KERNFORSCHUNGSZENTRUM

KARLSRUHE

Juni 1967

KFK 566

Institut für Angewandte Reaktorphysik

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*) Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung m.b.H., Karlsruhe

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Abstract:

The future of any advanced reactor type can be assessed by determining the savings in the total energy generation costs as well as in the raw material consumption by its introduction into a nuclear power generation system. For this purpose several probable nuclear strategies, for a given nuclear energy growth curve, with different thermal converters, advanced converters and fast breeders with either plutonium or uranium start-up, have been analysed. The results, with the clearly defined assumptions made in the paper, indicate that the THTR type, regarded as one of the advanced converters, would have some economic and raw material advantage over the LWR type or a two type strategy with LWR and sodium cooled oxide breeder. However, the strategies with steam cooled oxide and sodium cooled carbide breeders with U-235 start-up show definite and significant cost and raw material advantage over any other strategies. These breeders with uranium start-up represent their own particular type of converters which supply all of the plutonium required by them, and with their introduction the importance of high breeding ratio gets considerably reduced.

Although the uranium start-up breeders require larger amounts of U-235 at the beginning, the total uranium consumption with these systems over a long period of time would be considerably lower than those with any other thermal or advanced converter systems. The results indicate further that the sodium cooled carbide breeders with U-235 start-up have the highest economic potential and the lowest uranium consumption of the reactor types considered here, and that a simultaneous development effort would be necessary for the steam cooled and sodium cooled breeders because of the different degrees of difficulties associated with each system.

1. Introduction:

If one considers the question of the future of the advanced converters, one is automatically led to the question of the future of fast breeders to have a standard of comparison. In previous works /1,2/ the energy generation costs and natural uranium consumptions for various individual proven and projected thermal reactors as well as for projected sodium cooled fast breeder reactor types were compared and analysed. The costs and the natural uranium requirements for coupled reactor strategies with converter and breeder type reactors, in which all the plutonium produced in the breeders and converters was utilized for the installation of new breeders, were also compared extensively in these publications.

Recent analyses of similar type problems have shown that the previous types of models should be supplemented with some modified reactor versions to permit further interesting conclusions regarding nuclear strategies in an expanding nuclear economy.

Previously a number of thermal converters was compared with only two types of fast breeder systems, whereas the situation has been reversed now. In this study a number of technically feasible and economically attractive projections of fast breeder types has been compared with the proven light water reactor type (LWR) and an advanced and economically attractive converter of the THTR type. It is becoming more and more obvious that the fast breeder does not represent a single reactor type but rather a whole generation of reactors with different technical realizations of the same physical principle. All these technical variations promise significant advantages over the proven converter types. The variations consist mainly of different coolants and fuel types. In the present analysis fast breeders with steam and sodium cooling and with oxide and carbide (in the case of sodium cooling) type fuel have been considered.

It has also been found that all these Pu-fuelled breeders can be started up with U-235 also without having to forego any significant cost advantage and without any change in their technical lay-out. In this way such breeders are no longer, as was assumed earlier, dependent on the plutonium produced from the thermal converters but can supply the entire amount of Pu required by them from their own production and represent so to say, their own converter type.

Basically breeders with U-235 start-up offer two modes of operation. According to the one mode U-235 may be supplied to the parent reactor for its running requirement and all the plutonium produced used to start-up fresh plutonium fuelled fast daughter breeders. In the other mode, plutonium produced may be fed back to the parent reactor until it is converted into a complete plutonium fuelled fast breeder. The first mode of operation is strongly dependent on the price of plutonium; it is quite probable that under certain conditions the averaged energy generation cost might increase with increasing Pu price. With the second mode of operation the energy generation costs from the parent breeder are independent of the Pu price during Pu-recycling whereas, when it has been converted to a fully Pu-fuelled breeder, an increase in Pu price may either be of advantage (for high breeding ratio) or the costs may be independent of the Pu price (for low breeding ratio). On the basis of these considerations the second mode of operation has been chosen for the subsequent analysis.

The next point which causes some extension of the previous analysis is a more optimistic estimate of nuclear energy demand /3/. To assess the effect of variation in the rate of nuclear growth, the economics and the problem of uranium reserves have been compared in this study with the slightly less optimistic nuclear growth as shown in /1,2/.

The recent analysis has also shown that although the introduction of fast breeders into a nuclear system makes the problem of the exhaustion of natural uranium resources of secondary importance, the problem of the supply of enriched uranium and the associated problem of the separative work capability in a diffusion plant attains primary importance. In this connection it should be stressed that the question of the very size of the separation plant becomes rather important as the unit separative work costs appear to be extremely sensitive to the size of the separation plant and influence thereby the total energy generation costs from reactors based on enriched uranium.

In view of the changed conditions as discussed above the previous studies on nuclear strategies had to be extended. But for the purpose of comparison the same methods of analysis have been adopted in the present study. This means, a particular energy growth curve has been assumed and different reactor-types (the characteristics of which do not change with time) have been taken to meet the demand, either with a single reactor type (one type strategy) or with two reactor types (coupled strategy) one of which acts as a converter and the other as a breeder and all the excess Pu produced is installed in new breeders. For comparison, the newly considered two type strategies with U-235 and Pu start-up of breeders can be treated also according to the same method. The converter in such a two type strategy only starts with U-235 and needs no further supply of this fissile material. For the same purpose of comparison the starting point for all the nuclear strategies has been taken to be 1970. It is quite obvious that this type of model-analysis is not carried out to predict the future in all detail. Its main importance lies in determining the influence of important parameters on such models. However, the relative importance of such parameters which influence the future development in a major manner can be clearly assessed from this type of model-analysis. The results of such an analysis permit the setting of proper target values for the envisaged development.

2. Reactor Types and Nuclear Strategies Considered

For the following analysis seven different reactor types have been considered and their economic and technical data important for this study are summarized in Table Ia.

The light water reactor (LWR) corresponds to the LWR-AEG-1970 and the thorium high temperature reactor (THTR) to the THTR-BBK of /2/. The THTR type represents one of the most advanced thermal reactor types considered in the previous study /2/.

All the fast breeder versions with Pu and U-235 start-up have been computed anew for this study. Detailed data sets have been given in Table Ib. The three breeder versions, one with steam cooling and oxide fuel and one of the sodium cooled oxide type and one of the sodium cooled carbide type, correspond to the three types now under active consideration. The first type with its relatively low breeding gain and high fissile inventory represents a version, which appears to be a natural extension of the well proven light water reactors and may have the potential for an early introduction, e. g. by the late seventies. The second type represents the generally accepted version of the new breeder generation using sodium cooling and oxide fuel, whereas the third version corresponds to a high performance breeder the introduction date of which may be during the eighties.

The optimistic rate of nuclear energy growth in Germany mentioned earlier, is shown in Table II. For comparison the pessimistic growth which was considered as optimistic in /2/ has also been included.

Table Ia: Characteristic Data for the Reactors Considered

	Initial Fissile Inventory [t]	Pu-surplus [kg/a]	Total Capital Investments (+ First Core) [10^6 DM]	Energy Costs [DPf/kWh]				Time for Conversion to Pu fuelled Breeder [a]
				Investment + Oper.	Fuel Cycle First Core	Fuel Cycle Total f.c.costs	Total Energy Costs	
Light Water Reactor (LWR) (with Pu recycling)	3.43	(135) recycled	510 (650)	1.10	0.21	0.67	1.77	
Thorium High Temperature Reactor (THTR)	2.00	0	550 (620)	1.17	0.10	0.46	1.63	
Steam-Cooled U-235 Start-up Fast Breeder (DUBR)	3.60	(30)	510 (650)	1.10	0.24	0.50	1.60	ca. 14
Sodium-Cooled Fast Breeder with Oxide Fuel (NaBR(O))	2.41	166	580 (650)	1.23	0.13	0.37	1.60	
Sodium-Cooled Fast Breeder with Carbide Fuel (NaBR(C))	1.73	188	580 (640)	1.23	0.09	0.25	1.48	
Sodium-Cooled U-235 Start-up Fast Breeder with Oxide Fuel (NaUBR(O))	3.20	166	580 (700)	1.23	0.19	0.47	1.70	ca. 6
Sodium-Cooled U-235 Start-up Fast Breeder with Carbide Fuel (NaUBR(C))	2.17	188	580 (650)	1.23	0.12	0.32	1.55	ca. 4

Table Ib: Technical Data-Sheet for the Reactors Considered

		unit	LWR	THTR	DUBR	NaBR(O)	NaBR(C)	NaUBR(O)	NaUBR(C)
	Nett elec. power	MWe	1000	1000	1000	1000	1000	1000	1000
	Therm. efficiency	1	0.345	0.44	0.39	0.40	0.40	0.40	0.40
	Av. fuel rating	MW/kg	0.0221	0.024	0.0493	0.0605	0.0705	0.0605	0.0705
	Av. burn-up	MWd/kg	27.5	57.1	32.8	25.7	20.56	25.7	20.56
Isotope comp. at start-up	Th-232	%	0	95.17	0	0	0	0	0
	Waste U		0	0	0	94.50	95.40	0	0
	U-233		0	1.51	0	0	0	0	0
	U-235		2.56	2.31	6.5	0	0	7.3	5.78
	U-238		97.44	0.25	93.5	0	0	92.7	94.22
	Pu-239+241		0	0	0	5.50	4.60	0	0
Isotope comp. at discharge	Th-232	%	0	95.50	0	0	0	0	0
	Waste U		0	0	93.97	93.54	94.58	93.54	94.58
	U-233		0	2.17	0	0	0	0	0
	U-235		0.85	0.76	0	0	0	0	0
	U-238		98.34	0.21	0	0	0	0	0
	Pu-239+241		0.52	0	0.177*	6.46	5.42	0.646*	0.60*
	Fuel mass ratio	1	0.970	0.940	0.973	0.973	0.978	0.973	0.978
	No. of fuel batches		4	∞	3	3	3	3	3
	Load delay	a	1.22	0.78	0.87	0.50	0.72	1.06	0.76
	Fabrication time	a	0.50	0.50	0.37	0.50	0.36	0.36	0.36
	Reprocessing time	a	0.60	0.60	0.50	0.60	0.40	0.80	0.40
	In-pile time	a	4.87	9.31	2.60	1.66	1.14	1.66	1.14

* Excess Pu after conversion to Pu-Breeder

Table II: Estimated nuclear capacity in Germany /GWe/

	1970	1980	1990	2000	2040
Upper Estimate	2	25	85	195	800
Lower Estimate	2	20	62	132	770

The various nuclear strategies analysed in this paper are shown below:

1. LWR (recycling) one type strategy
2. THTR one type strategy
3. DuBR one type strategy
4. LWR + NaBR(O) coupled strategy
5. LWR + NaBR(C) coupled strategy
6. NaUBR(O) + NaBR(O) coupled strategy
7. NaUBR(C) + NaBR(C) coupled strategy

It is worthwhile mentioning here that the steam cooled oxide fast breeder with uranium start-up corresponds in reality to a one type strategy, as the amount of Pu produced in excess is so small that only a very small number of Pu fuelled breeders can be installed even in the year 2000.

3. Separative Work Capability and Costs

Any nuclear strategy based on enriched uranium requires isotope separation capability. The extent and duration of such capabilities depend mainly on reactor types used and the nuclear energy growth curve assumed. The unit separative work costs are rather sensitive to the installed separative work capability of the isotope separation plant /4/ and some relation between the size of the plant and the unit separative work costs is necessary to determine the total energy generation costs for a nuclear strategy with enriched uranium fuelled reactors. In the following paragraphs, the assumptions, made to assess the specific separative work costs for isotope separation plants with different capacities, have been discussed and an analytical expression derived relating the unit costs with the capacity.

3.1. Assessment of the US Plant Capabilities and Costs

The major part of the present enriched uranium requirement of the Western world for the generation of power is supplied from the American diffusion plants. The situation is not expected to change drastically during the foreseeable future. As a first approximation, therefore, it appears reasonable to take the American capability as the reference point.

Although all the relevant technical and cost data for the American plants are still classified, the total capability estimate for these plants by a number of private industries /5,6/ range between 19 - 21 $\cdot$ 10^6 kg units/a. Since there are three diffusion plants, each capable of utilizing the same amount of installed electrical power, the capacity of all the three plants may be taken to be the same, although the estimated capital investment varies slightly from plant to plant. The capacity of a single diffusion plant in the USA, according to these estimates would, therefore, be around 7 $\cdot$ 10^6 kg units/a. The published total investment costs for the three plants /6/ is around \$ 2,3 $\cdot$ 10^9. Assuming that with improved technology somewhat larger plants would be possible, an American plant with 8 $\cdot$ 10^6 kg units/a, with a total capital investment of \$ 1 $\cdot$ 10^9 and a unit separative work cost of \$ 30/kg have been taken as the reference point for the present study.

3.2. Plant Scale-up Factor and Costs of a European Diffusion Plant

A French detailed estimate /4/ on European diffusion plants indicates that they would have a scale-up factor of around 0,4. Such a low scale-up factor is accounted for by the fact that a large part of the capital investment is a function of the number of stages only and some are independent of the throughput of the plant.

It was indicated further that a European diffusion plant with the largest possible capacity would still have about 30 % higher unit separative work costs than an American diffusion plant with the same capacity.

3.2.1 Annual Costs in a Diffusion Plant

The annual costs comprise of the capital charges, personnel costs, electrical energy consumption, maintenance charges and any other fixed charges (Royalties, patent fees, control etc.). Sum of these costs divided by the total separative work capability in kg units/a gives the costs for one kg unit of separative work. The raw material costs (UF_6) are not included here as they are considered separately while calculating the enriched uranium price.

The number of operation and maintenance personnel is mainly a function of the number of separative stages. In case the number of stages in diffusion plants with different capacities is kept the same, the personnel costs may be taken to be independent of the plant capacity. Similarly, the fixed charges, like royalties and patent fees payable for the process or for specialized equipment as well as analytical control and laboratory charges are also to a large extent independent of the plant throughputs. The amount of electrical energy used in a plant is directly proportional to the separation capability of the plant, but the unit cost of energy increases with decreasing size of the plant as the power generation units (for example nuclear power reactors) have also similar scale-up factors.

3.3. Assumptions

All the assumptions made in determining the annual charges for European diffusion plants with different separative work capabilities are summarized below:

3.3.1 The largest probable size of a single diffusion plant in the USA would be around $8 \cdot 10^6$ kg/a.

3.3.2 The total capital investment for this American plant would be $4{,}0 \cdot 10^9$ DM and the unit separative work costs from this plant would be 120 DM/kg.

3.3.3 The total capital investment for the same size plant if built in Europe would be 30 % higher, i. e. $5{,}2 \cdot 10^9$ DM.

3.3.4 The capital investment in the range of $1 - 8 \cdot 10^6$ kg/a separative work capability for European plants would change according to the relation:

$$K_T [10^9 \text{ DM}] = 5{,}2 \left[\frac{A_T}{8 \cdot 10^6}\right]^{0{,}4} \qquad (1)$$

where K_T indicates the capital investment in 10^9 DM for a diffusion plant having a capacity of A_T kg of separative work per year.

3.3.5 The energy costs in Dpf/kWh, for the energy production units installed for the diffusion plant, in the capacity range of 0,1 - 1 GWe, would follow the following relation:

$$C_E [\text{Dpf/kWh}] = 1{,}6 \left[\frac{1}{E}\right]^{0{,}4} \qquad (2)$$

where C_E gives the electrical energy generation costs in Dpf/kWh for a power station with an installed capacity of E GWe in the range $0{,}1 \leq E \leq 1$.

It has been further assumed that the largest reactor unit installed would be 1 GWe. If the requirement of the diffusion plant exceeds this value, several reactors would be installed in parallel and the weighted average of the electrical generation costs from these reactor would form the basis for calculation.

3.3.6 The number of operation and maintenance personnel required for a $8\cdot 10^6$ kg/a European plant would be 2400, i. e. one third of the total number of personnel for the three American plants. This number of 2400 would remain the same for all the other European plants in the range of 1 - $8\cdot 10^6$ kg/a separative work capability. Similarly, the yearly fixed charges of $120\cdot 10^6$ DM/a consisting of royalties, patent fees, control charges and other miscellaneous items, are 10 % of the rest of the annual charges for a $8\cdot 10^6$ kg/a plant and would remain the same for all the other plants.

3.3.7 The diffusion plants are amortized over 25 years with an interest rate of 7 %/a and a tax rate of 2,9 %/a, giving an amortization rate of 11,76 %/a.

3.4 Annual Charges and Unit Separative Work Costs as a Function of Diffusion Plant Capacity

The capital investment, the annual charges and the unit separative work costs for different European diffusion plant capacities have been summarized in TableIII. The unit costs as a function of plant capability can be reproduced within an accuracy of about 2 % with the following simple expression [7]:

$$C_T\,[\mathrm{DM/kg}\ A_T] = 160 \left[\frac{8\cdot 10^6}{A_T}\right]^{0,6} \qquad (3)$$

The estimated capital investment reduces rather slowly from $5,2\cdot 10^9$ DM for a $8\cdot 10^6$ kg/a plant to $2,26\cdot 10^9$ DM for a 1.10^6 kg/a plant. The unit separative work costs are 160 DM/kg for the $8\cdot 10^6$ kg/a plant and are about 30 % higher than the corresponding American plant and increase fairly rapidly to 560 DM/kg for the 1.10^6 kg/a plant. Subject to the assmuptions in 3.3., the rapid increase in separative work costs with decreasing diffusion plant size brings out clearly the economic disadvantage associated with small size diffusion plants.

3.5 Other Processes for U-235 Enrichment

A number of basically different methods [8,9] may be used in principle for the enrichment of uranium. Since no reliable cost estimates for large scale plants with other methods have yet been published, the foregone cost estimates for unit separative work with gaseous diffusion form the basis for the subsequent analysis.

Table III: Characteristic Cost Data for European Diffusion Plants with Different Separative Work Capability

Sep. W. Capability 10^6 kg/a [A_T]	8	6	4	2	1
I. Capital Costs [10^9 DM]	5,20	4,65	3,94	3,00	2,26
II. Annual Charges [10^6 DM/a]					
1. Capital Charges (11,76 %/a of Capital Costs)	612	548	464	353	266
2. Personnel (2400 at DM 24000/a and person)	58	58	58	58	58
3. Energy Costs	335	260	180	91	60
4. Maintenance (3 % of Construction Costs)	156	140	119	90	68
5. Royalties, Patents, Control, Misc. (Fixed Charges/a)	120	120	120	120	120
6. Total Annual Charges	1281	1126	941	712	572
III. Unit Separative Work Costs [DM/kg A_T]	160	188	235	356	572
IV. Unit A_T Costs according to Equ. 3 [DM/kg A_T]	160	190	242	368	560
Installed capacity of reactors to meet the energy requirements of the diffusion plants [GWe]	3	2,25	1,5	0,75	0,33
Specific energy generation Costs (weighted av.) [Dpf/kWh]	1,6	1,74	1,77	1,80	2,35

4. Results of the Strategies Considered with Respect to Costs and Demand of U-nat, U-235 and Separative Work

The comparison of different models of nuclear energy production is carried out on the basis of cost figures and that of the demand for raw material i. e. U-nat and U-235, as these figures are of primary economic importance. Furthermore, the question of the urgency and size of a European Isotope separation plant, which becomes more and more important for the supply of fissile material of a large European nuclear energy industry, may be analysed on the basis of the figures on the demand for separative work capability for different nuclear strategies. These demands are based on nuclear growth curves of Table II.

In Table IV the results for the demand of fuel material for the seven strategies considered are given. The required demand of three types of materials has been calculated - U-235, enriched uranium (according to the enrichment necessary for the different reactor types /27) and natural uranium. The data are given for the upper and lower nuclear energy demand curve. The last column of Table IV represents the amount of Pu bound in all reactors for the considered strategy in the year 2000. The amount is a measure of the potential for the installation of advanced types of breeders with reduced inventory demand, i. e. high performance breeders.

Table V gives the required separative work for the different strategies and by these figures an indication on the size of an European separation plant, which is able to meet this requirement. In this analysis tail end concentration is not changed for different plant size and is taken to be equal to the American plant.

Table VI contains specific cost-figures for all reactors considered which are supplied with enriched uranium. As the costs for separative work are strongly dependent on the size of the separation plant, this size indirectly influences all power production costs of U-235 fuelled reactors. This dependence which is most remarkable for LWR is shown in Table VI. In this analysis U_3O_8 and Pu prices are taken according to the US price lists. Partial load of the separation plant operation has not been considered.

Table VII gives the salient results for the economic comparison of different strategies. The annual energy production costs are mean costs per kWhe of all reactors in operation in the respective year for a given strategy. The present worth represents the cumulative costs of energy production of a given strategy in the period 1970 upto 2000 actualized with 7 % discount rate to the year 1970. The cost figures as a function of the separation plant size are obtained as follows. Using American supply of enriched uranium one obtains the lower limit of the cost figures. The upper limit results from adopting the minimum separation plant size for each strategy. The last column gives cost figures for the use of a large European separation plant of about $8 \cdot 10^3$ t/a A_T. These figures lie in between the limits of the first and second column.

Table IV: Demand for Fuel Material of Different Strategies

		Annual Requirement /t/a/						Cumulative Requirement /10^3 t/				
		U-235			enriched Uranium			U-235	enrich. Uranium	natural Uranium		Bound Pu-Amount /t/
		1980	1990	2000	1980	1990	2000	2000	2000	2000	2040	2000
LWR (recycle)	LD*	10,1	27,8	58	460	1390	2900	0,85	42	180	1800	70
	UD	12,4	38,0	86	560	1900	4300	1,25	59	260	2000	100
THTR	LD	3,8	11,2	23,3	4	15	30	0,37	0,4	90	1200	-
	UD	4,6	15,4	34,8	5	20	40	0,53	0,6	115	1300	-
DUBR	LD	11,1	20,4	30,8	170	310	470	0,48	7	100	400	315
	UD	14,0	28,3	56,0	210	430	870	0,70	11	145	600	430
LWR+NaBR(O)	**LD**	10,7	25,8	37,3	430	1060	1600	0,74	30	155	440	190
	UD	13,2	35,3	66,4	530	1400	2700	1,10	45	225	640	270
LWR+NaBR(C)	**LD**	10,4	21,1	25,2	420	870	1100	0,60	25	125	180	200
	UD	12,4	29,3	43,7	490	1200	1800	0,85	35	180	320	270
NaUBR(O)+NaBR(O)	**LD**	9,2	11,8	11,5	130	165	155	0,30	4,0	60	90	260
	UD	11,5	16,9	22,7	160	230	315	0,45	6,2	95	125	370
NaUBR(C)+NaBR(C)	**LD**	5,3	3,5	0	90	64	0	0,11	1,8	22	22	265
	UD	6,6	5,9	2,0	110	100	30	0,18	3,1	36	36	370

* **LD** = lower demand curve
UD = upper demand curve

Table V: Separative Work Required

		Separative Work [10^3 t/a]			Trend for the year 2040 [10^3 t/a]	Minimum Size of Separation Plant [10^3 t/a]
		1980	1990	2000		
LWR (recycle)	LD*	1,2	3,7	8,1	46	8
	UD	1,5	5,0	12,0	49	8
THTR	LD	0,9	2,6	5,4	30	6
	UD	1,1	3,6	8,0	31	8
DUBR	LD	1,9	3,5	5,3	15	5
	UD	2,3	4,9	9,5	12	8
LWR+NaBR(O)	LD	1,3	3,6	6,1	0	6
	UD	1,6	4,8	9,5	0	8
LWR+NaBR(C)	LD	1,3	3,0	4,0	0	4
	UD	1,5	4,1	6,6	0	6
NaUBR(O)+NaBR(O)	LD	1,6	2,1	2,0	0	2
	UD	2,0	3,0	4,0	0	4
NaUBR(C)+NaBR(C)	LD	0,8	0,6	0	0	1
	UD	1,1	1,0	0,3	0	1

* LD = lower demand curve
UD = upper demand curve

Table VI: **Specific Energy Production Costs as a Function of Separation Plant Size**

	European Plant				USA Plant
Separative Work Capability [10^3 t/a]	2	4	6	8	≈ 20
Unit Separative Work Costs [DM/kg A_T]	368	242	180	160	120
Energy Production Costs [Dpf/kWh]					
LWR	2,30	2,02	1,91	1,85	1,77
LWR (recycle)	2,22	1,98	1,89	1,84	1,77
THTR	1,95	1,78	1,71	1,68	1,63
DUBR	1,92	1,75	1,68	1,65	1,60
NaUBR(O)	1,98	1,83	1,77	1,74	1,70
NaUBR(C)	1,72	1,63	1,60	1,58	1,55

Table VII: Costs of Nuclear Energy Production as a Function of Different Nuclear Strategies and Different Size of Separation Plants

		USA Separation Plant ($\approx 20\cdot10^3$ t/a)			European Separation Plant with Minimal Size for respective Strategy			European Separation Plant /$8\cdot10^3$ t/a A_T7		
		Annual Costs /10^9 DM/a7		Present Worth of Cum.Costs 1970-2000 /10^9 DM7	Annual Costs /10^9 DM/a7		Present Worth of Cum.Costs 1970-2000 /10^9 DM7	Annual Costs /10^9 DM/a7		Present Worth of Cum.Costs 1970-2000 /10^9 DM7
		1990	2000		1990	2000		1990	2000	
LWR (recycle)	LD*	6,90	14,7	41,1	7,2	15,2	42,7	7,2	15,2	42,7
	UD	9,15	21,1	52,3	9,7	22,0	54,5	9,7	22,0	54,5
THTR	LD	6,35	13,5	37,8	6,65	14,1	39,6	6,55	13,9	38,9
	UD	8,40	19,4	48,1	8,80	19,9	49,4	8,8	19,9	49,4
DUBR	LD	6,15	13,3	37,0	6,4	13,9	38,8	6,3	13,4	38,1
	UD	8,10	19,1	47,1	8,5	19,6	48,0	8,5	19,6	48,0
LWR+NaBR(O)	LD	6,75	14,1	40,4	7,15	14,8	42,9	7,0	14,5	41,5
	UD	8,95	20,4	51,4	9,3	21,0	53,0	9,3	21,0	53,0
LWR+NaBR(C)	LD	6,55	13,3	39,2	7,15	14,1	43,1	6,75	13,5	40,4
	UD	8,65	19,3	49,8	9,15	20,0	52,5	8,9	17,7	51,5
NaUBR(O)+NaBR(O)	LD	6,57	13,8	38,7	7,45	15,3	44,3	6,75	14,1	39,7
	UD	8,65	19,8	49,7	9,3	21,0	53,2	8,9	20,3	51,0
NaUBR(C)+NaBR(C)	LD	5,96	12,2	35,1	6,7	13,4	39,0	6,05	12,5	35,6
	UD	7,85	17,9	45,1	8,9	19,5	51,3	7,8	18,1	45,8

* LD = lower demand curve
UD = upper demand curve

5. Discussion of the Results

The results as presented in Chapter 4 may be discussed under the following four major heads:

1. Comparison of the nuclear strategies based on fast breeders with U- and Pu-start-up with that with the most advanced converter.
2. Comparison of the two-type strategies with thermal converters and Pu-fuelled fast breeders and those with fast breeders with U and Pu-start-up.
3. Comparison between the steam cooled fast breeder version and the light water reactor and comparison between the two sodium cooled fast breeder versions.
4. Diffusion plant capabilities and costs as a function of different nuclear reactor strategies.

5.1 Comparison of the Nuclear Strategies Based on Fast Breeders with U- and Pu-start-up with that with THTR Type.

5.1.1 The THTR version indicates, both, an economic advantage and a reduction in U consumption over the one type strategy with LWR alone as well as over coupled strategies with LWR-NaBR (oxide and carbide type) upto the year 2000 as shown below:

	Present worth upper demand curve	U-235 cum.	U-nat upto 2000
THTR	48,1 GDM	530 t	115 000 t
LWR	52,3 "	1 250 t	260 000 t
LWR-NaBRO	51,4 "	1 100 t	225 000 t
LWR-NaBRC	49,8 "	850 t	180 000 t

5.1.2 As in the case of the LWR type, the THTR type is incapable of solving the long term problem of U-reserves although their introduction causes a significant reduction in the accumulated requirement of U-nat.

	U-nat upto 2040
LWR	2 000 000 t
THTR	1 300 000 t

The THTR type reactor has the lowest inventory of U-235 of all the reactors considered here. However, since this U-235 is required in an almost pure form, the diffusion plant capability required is rather high and increases continuously with time. Therefore, like LWR strategies, a nuclear strategy based on THTR alone has to depend always on diffusion plant capabilities for their enriched uranium supply.

5.1.3 The one type strategy with THTR shows only insignificant advantage over the steam cooled version with U-start-up regarding the U-requirement from the short term point of view and shows a considerably higher consumption of uranium over a longer period of time. Economically and technologically the steam cooled version with U-start-up appears to have significant advantages over the THTR type.

year	Present worth 2000	U-235 2000	U-nat 2040
THTR	48,1 GDM	530 t	1 300 000 t
DUBR	47,1 GDM	700 t	600 000 t

5.1.4 The U-nat consumption and the U-235 requirement with THTR strategy are higher than those with two type strategies with breeders with U and Pu start-up. This is particularly obvious in case of the carbide strategies. Economically the THTR type appears to be better than the sodium cooled oxide version although the situation is reversed with the carbide type.

year	Present worth 2000	U-235 2000	U-nat 2040
THTR	48,1 GDM	530 t	1 300 000 t
NaUBR-NaBR(O)	49,7 "	450 t	125 000 t
NaUBR-NaBR(C)	45,1 "	180 t	36 000 t

5.1.5 An important advantage for the THTR type lies in the fact that the total investment cost including the first core is lower than that for any of the reactors considered here (620 MDM as against 650 MDM and above). However, it has the disadvantage of not having a plutonium build-up potential which enables the start-up of more advanced and economic fast breeder types.

5.2 Comparison of the Two Type Strategies with Thermal Converters and Pu-fuelled Fast Breeders and those with Fast Breeders with U- and Pu-start-up.

5.2.1 The point of view which has been prevalent upto the present time that a thermal converter generation is essential for the introduction of Pu-fuelled fast breeders no longer appears to be valid. A fast breeder with U-235 start-up contains so to say its own particular type of converter and supplies all its Pu required regardless of the breeding ratio. Such a system coupled with the Pu-breeder type offers significant economic and raw material advantages over the normal thermal converter-breeder coupled strategies.

year	Present worth 2000	U-235 2000	U-nat 2040
LWR+NaBR(O)	51,4 GDM	1 100 t	640 000 t
NaUBR(O)+NaBR(O)	49,7 "	450 t	125 000 t
LWR+NaBR(C)	49,8 "	850 t	320 000 t
NaUBR(C)+NaBR(C)	45,1 "	180 t	36 000 t

5.2.2 On the basis of the discussion in 5.2.1 it is quite evident that the introduction of Pu-fuelled fast breeders is dependent on their technical feasibility and better economics and not on the availability of Plutonium from thermal converters or breeders. On account of this, the great importance attached to the breeding ratio of fast breeders until now looses a part of its significance. This is particularly evident from the results of the strategy based on steam cooled version.

5.3 Comparison Between the Steam Cooled Fast Breeder Version and the Light Water Reactor and Comparison Between the Two Sodium Cooled Fast Breeder Versions.

5.3.1 It is surprising to note that the strategy based on steam cooled version with U-start-up indicates a number of advantages. Because of its favourable economic structure the total energy generation costs are the lowest except those with strategies with carbides. The U-requirement in this strategy is also reduced significantly over all the other one-type-strategies and the two-type-strategies with LWR-NaBR. Besides that, the steam cooled reactor strategy is capable of storing large amounts of Pu produced, in a more economic manner than the light water types for subsequent utilization in more economic breeders. This version corresponds to a natural evolution of the LWR type and can utilize the recycled Pu more economically. It appears reasonable to assume that this type would be ready for large scale introduction during the late seventies.

5.3.2 The sodium cooled fast breeders with oxide type fuel do not appear to be economically as attractive as the THTR type or the steam cooled version with Uranium start-up. It appears that the highly efficient sodium cooling requires the highly efficient carbide fuel to bring out the inherent and the large potential of the sodium cooling. For this reason the carbide type fuel seems to be the ideal one for the sodium fast breeder systems and the oxide fuel represents only an intermediate goal for this type of breeders.

5.4 Diffusion Plant Capabilities and Costs as a Function of Different Nuclear Reactor Strategies.

5.4.1 The lowest present worth of the energy generation costs upto the year 2000, amongst all the non-carbide strategies are given by the steam-cooled breeder strategy with U-235 start-up ($48 \cdot 10^9$ DM with a European Diffusion plant and $47,1 \cdot 10^9$ DM with American U-235 supply). This strategy, therefore, may form a suitable basis for assessing the proper size of a European diffusion plant. The required separative work capability for this strategy is about $8 \cdot 10^6$ kg unit/a in the year 2000. A lower separative work capability and therefore a lower capital investment for the diffusion plant may be obtained by going over to some other strategies, for example, to the ones with sodium cooled reactors with Plutonium or uranium start-up. The present worth of the total energy costs for these strategies are however higher so that the lower diffusion plant capital investments do not pay off. For the non-carbide strategies, therefore, the most suitable diffusion plant capacity appears to be about $8 \cdot 10^6$ kg/a. For this size, a European plant seems justifiable, as the probable difference in the present worth of the energy costs between those with enriched uranium from the USA and those from a European plant is less than $1 \cdot 10^9$ DM over a period of 30 years, which may then be taken as a long term insurance for the supply of U-235.

5.4.2 The picture changes entirely if the carbides turns out to be a suitable fuel for breeders. With this fuel the maximum required diffusion plant capacity upto the year 2000 is only $1 \cdot 10^6$ kg/a. Since the unit separative work costs in such a small plant is expected to be very high (DM 560/kg instead of DM 160/kg in a $8 \cdot 10^6$ kg/a plant), the present worth actualized to 1970 of the total energy costs come out to be $51,3 \cdot 10^9$ DM; with enriched uranium supplied from the USA, these costs are only $45,1 \cdot 10^9$ DM i. e. lower by about $6 \cdot 10^9$ DM. This difference corresponds to about $12 \cdot 10^9$ DM if not actualized.

These figures indicate two significant disadvantages of a small diffusion plant. Firstly, the specific separative work costs are very high which cause an increase in the energy generation costs of individual reactors with enriched uranium (Ref. Tab. 6). Secondly, the energy generation costs in different nuclear strategies based on such small plants may increase considerably and remain high so long as those strategies depend on such small plants for their enriched uranium supply. Coupled with these considerations, if reference is made to the fact that with carbide breeders with U-235 start-up, the total accumulated requirement of pure U-235 upto the year 2000 would be only 180 t (on the basis of models considered here), it appears reasonable to obtain this relatively small amount entirely from the USA. Such a course of action seems all the more justifiable in view of the fact that in case the carbides prove their worth, the U-235 requirement in the USA itself would be reduced so that the existing US diffusion plant capability would be in a position to supply to a larger installed nuclear capacity than that estimated today.

5.4.3 In case the carbide line does not succeed, the present worth difference for the strategies with the fast steam cooled breeders between the American and European supply of enriched uranium is only $1 \cdot 10^9$ DM as mentioned above, whereas the difference comes out to be larger than $6 \cdot 10^9$ DM in case of the carbide strategy. In other words, the use of the carbides decreases the really necessary amount of U-235 in Europe and thereby makes the installation of an European diffusion plant uneconomic and superfluous. In case of a steam cooled oxide strategy on the other hand, a large scale diffusion plant is necessary and because of the sound economic structure of the latter, the economics of this strategy also becomes attractive.

However, a cross comparison between the steam cooled version with the largest European diffusion plant and the carbide version with the American supply gives a $3 \cdot 10^9$ DM advantage for the carbide line, indicating its economic superiority over the steam cooled version.

5.4.4 The conclusions 5.4.1 to 5.4.3 indicate that in case the carbide line of fast breeders does not turn out to be as successful as has been assumed in the foregone analysis, a diffusion plant of at least $8 \cdot 10^6$ kg/a capacity should be installed in Europe. On the other hand, if the carbide line becomes successful, no diffusion plant is required to be installed and the necessary amounts of U-235 which are relatively small, can be obtained from an outside source. Since the technical feasibility of the carbide line and the large scale diffusion plant requirement can be assessed only during the early eighties, no decision on the diffusion plant installation should be taken before that time.

6. Conclusions

The discussions of the results as given in chapter 5 can be summarized in the form of the following conclusions:

6.1 Although the THTR which appears to be the most advanced and technologically feasible converter at present is incapable of solving the problem of U supply from a long term point of view it shows more favourable economics and short term U requirement as compared to the single type strategy with LWR or the two type strategies with LWR and NaBR(O). However, the steam cooled version and sodium cooled carbide version of fast breeders, both with U-235 start-up, appear to offer significant economic and raw material advantages over the THTR.

6.2 It is not necessary to have a thermal converter based nuclear strategy to provide for plutonium required for the subsequent more economic breeder. With the help of U-235 start-up any breeder represents its own converter type for the supply of its own plutonium and therefore the rate of introduction of this type of reactors is independent of the breeding ratio.

6.3 The steam cooled version of fast breeders with U-235 start-up represents the legitimate, economic and the natural evolution of the light water reactor type and provides the best means for Pu recycling. The most efficient sodium cooling which requires a special technology calls as a final target for the most efficient carbide type fuel to bring out the inherent and significant advantages of a future high performance breeder. Thus because of the different degrees of difficulties associated with the steam cooled oxide and the sodium cooled carbide versions which may lead to a phased introduction of the two types, both, the steam cooled and the sodium cooled fast systems, have to be developed simultaneously. The late seventies appear to be a proper target date for the introduction of the steam cooled version, whereas that for the sodium cooled carbide version can be the eighties.

6.4 In case the carbide line does not appear to be successful a diffusion plant with a capacity of at least $8 \cdot 10^6$ kg/a has to be installed in Europe. If the carbide line can meet its target values, no diffusion plant is required. The decision regarding its installation needs to be taken only during the eighties.

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