ANALYSIS OF THE CONDITIONS OF EQUILIBRIUM OF THE MIXED NUCLEAR ENERGY SYSTEM (MNES)

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Summary

Reported in this work are the results of calculations on mixed nuclear energy systems (MNES) based on a mathematical model that has been presented in another publication of the authors [1]. Assuming different types of fast and thermal reactors, the optimum composition and nuclear fuel utilization characteristics of the so called mixed nuclear energy system at fuel equilibrium (MNESFE) are determined, and conclusions are drawn from the results to many important system characteristics.

The definition of the Mixed Nuclear Energy System (MNES) was given in another work [1] in which the mathematical model and algorithm of the conditions of equilibrium of MNES were also presented.

In the present work, calculations are made on the basis of this model assuming different types of fast and thermal reactors, then the results obtained are analyzed in respect of feasibility as well as efficiency of utilization of nuclear fuel reserves. The investigations take the reactor types included in Tables I and II of [1] into consideration, together with the fuel circulation parameters given in the Tables. Note that these parameters apply to uranium fuelled thermal reactors only and they will vary if the fuel is enriched with plutonium. However, no reliable data on such reactors are available and, although thermal reactors in a Mixed Nuclear Energy System at Fuel Equilibrium (MNESFE) utilize fuel enriched with plutonium, we had to confine ourselves to using data given in the above Tables for the calculations. The calculations can be repeated using the adequate data if available. The analyses showed that this choice had little effect on the results and on the conclusions that could be drawn from them.

Nuclear energy system containing fast reactors alone

The condition of equilibrium of a nuclear energy system containing fast reactors alone is described in Chapter 5 of [1]. Here we showed that the system containing fast reactors alone is at fuel equilibrium if the doubling time of the system capacity had compiled with the doubling time of the fissile material of fast reactors (and/or) i.e. if the exponent of capacity growth of the system is identical with the 'fast alone exponent'. This condition is described mathematically by relationship (70) in [1].

Tabulated in Table I are the calculated values of 'fast alone exponent' and fissile material doubling time for different types of nuclear power plants, assuming different external cycle lengths (Θ). In the calculations, the approximation $\tau_t+\vartheta_t=\tau_f+\vartheta_f=\Theta$ was used.

The Table allows the following important conclusions to be drawn:

— There is a considerable variance in the doubling time of fissile material of fast reactors of different type even in case the external cycle length is identical. Some types of a long doubling time are incapable of keeping pace with the capacity growth rate of a realistic system (see e.g. 5/c in [1]) while the extremely short fissile material doubling time of other types would certainly result in excess plutonium production (see e.g. 5/b in [1]).

— Even within given type of fast reactor, ample possibilities offer themselves for reducing the fissile material doubling time i.e. for improving the efficiency of utilization of the nuclear fuel reserves (cf. LMFBR/1 → LMFBR/3 transition).

— The effect of the external cycle length on the doubling time of fissile material is conspicuously strong. A reduction of the external cycle length may considerably compensate for the unfavourable effect of a small breeding factor (a reduction of 1 to 2 years in external cycle length compares well with an increase by 0.1 to 0.2 of the breeding factor in some cases). Economically, this fact may be of tremendous importance provided that the reduction of the cycle length requires less expenditure from a technical point of view than the increase of the breeding factor of fast reactors.

Capacity ratios for MNES of different combinations of thermal and fast reactors

The contribution of nuclear power plants with thermal reactor (P_t) to the total capacity of the nuclear energy system assumed to contain different types of thermal and fast reactors can be calculated by solving equation (42), (56) and (79) of [1] for $P_t(t)$ and $P_f(t)$. Figures 1 through 6 have been presented to illustrate the results. The Figures give the relative value

$$p_t=\frac{P_t}{P_t+P_f}\cdot 100 \qquad (\%) \qquad (1)$$

of the capacity of nuclear power plants with thermal reactor as a function of exponent of capacity growth c (Figs 1 through 3) for two different external cycle

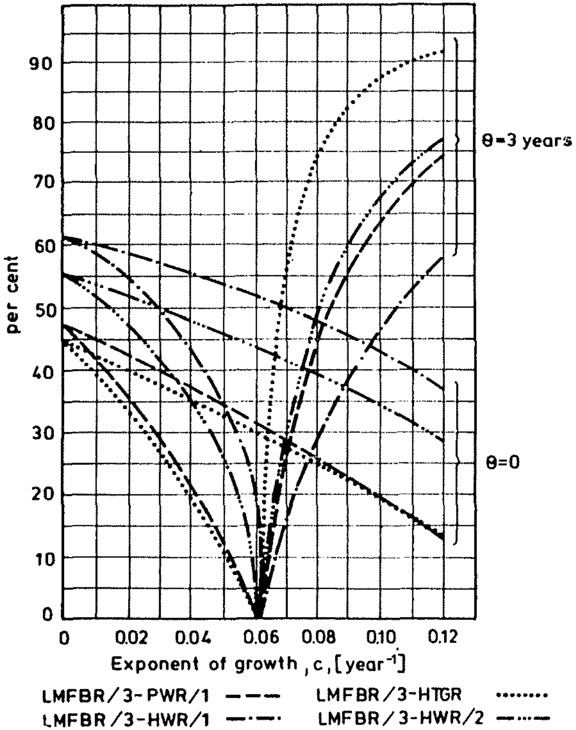

Fig. 1. Ratio of the capacity of nuclear power plants with thermal reactors as a function of exponent of capacity growth in a MNES consisting of LMFBR/3 + thermal reactors (in the case of $\Theta = 0$, and $\Theta = 3$ years)

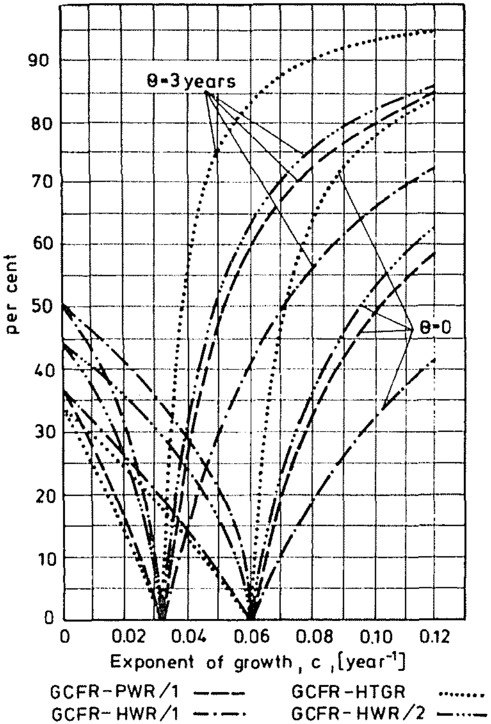

Fig. 2. Ratio of the capacity of nuclear power plants with thermal reactors as a function of exponent of capacity growth in a MNES consisting of GCFR + thermal reactors (in the case of $\Theta = 0$, and $\Theta = 3$ years)

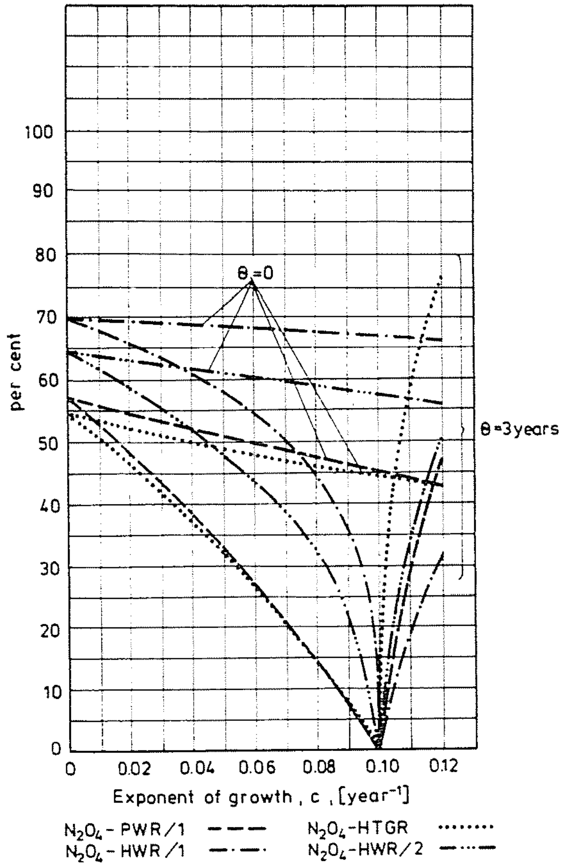

Fig. 3. Ratio of the capacity of nuclear power plants with thermal reactors as a function of exponent of capacity growth in a MNES consisting of N_2O_4-cooled fast reactors + thermal reactors (in the case of $\Theta = 0$ and $\Theta = 3$ years)

lengths ($\Theta = 0$ or 3 years) as parameter, and as a function of external cycle length for two different exponents of capacity growth ($c = 0.04$ or 0.08 year^{-1}) as parameter. Figures 1 and 4 are related to LMFBR/3, Figs 2 and 5 to GCFR while Figs 3 and 6 to N_2O_4-cooled fast reactor, each fast reactor being associated with four different types of thermal reactors.

The following important conclusions can be drawn from the Figures:

— The ratio of thermal reactor capacity within the MNESFE ($c < c_f$) depends first of all on the conversion factor of thermal reactors and breeding factor of fast reactors. Usually, the higher these values are the larger number of thermal reactors may be contained in the nuclear energy system out upset of the equilibrium. Some contribution can be attributed also to the value of the specific fuel loading. As seen, in case of given type of thermal reactor, the value

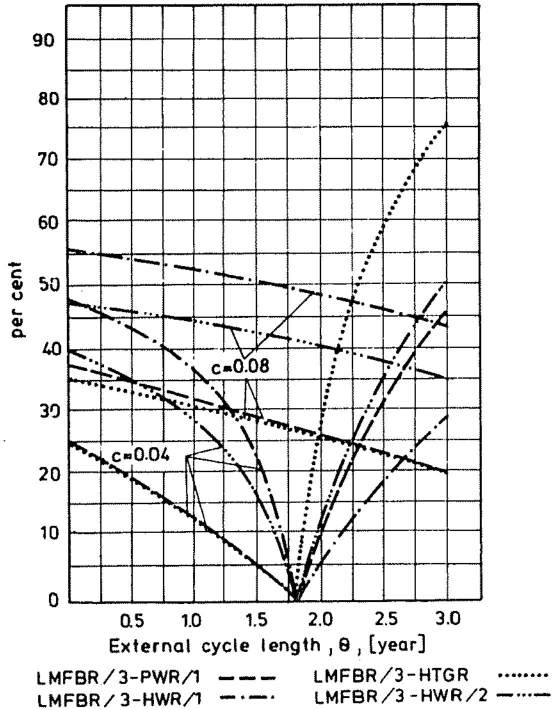

Fig. 4. Ratio of the capacity of nuclear power plants with thermal reactors as a function of external cycle length (Θ) in a MNES consisting of LMFBR/3 + thermal reactors (in case of $c = 0.04$ year^{-1} and $c = 0.08$ year^{-1})

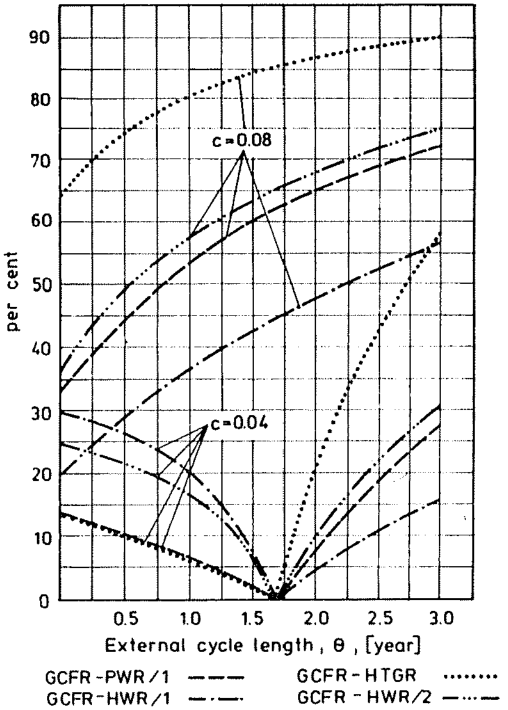

Fig. 5. Ratio of the capacity of nuclear power plants with thermal reactors as a function of external cycle length (Θ) in a MNES consisting of GCFR + thermal reactors (in case of $c = 0.04$ year^{-1} and $c = 0.08$ year^{-1})

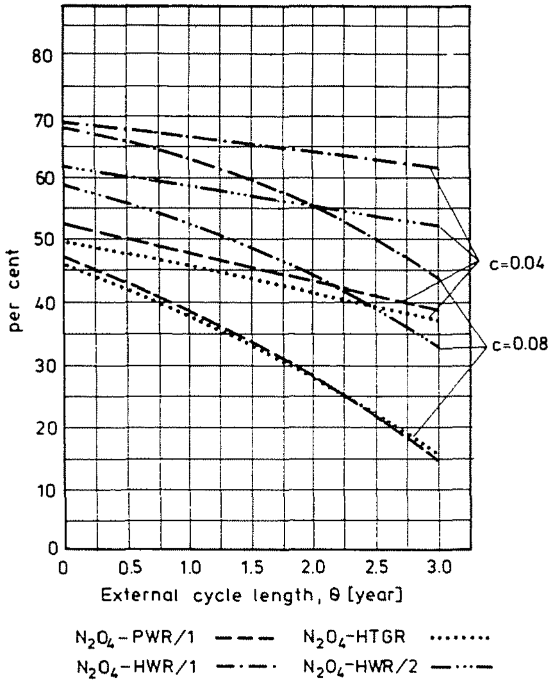

Fig. 6. Ratio of the capacity of nuclear power plants with thermal reactors as a function of external cycle length (Θ) in a MNES consisting of N_2O_4-cooled fast reactors + thermal reactors (in case of $c = 0.04$ year^{-1} and $c = 0.08$ year^{-1})

of p_t is the highest for the N_2O_4-cooled fast reactor and the lowest for GCFR. Obviously, this difference comes from the divergence of the breeding factors. In case of given type of fast reactor, the highest value of p_t is obtained for HWR/1 and lowest p_t for PWR or HTGR owing first of all to the high conversion factor of HWR/1.

— In case of a MNES containing fast reactors of insufficient breeding factor ($c > c_f$), the contribution of the conversion factor and breeding factor is similarly predominating but now in the opposite sense: the higher is the conversion factor, the smaller is the number of thermal reactors required to produce plutonium for the fast reactors (of course, other factors have also some — secondary — role). Accordingly, such a system contains thermal reactors of maximum number in case of PWR and especially HTGR, and in a minimum number in case of HWR/1.

— The role of the external cycle length (Θ) is significant also in respect of the ratio of thermal and fast reactor capacity. In case of the MNESFE ($c < c_f$), the longer is the external cycle length (Θ), the lower is the ratio of thermal reactor capacity within the system, and the opposite is true in case of $c > c_f$.

Hence, as follows also from what has been said in Chapter I, efforts shall be made to reduce the external cycle length as far as possible in order to comply with the conditions of equilibrium also in case of the possible highest system capacity growth rate and highest ratio of thermal reactor capacity.

Utilization efficiency of nuclear fuel reserves in case of mixed nuclear energy systems of different combinations of thermal and fast reactors

The utilization efficiency of nuclear fuel reserves is given by relationship (46) in [1]. The results of our calculations are illustrated in Figs 7 through 12, the Figures also allowing conclusions to be drawn for the cases described in Chapter II (natural uranium being assumed as the nuclear fuel in the calculations):

— In case of an exponent of system capacity growth lower than the 'fast alone exponent' ($c<c_f$), the nuclear fuel utilization efficiency that can be achieved in a MNES is usually not inferior to that in a system containing fast reactors alone. Moreover, in a MNESFE containing PWR/1 and especially HTGR, the utilization efficiency is even better than in a MNES containing fast reactors only, independently of which type of fast reactor is associated with the thermal reactor (see Figs 7 through 9).

— In case $c<c_f$ (not too close to c_f) with the same growth rate of system capacity, the nuclear fuel utilization efficiency that can be achieved in the MNESFE depends only slightly on the type of fast reactors while the dependence on the type of thermal reactor is significant.

In case of a realistic exponent of capacity growth of $c=0.04$ to 0.10 year^{-1}, the utilization efficiency will amount to only some per cents in any system (provided of course that the condition $c<c_f$ is fulfilled). That means that the widely accepted opinion according to which the use of fast reactors will result in a utilization efficiency of a couple of ten per cents is wrong.

An analysis of the results shows that the utilization efficiency depends especially strongly on the specific fuel loading (m_{ui}) of the reactors (first of all of the thermal reactors), viz. the lower is this value m_{ui} the higher is the utilization efficiency. This explains why quite a poor utilization efficiency can be achieved with HWR/1 of considerably better breeding capacity (higher conversion factor) but of a much larger specific fuel loading as compared with PWR/1 and HTGR of inferior conversion factor but of relatively small specific fuel loading (see later in this work for details).

The value of the nuclear fuel utilization efficiency changes rapidly in the vicinity of the 'fast alone exponent'. In case $c>c_f$ i.e. in the MNES not at fuel equilibrium, the utilization efficiency lies well — perhaps by more than one order

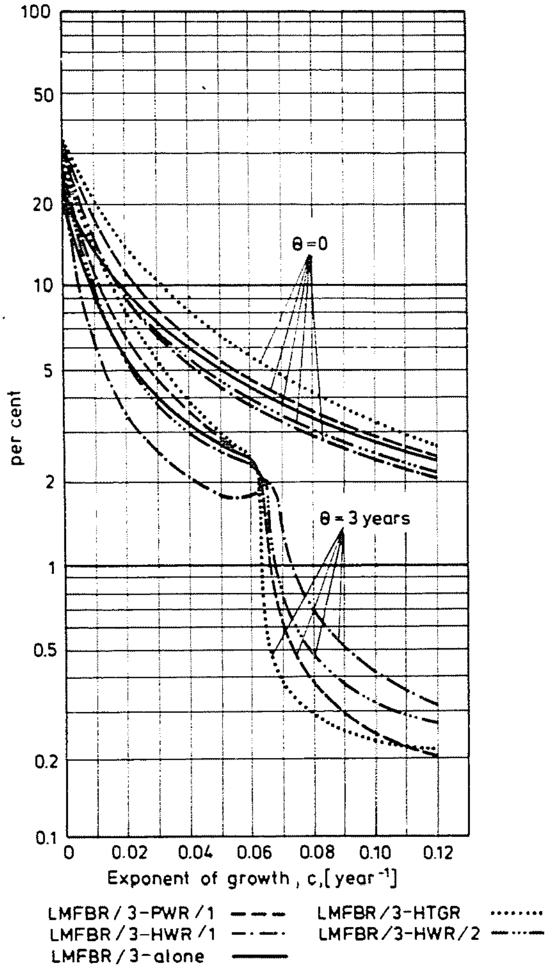

Fig. 7. Natural uranium utilization efficiency as a function of exponent of capacity growth in a MNES consisting of LMFBR/3 + thermal reactors (in case of $\Theta = 0$ and $\Theta = 3$ years)

of magnitude — below that achievable in the MNESFE i.e. in case $c < c_f$. Therefore, the value of the 'fast alone exponent' is not indifferent at all. In this respect, the type of the fast reactor in the mixed system is decisive: in the mixed system, the fast reactor can be considered to be the better having the higher fast alone exponent i.e. the shorter fissile material doubling time (see Table I). The achievements in the development of LMFBR (see LMFBR/1→LMFBR/3 development) shall be evaluated in this light, and this enlights at the same time why not much can be expected of GCFR as far as nuclear fuel utilization is concerned (see Figs 8 and 11). The N_2O_4-cooled fast reactor seems to be rather attractive but unfortunately this type exists only on the designer's drawing

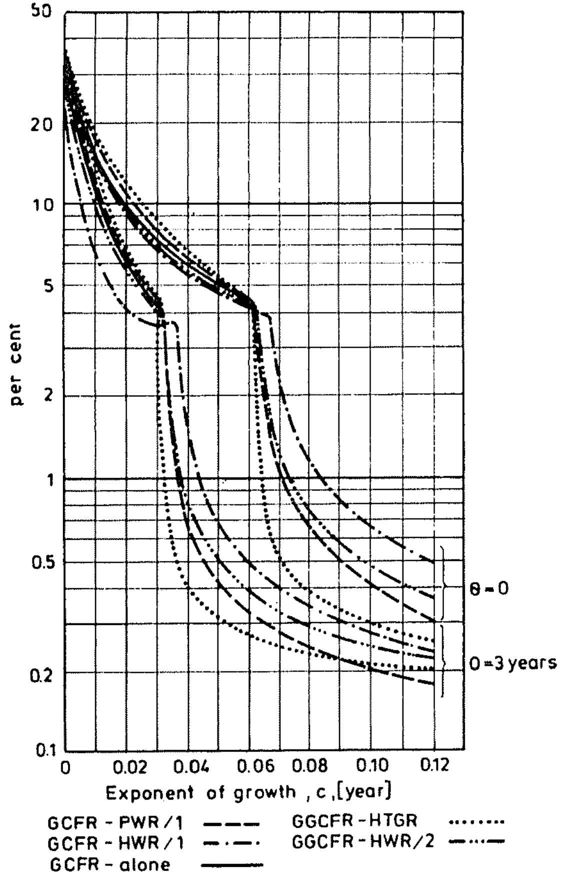

Fig. 8. Natural uranium utilization efficiency as a function of exponent of capacity growth in a MNES consisting of GCFR + thermal reactors (in case of $\Theta = 0$ and $\Theta = 3$ years)

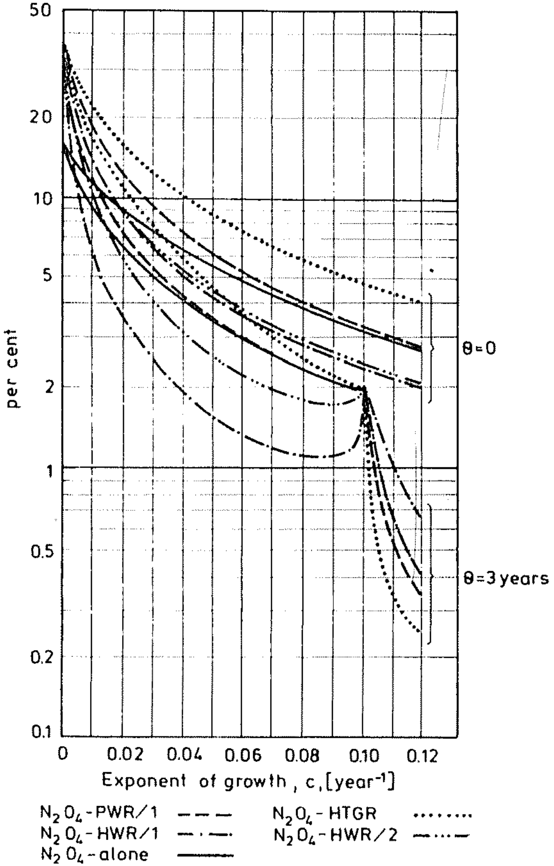

Fig. 9. Natural uranium utilization efficiency as a function of exponent of capacity growth in a MNES consisting of N_2O_4-cooled fast reactors + thermal reactor (in case of $\Theta = 0$ and $\Theta = 3$ years)

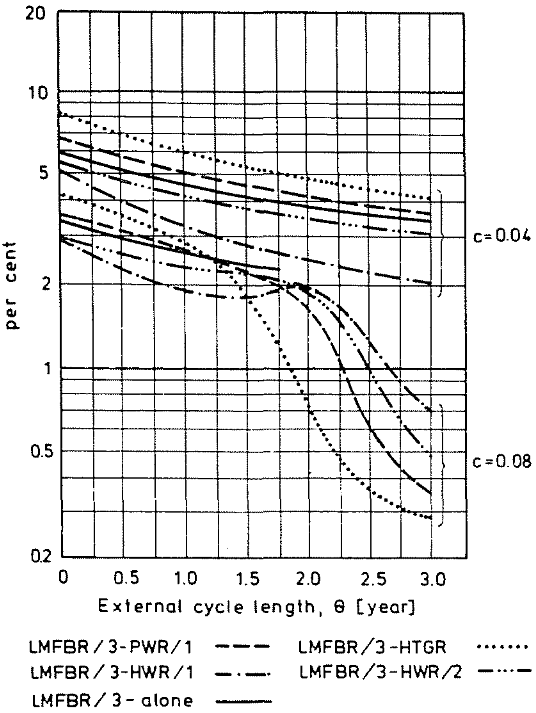

Fig. 10. Natural uranium utilization efficiency as a function of external cycle length (Θ) in a MNES consisting of LMFBR/3+thermal reactors (in case of $c=0.04$ year^{-1} and $c=0.08$ year^{-1})

paper for the time being. Anyway, if only a part of the expected development were successful, a sufficient number of thermal reactors could be supplied with fissile material by such a fast reactor (see Figs 1 through 3) and, on the other hand, quite a good nuclear fuel utilization efficiency could be achieved even in case of relatively fast capacity growth rates and long external cycle lengths (see Figs 9 and 12). In this respect, the advanced versions of LMFBR (especially LMFBR/3) range between GCFR and N_2O_4-cooled fast reactor.

The Figures allow of a judgement of the significant influence of the external cycle length on the nuclear fuel utilization efficiency. As can be seen in Figs 4 thru 6, a so called '*fast alone external cycle length*' (Θ_f) can be determined for any combination of fast and thermal reactors and any system capacity growth rate, below which the system is and above which it is not at fuel equilibrium (see Figs 4 through 6). A rapid change in the value of utilization efficiency occurs especially in the vicinity of Θ_f and therefore a reduction of the actual external cycle length below Θ_f is worth by any effort. The choice of the best type of fast reactor is significant also in this respect. E.g. LMFBR/3 and the N_2O_4-cooled fast reactor afford a relatively long external cycle length,

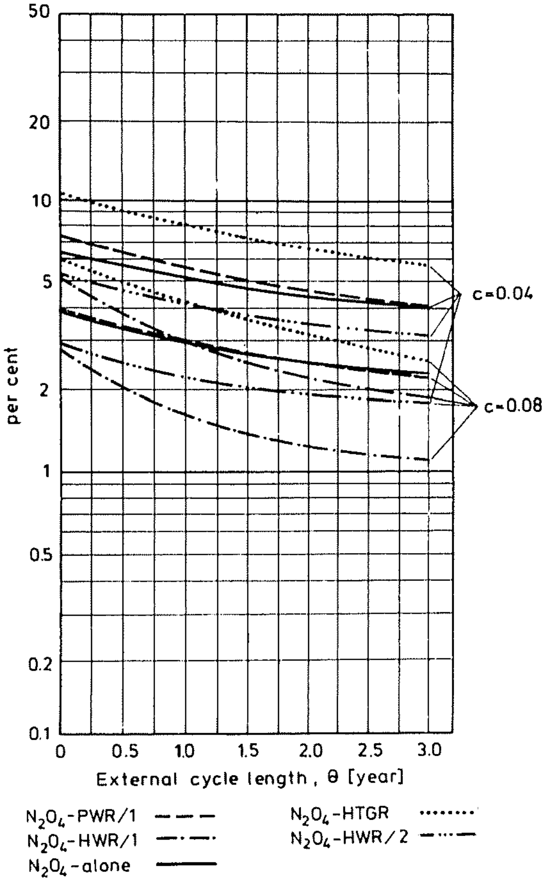

Fig. 11. Natural uranium utilization efficiency as a function of external cycle length (Θ) in a MNES consisting of GCFR + thermal reactors (in case of $c = 0.04$ year^{-1} and $c = 0.08$ year^{-1})

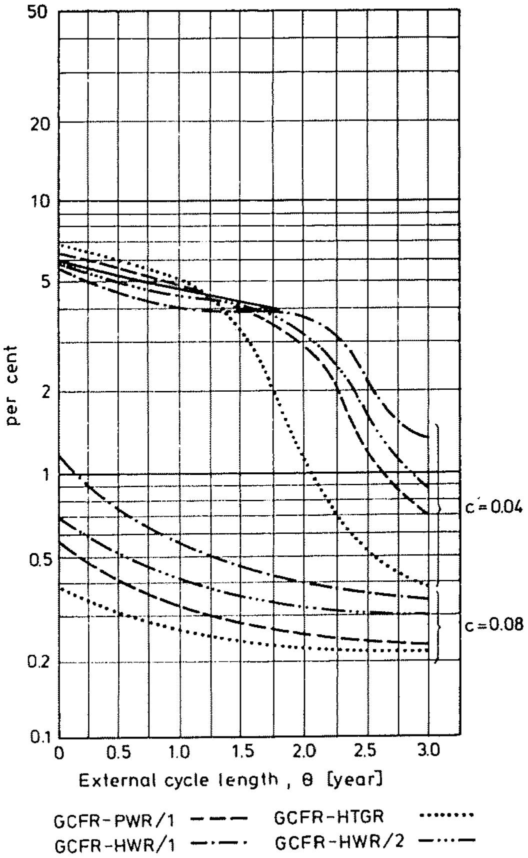

Fig. 12. Natural uranium utilization efficiency as a function of external cycle length (Θ) in a MNES consisting of N_2O_4-cooled fast reactor + thermal reactors (in case of $c = 0.04$ year^{-1} and $c = 0.08$ year^{-1})

however, the other types result in rather unfavourable conditions even in case of an external cycle length of $\Theta=1$ year. In this respect, $\Theta=3$ years for LMFBR/3 are compatible with $\Theta \cong 0.6$ year for LMFBR/2. It is a question of further analysis whether the development required for the LMFBR/2 →LMFBR/3 or $\Theta=3$ years → $\Theta \cong 0.6$ year transition is more feasible and profitable.

Combination of pressurized water reactor with different types of fast reactor

The decisive majority of nuclear power plants being now in operation, under construction, or in the design phase in the world contain light-water cooled reactors and even within this type, pressurized water reactors are predominating. Therefore the share of PWRs within the system will be considerable by the time fast reactors enter the system increasingly and then by the time the conditions of equilibrium exist. Beyond the general problem posed in Chapter 3, the question arises now which type of fast reactor should reasonably be combined with the thermal reactor of given type — PWR — in the mixed system. Presented with a view to illustrate the results obtained in this relation are Figs 13 and 14 where the ratio of capacity (Fig. 13) and the nuclear fuel utilization efficiency (Fig. 14) are given as a function of exponent of system capacity growth for PWR/1 + different fast reactor combinations, assuming an external cycle length of $\Theta=0$ and $\Theta=3$ years.

It can be seen in the Figures that in case of $\Theta=0$, the system can tolerate thermal reactors in largest number when PWR/1 is associated with N_2O_4-cooled fast reactor and that also the PWR/1 + LMFBR/3 combination results fairly good conditions (e.g. in case $c=0.06$ *year*$^{-}$1, round 1/3 of the system capacity comes from PWRs, and in case $c=0.10$ year^{-1}, the ratio of PWR capacity comes to about 20%). Under identical conditions, the value of nuclear fuel utilization efficiency in a PWR/1 + LMFBR/3 combination lies only slightly below that obtainable in a PWR/1 + N_2O_4 fast reactor combination.

In case of an external cycle length of $\Theta=3$ years, the chances of a PWR/1 + LMFBR/3 combination decline considerably and the conditions of equilibrium can be ensured only if $c<0.06169$ year^{-1} (or $T_{2x}>11.25$ years). If the growth is smaller than the value given above a utilization efficiency of some percents can be achieved with the above combination, being almost equal with that in a PWR + N_2O_4 fast reactor combination. However, the value of utilization efficiency reduces rapidly, by about an order of magnitude, as the rate of system growth increases, and lies well below the value obtainable in the PWR/1 + N_2O_4 fast reactor combination where the conditions of equilibrium can be ensured if $c<0.09927$ year^{-1} (or $T_{2x}>6.98$ year).

Table I

Fast alone exponent c_f for different fast reactor types and external cycle length (Θ)

External cycle length (year)			0	0.5	1.0	2.0	3.0
Fast alone exponent, c_f (year^{-1})	LMFBR/1	(b=1.24)[1]	0.0647	0.0526	0.0445	0.0341	0.0277
	LMFBR/2	(b=1.32)[1]	0.0818	0.0644	0.0533	0.0398	0.0324
	LMFBR/3	(b=1.58)[1]	0.156	0.123	0.102	0.0767	0.0617
	GCFR	(b=1.37)[1]	0.0605	0.0526	0.0467	0.0382	0.0324
	N_2O_4-cooled	(b=1.62)[1]	0.559	0.306	0.214	0.135	0.099
Fissile material doubling time, T_{2x} (year)	LMFBR/1	(b=1.24)[1]	10.71	13.18	15.58	20.33	25.02
	LMFBR/2	(b=1.32)[1]	8.47	10.76	13.00	17.42	21.30
	LMFBR/3	(b=1.58)[1]	4.44	5.64	6.80	9.04	11.23
	GCFR	(b=1.37)[1]	11.46	13.18	14.84	18.15	21.39
	N_2O_4-cooled	(b=1.62)[1]	1.24	2.27	3.24	5.13	7.00

[1] b — breeding factor

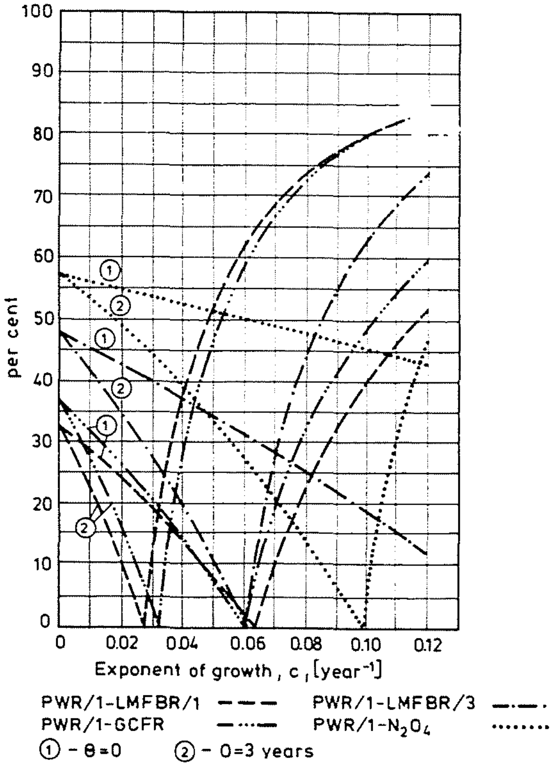

Fig. 13. Ratio of the capacity of nuclear power plants with PWR/1 as a function of exponent of capacity growth in a MNES consisting of PWR/1 + fast reactors (in case of $\Theta = 0$ and $\Theta = 3$ years)

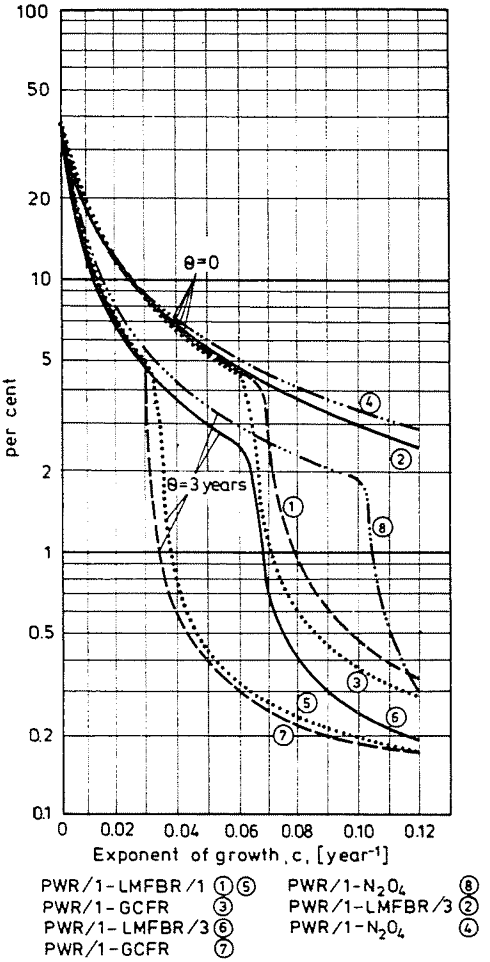

Fig. 14. Natural uranium utilization efficiency as a function of exponent of capacity growth in a MNES consisting of PWR/1 + fast reactors (in case of $\Theta = 0$ and $\Theta = 3$ years)

Since the practical feasibility of the N_2O_4-cooled fast reactor is still questionable, urgent interests are involved in the reduction of the external cycle length. If e.g. this time were reduced to 1 year, then the conditions of equilibrium i.e. a high utilization efficiency could be ensured even by LMFBR/3 at a system growth rate of $c < 0.102$ year^{-1} (or $T_{2x} > 6.8$ years), a system quite acceptable in practice.

The Figures evidently show that neither LMFBR/2 nor GCFR can be combined with PWR to bring about the conditions of equilibrium as these types result in an undesirably long fissile material doubling time and/or low 'fast alone exponent' even in case of a rather short external cycle length (see Table I).

Effect of fuel engaged in the reactors on utilization efficiency

As can be read in [1], only part of the nuclear fuel demand of the nuclear energy system is used to substitute for the fuel continuously consumed in the operating reactors while the rest is built into the initial loading of new reactors entering the system. The ratio of this latter quantity within total fuel consumption depends first of all on the system capacity growth rate (i.e. on the ratio of new reactors) and on the specific fuel loading of the reactors.

The results of selected calculations are illustrated in Figs 15 and 16. Figure 15 shows the ratio of fuel consumed in the initial loading of new reactors within total fuel consumption as a function of the exponent of capacity growth in a system containing LMFBR/3 in combination with different thermal reactors, assuming that $\Theta = 0$. The Figure explains why a mixed system is not quite inferior but in some cases even superior to the system containing fast reactors alone in respect of utilization of nuclear fuel. It can be seen in the Figure that about 75 to 90% of nuclear fuel consumption comes from the fresh fuel loading of new reactors, that means that the utilization efficiency depends decisively on

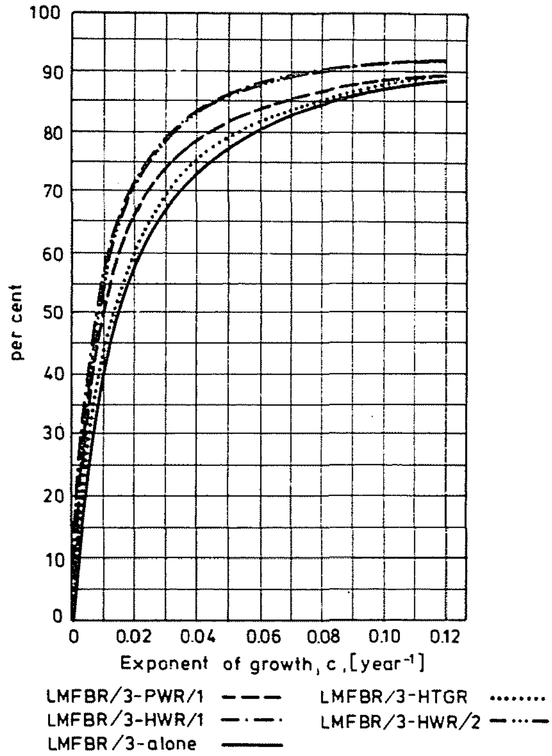

Fig. 15. Ratio of natural uranium demand for the initial loading in a MNESFE consisting of LMFBR/3 + thermal reactors in case of $\Theta = 0$

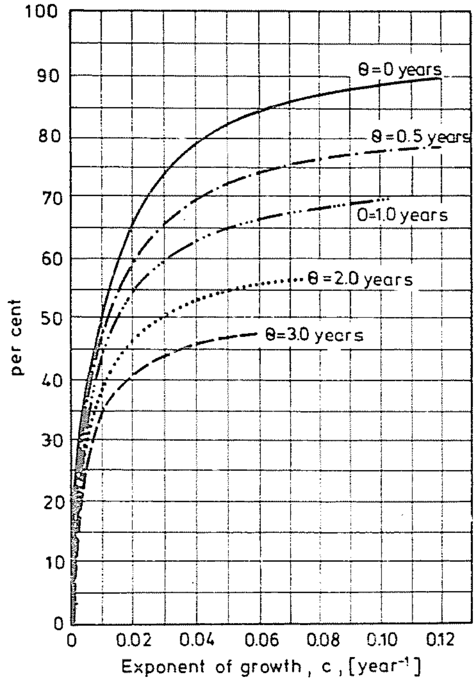

Fig. 16. Ratio of natural uranium demand for the initial loading in a MNESFE consisting of LMFBR/3 + PWR/1 (in case of $\Theta = 0$; 0.5; 1.0; 2.0; 3.0 years)

the specific fuel loading of the reactors. From this viewpoint, there is little difference between LMFBR and e.g. PWR and HTGR as seen in Tables I and II of [1]. What we have said now explains why the utilization efficiency of HWR + fast reactor combinations is inferior to that of other system combinations. According to the data of Tables I and II mentioned above, the specific fuel loading of HWR is very large as compared with the other reactor types.

In case of a realistic external cycle length, the fuel demand of new reactors is not so decisive although it generally exceeds the continuous consumption of operating reactors even in this case as illustrated in Fig. 16, indicating the fuel demand of the initial loading of new reactors in case of LMFBR/3 + PWR/1 MNESFE as a function of exponent of system capacity growth for different external cycle lengths as parameters.

Potential uses of depleted uranium in the MNESFE

Depleted uranium (of a ^{235}U content of 0.2 to 0.3%) is expected to accumulate in considerable amounts as a result of isotopic enrichment in the period preceding the time the conditions of equilibrium are prevailing. (This period will be discussed in detail in the next Chapter.)

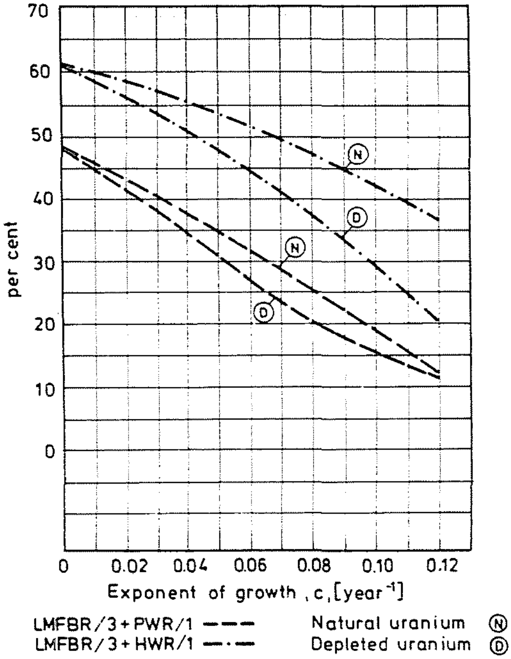

Fig. 17. Ratio of the capacity of nuclear power plants with thermal reactors as a function of exponent of capacity growth in a MNES consisting of LMFBR/3+PWR/1 and LMFBR/3+HWR/1 in case of the use of natural uranium and depleted uranium ($\Theta = 0$)

Certainly, this depleted uranium finds use in the breeding blanket of fast reactors. However, after enrichment with plutonium, the same depleted uranium can no doubt be used also to fuel thermal reactors in the MNESFE. Calculations to confirm this have been carried out using the relationships derived in [1]; here only the parameters in the equations had to be choosen accordingly to the depleted uranium.

Figure 17 and Table II illustrate the results of calculations. Figure 17 shows the ratio of thermal reactor capacity as a function of the exponent of capacity growth for LMFBR/3+PWR/1 and LMFBR/3+HWR/1 MNESFE combinations fuelled with natural uranium and, on the other hand, with depleted uranium, assuming an external cycle length of $\Theta = 0$ (the value of 'fast alone exponent' being 0.156 year^{-1}). The Figure shows little difference in the ratio of thermal and fast reactor capacity between the two types of fuel in a LMFBR/3+PWR/1 system, especially in case of low values of the exponent of capacity growth. Obviously, this can be attributed to the fact that in case of an enrichment to 2.5–4%, it makes little difference whether the plutonium is added to uranium of a fissile material content of 0.7%, or 0.2 to 0.3%. The differences in the ratio of thermal and fast reactor capacity are, however, significant in case of

Table II

Nuclear fuel utilization efficiency as a function of exponent of capacity growth for different combinations of nuclear energy system (in case $\Theta = 0$), (per cent)

Exponent of growth, c (year^{-1})	LMFBR/3 alone		LMFBR/3+PWR/1		LMFBR/3+HWR/1		LMFBR/3+HTGR	
	N. U.	D. U.	N. U.	D. U.	N. U.	D. U.	N. U.	D. U.
0.00	21.52	21.52	34.41	34.37	32.35	32.34	36.02	35.96
0.01	12.80	12.80	16.59	16.56	13.74	13.78	19.91	19.79
0.02	9.11	9.11	10.91	10.88	8.76	8.82	13.52	13.38
0.03	7.07	7.07	8.11	8.09	6.45	6.51	10.12	10.01
0.04	5.78	5.78	6.45	6.43	5.11	5.19	8.02	7.93
0.05	4.89	4.89	5.35	5.32	4.25	4.33	6.59	6.52
0.06	4.23	4.23	4.56	4.54	3.64	3.73	5.55	5.49
0.07	3.73	3.73	3.97	3.95	3.19	3.29	4.76	4.71
0.08	3.34	3.34	3.52	3.50	2.85	2.95	4.14	4.10
0.09	3.02	3.02	3.15	3.14	2.58	2.69	3.65	3.61
0.10	2.76	2.76	2.86	2.84	2.36	2.48	3.24	3.21
0.11	2.54	2.54	2.61	2.60	2.19	2.31	2.90	2.88
0.12	2.35	2.35	2.40	2.39	2.04	2.17	2.61	2.59

N. A.: natural uranium; D. U.: Depleted uranium

LMFBR/3+HWR/1 MNESFE combination, especially if the values of the exponent of capacity growth are higher. If depleted uranium is used for fuelling, the system will tolerate a considerably smaller number of thermal reactors to bring about the conditions of equilibrium than in case the fuel is natural uranium, obviously because HWR/1 is natural uranium fuelled and therefore it makes quite a difference whether uranium is fed to the new reactor without enrichment (in case of natural uranium fuelling) or after enrichment with plutonium (in case of depleted uranium fuelling).

Table II shows the nuclear fuel utilization efficiency as a function of the exponent of capacity growth for three different MNESFE combinations at an external cycle length of $\Theta = 0$ in case of natural uranium fuelling, and depleted uranium fuelling. Visibly, the utilization efficiency is practically identical for both types of nuclear fuel (the deviation being max. 1% rel.).

These results are very important: what they suggest is that *depleted uranium is practically equivalent to natural uranium in a mixed nuclear energy system at fuel equilibrium*, a difference between both types of fuel lying only in that the MNESFE based on depleted uranium may contain thermal reactors in a reduced number as compared with the natural uranium fuelled system. However, if the system contains thermal reactors with enriched fuel — e.g. PWR — even this effect will be negligible.

Transition period before reaching conditions of fuel equilibrium

The ratio of thermal reactor capacity within the MNESFE can be adjusted usually at 20 to 40% (see Chapter 2). However, in the present nuclear energy systems, the thermal reactor capacity comes to almost 100%. It follows that there will be a relatively long transition period before the conditions of the MNESFE are reached. Also the characteristics of this transition period have been analyzed in detail.

The results of calculations are given in Table III [2]. It can be seen that the transition period is rather long (10 to 50 years) and that it depends mainly on the reactor types used, on external cycle length, and on the system capacity growth. Interestingly, a shorter transition period is obtained for systems where the conditions of equilibrium are more favourable. The effect of the external cycle length is significant: the longer the external cycle length is, the longer is the transition period.

The Table suggests that considerable amounts of depleted uranium are accumulating in the transition period, which can be utilized later in the MNESFE. Taking this into consideration, the results discussed in Chapter 6 are of special importance.

The Table also suggests that the average utilization efficiency of natural uranium in the transition period is rather poor as compared with the same value in the MNESFE. Tabulated in the Table are the values of utilization efficiency averaged over a period of 50 years including also the transition period.

Conclusions

The investigations have lead to the following general conclusions:

(a) The mixed nuclear energy system at fuel equilibrium is *technically feasible*, the chances of feasibility being the better the slower the system capacity growth. Since a certain reasonable retardation of the nuclear power plant construction programmes is experienced nowadays all over the world and the same realistic growth is expected also in the future, *the chances of the MNESFE are better today and in the future than we have believed earlier.*

(b) *Considering utilization of nuclear fuel reserves, the MNESFE is not inferior but, in some cases, even superior to a system containing fast reactors alone.* Therefore, from the viewpoint of economic utilization of nuclear fuel reserves, it seems absolutely expedient to bring about appropriate mixed systems in the long run. This means that we need thermal reactors not only today but also in the nuclear energy system of the future.

On the basis of the calculations, also the ways and trends to be followed in reactor and nuclear fuel cycle development can be outlined:

Table III

Fuel utilization characteristics of the first 50-year period of MNESFE for two different combinations of fast and thermal reactors
($P_{f0}=5$ GW(e), $P_{t0}=25$ GW(e), $\gamma=0.8$, $L_f=L_t=0.7$)

Parameter		LMFBR/2—PWR/1				N_2O_4-cooled—PWR/1			
	c [year^{-1}]	0.04		0.06		0.04		0.06	
	Θ [year]	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0
Ratio of capacity of power plants with thermal reactors $(P_t/P)100$ [%]	at beginning of transient period	83.33	83.33	83.33	83.33	83.33	83.33	83.33	83.33
	in system at equilibrium	37.89	27.11	32.41	13.56	52.81	44.33	50.55	36.76
Length of transient period [year]		28.62	46.36	24.05	*	15.31	21.99	11.28	19.99
Uranium accumulated during the transient period [t]	depleted uranium	36 813	71 567	33 749	—	13 623	30 370	10 229	32 306
	uranium from spent fuel	7 428	14 925	6 906	—	2 649	5 929	1 976	6 273
Natural uranium utilization efficiency [%]	mean for transient period	2.575	2.869	2.603	—	2.781	2.041	2.668	1.948
	in system at equilibrium	6.455	4.103	4.567	—	7.044	4.681	5.084	3.275
	mean for first 50 years	5.154	3.063	4.234	—	6.480	4.098	4.961	3.114
How long depleted uranium accumulated before reacting the conditions of equilibrium can meet the demand of fast reactors in system at equilibrium [years]		53.38	35.10	30.82	—	64.74	54.01	24.52	31.17

* Reaching of conditions of equilibrium is not possible

— On the basis of the investigations, not much is expected from GCFR in a MNESFE. LMFBRs are more promising provided the characteristics of this reactor continue improving. A considerable improvement could have been brought by the N_2O_4-cooled fast reactor. The characteristics of this reactor type are estimated to be very favourable on the basis of theoretical analyses. Unfortunately, the practical feasibility has not been proved yet.

— *Reduction of the amount of fuel engaged in the reactors* is a rather efficient way to improve the nuclear fuel utilization efficiency (see Chapter 5). The development of such reactor types (e.g. PWR, HTGR) is therefore considered to be a fairly good choice.

— *Reduction of the external cycle length* is a point deserving distinctive attention in respect of both feasibility of the MNESFE and improvement of the nuclear fuel utilization efficiency. For this purpose, the cooling time of spent fuel elements shall be reduced to minimum, and techniques (e.g. dry process) suited for reprocessing of fuel elements of considerably higher activity than by the wet processes (e.g. Purex process) widely used at present shall be developed.

(c) For a MNESFE, similarly to systems containing fast reactors alone, depleted uranium is equivalent to natural uranium or, from an economical point of view, even more favourable as this primary energy carrier contains no impurities and thus it need not be concentrated in ore (nor mined) while the natural uranium has to be mined, concentrated, dissolved and cleaned from impurities. This fact shall be taken into consideration in both the realization of uranium ores and evaluation of depleted uranium produced in enrichment so far. *From an energetic point of view, the accumulated reserves of depleted uranium are of tremendous value and the preservation of these reserves is the national interest of every country.* It is therefore certainly worth considering whether in accomplishment of the national nuclear energy programme a country having its own uranium ore resources but incapable of isotopic enrichment had better to sell uranium only in an amount required to meet the country's enriched uranium demand and insists upon the depleted uranium produced in the enrichment process as a valuable energy carrier.

(d) For economical reasons, there are very few countries in the world (e.g. USA, USSR) that can afford operating a complete nuclear fuel cycle. Smaller countries shall therefore rely upon *international co-operation*. Taking this into consideration, the MNES offers rather significant advantages also in the field of safety and environmental protection [2]. On the basis of the MNES, a so called *regional nuclear energy system* (RNES) can be brought about, where the most dangerous components (such as fast reactors, reprocessing plants, fuel element fabrication plants, high-activity waste disposal) as well as the routes interconnecting all these components are concentrated in one country or in a few countries while the other countries within the regional system — as few countries can do without the peaceful uses of nuclear energy — should construct and operate only nuclear power plants with thermal reactors both now and in the long run.

(e) Another *economic advantage* offered by the MNESFE is that the *specific investment* costs of nuclear power plants with thermal reactors lie at present, and are expected to lie also in the future, below the same costs of nuclear power plants with fast reactors. *Preservation of thermal systems of proven technology* and the benefits of *standardization* of nuclear power plants in the different countries are additional technical and economical advantages the MNES can grant.

Of course, the accomplishment of a regional nuclear energy system based on a MNESFE is subject to many political, financial and legal conditions and to the interests of economic policy. This work was confined to the analysis of the problems of fuel utilization, and other technical problems. Political, legal, financial etc. questions shall be analyzed and answered by people called to do so.

References

1. CSOM, GY.: Conditions of Fuel Equilibrium of the Mixed Nuclear Energy System. Periodica Polytech. same No. and Vol.
2. CSOM, GY., FEHÉR, S.: Advantages of the Regional Nuclear Energy System and Conditions for Realizing such a System, International Conference on Nuclear Power Experience, Vienna, 13–17 September 1982, IAEA-CN-42/372

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