisfy a demand of enriched uranium corresponding to an installation of 1oo GW_e LWRs. Thus, there may very well come a bottle neck with regard to the supply of enriched uranium into being in the 9o's, when our two type strategies predict a maximum of converter power installed. This may happen in case not only Germany but other countries as well pursue a LWR breeder strategy. This difficulty may be overcome by the installation of a supplemental generation of D_2O reactors at any case. So, it may be worth while to investigate the problem concerning the installation of diffusion plants more closely.

Concluding, some comments on our estimate of the reprocessing capacities may be worth while. This estimate makes one point very clear: natural uranium reactors need a much higher reprocessing capacity as compared to reactors using enriched uranium and breeders as well. The magnitude of the reprocessing capacity in a sense is complementary to that of the separation plant capacities. Here, one may argue that there is no reprocessing necessary for the natural uranium reactors in one type strategies. The installation of breeders, however, will imply the reprocessing of natural uranium fuel at any rate. Because breeders will become more and more predominant, the difference in annual throughputs then will not be very large, at least not for the two type strategies LWR (ORNL) - Na-1 BR (KFK) and D_2O (SSW) - Na-1 BR (KFK).

In order to make the limitations of the arguments used here clear, we should like to mention, that it was not possible for us to investigate the following possibilities up to the date set by the FORATOM-meeting:

1. Recycling plutonium into thermal reactors
2. Installing a generation of fast breeders using U-235 instead of plutonium for start-up.

The alternative 1 may always be used, if a bottle neck with regard to the supply of enriched uranium comes into being; however, taking into account the low criticality factor of plutonium as compared to U-235 in a thermal reactor and realizing that the further installation of fast breeders will become impossible means that the installation of the breeder generation will be considerably delayed. This then will lead to an increasing cumulative demand for natural uranium. The alternative 2 also merits some attention. Fast breeders using U-235 have a breeding ratio of at least 1.o5 to 1.1o and so represent the most efficient "converter". One has to investigate the cumulative demand for natural uranium in this case as well as the date of the maximum demand for enriched uranium.

Concluding the discussion of the results, we want to point out repeatedly, that this study has aimed at a limited goal. This goal was not, to come to an extensive rating of all the aspects of the different types and the respective strategies. A rating of this type had to enter into technical details and into details of the cost factors more thoroughly. Problems of foreign exchange had to be considered too in close connection to political questions. All this is beyond the goal of this study. The data supplied by this study, however, were supposed to provide a basis for discussions of this type and to set a framework, considering the problem of uranium resources in particular.

9. Conclusions

With special reference to the discussion of the results as presented in chapter 8, it is possible to formulate the following conclusions:

1. An upper estimate of the demand for nuclear power installed leads one to expect 13o GW_e in the year 2ooo.

2. In 1975 the total annual cost of nuclear energy will amount to about 1 billion DM. In 1977, the annual investments alone and in 1979, the capital charges of the annual investments will reach the amount of 1 billion DM annually.

3. In 197o about 5oo kg of plutonium will have been produced within the Federal Republic; in 198o this will be between 1o and 2o t.

4. If the total consumption of natural uranium in the Federal Republic is assumed not to exceed 2oo to 3oo $\cdot$ $1o^3$ t, fast breeders must be used. Otherwise, the demand for natural uranium will rapidly increase to some millions of tons after the year 2ooo. This amount most likely could be made available out of the seawater only, should this turn out to be technically as well as economically feasible.

5. The alternative, to install a generation of fast breeders initially fueled with U-235 has not yet been investigated in this study. If the plutonium demand of a fast breeder generation is satisfied by means of converter reactors, the demand for natural uranium will remain below about 2oo $\cdot$ $1o^3$ t for any combination of converter/breeder, as long as the breeder has a breeding ratio of about 1.4 or more. In this case, no supplemental generation of high converting reactors will be necessary.

6. From the view point of conservation of the uranium resources one should preferably combine a converter having a low conversion ratio with a breeder, having a high breeding ratio instead of coupling a converter having a high conversion ratio to a breeder having a low breeding ratio.

7. If the fast breeder of the breeder generation has a breeding ratio below 1.4, a supplemental generation of reactors, for instance D_2O--reactors, will become necessary. The installation of this generation would reach its maximum between 1985 and 199o.

8. In case one wants to keep the total consumption well below $200 \cdot 10^3$ t for Germany (Federal Republic), a breeding ratio of at least 1.4 turns out to be necessary for the fast breeders and a supplemental generation of D_2O reactors, for example will become mandatory.

9. From an evaluation of all the available data blocks concerning reactor cost, the fast breeder offers the most favorable cost outlook.

1o. The maximum converter installation is expected to occur in the nineties. Should these turn out to be light water reactors, one expects a capacity of 45 GW_e . This would tie up about half the capacity of the separation plants presently installed in the USA. It still has to be shown that an adequate supply of enriched uranium will be available under these circumstances.

11. The capacity of the reprocessing plants needed is relatively small for reactors running on enriched uranium (about 45oo t annually in 2ooo). Natural uranium converters, on the other hand, will need a capacity up to 2o,ooo t annually, should they be required to satisfy by themselves the total demand for nuclear energy. In the case of two type strategies LWR (ORNL) - Na-1 BR (KFK) and D_2O (SSW) - Na-1 BR (KFK) this difference will not be very large in the year 2ooo (47oo and 76oo t/a respectively).

References

[1] W.H. ZINN; oral communication

[2] K. ERGEN, E.L. ZEBROSKI: Breeding - how soon a necessity? Nucleonics, Febr. 1960 (p. 60)

[3] E.A. ESCHBACH: Plutonium value analysis. 3. ICPUAE, P/246, Geneva 1964

[4] CIVILIAN NUCLEAR POWER, A report to the President. USAEC (Nov. 20, 1962)

[5] J.R. DIETRICH: Efficient utilization of nuclear fuels. Power Reactor Technology, 6, No. 4 (1963)

[6] R. GIBRAT: L'economie energetique nucleaire a long terme.
Energie nucleaire, Vol. 5, No. 6, 397 (Sept. 1963)
Vol. 5, No. 7, 485 (Nov. 1963)

[7] D. RITTER und G. BLÄSSER: Brennstoffbilanzen der Kernenergie, Atomwirtschaft, Febr. 1965

[8] J.J. WENT: Considerations for a longterm development for the use of fission energy and the consequence for presently developed power reactors. Nukleonik 6, No. 5 (Sept. 1964)

[9] EURATOM-BERICHT EUR/C/4000/4/64d: Lage und Perspektiven der Kernenergie in der europäischen Gemeinschaft (June 1965)

[10] C.J. BALDWIN, C.A. HOFMAN: System planning by simulation with mathematical models. Proc. Am. Power Conf. Vol. XXII, 598 (1960)

D.N. REPS, J.A. ROSE: Strategy for expansion of utility generation. Power Apparatus and Systems (Febr. 1960)

C.J. BALDWIN et al.: Economic aspects of systems expansion with nuclear units. Power Apparatus and Systems (Febr. 1963)

[11] ORNL-REPORT No. 3686: A comparative evaluation of advanced converter (Jan. 1965)

[12] R. GIBRAT: oral communication

[13] REPORT GEAP-4418: Liquid metal fast breeder reactor design study (Jan. 1964)

[14] Referenzstudie für den Natriumgekühlten schnellen Brutreaktor (Na-1). Gesellschaft für Kernforschung mbH. Karlsruhe KFK 299 (Dec. 1964)

[15] A detailed version will be published in "Berichte des Kernforschungszentrums Karlsruhe", probably in late 1965

[16] Internal report of the "Studienkreis Kernenergiereserven"

[17] MONTANUNION, EWG, EURATOM: Untersuchungen über die langfristigen energiewirtschaftlichen Aussichten der Europäischen Gemeinschaft. Luxemburg 1964

[18] G.F. TAPE et al.: Future energy needs and the role of nuclear power. 3. ICPUAE, P/192, Geneva 1964

[19] R. GIBRAT: The essential factors in a balanced economy. 3. ICPUAE, P/99, Geneva 1964

[20] H. GRÜMM: Dynamik der Kernbrennstoffzyklen. Nukleonik (in print)

[21] H. SCHMALE, A. PERSSON and P. ERKES: Verfahren zur Berechnung der Brennstoffkreislaufkosten von Kernkraftwerken in Form eines festen und eines variablen Kostenanteils. Weltkraftkonferenz 1964, Report 128

[22] H. GRÜMM: Vereinfachte Verfahren zur Berechnung des Brennstoffkostenanteils. Atomwirtschaft (in print)

[23] USAEC-REPORT TID 82o1: An analysis of the current and long term availability of Uranium and Thorium (1959)

[24] USAEC-REPORT TID 82o7: Energy from Uranium and Coal Reserves (196o)

[25] CIVILIAN NUCLEAR POWER: A report to the President. USAEC (1962), App. II, p. 31, table 1

[26] R.L. FAULKNER, W.H. McVEY: Fuel resources and availability for civilian nuclear power 1964 - 2ooo. 3. ICPUAE, P/256, Geneva 1964

[27] R. SPENCE et al.: Nature <u>2o3</u>, 111o (1964)

[28] J. GAUSSENS, H. PAILLOT: Study of the long-term values and prices of Plutonium. CEA-R 2795

[29] E.A. ESCHBACH et al.: Pure - A computer code for calculating Plutonium value. Report HW 71811 (1961)

[30] F.L. DAWSON: Plutonium as a power reactor fuel. Report HW 75oo7 (1962)