KERNFORSCHUNGSZENTRUM
KARLSRUHE

Februar 1967 KFK 569

Institut für Angewandte Reaktorphysik

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PROSPECTS OF PLUTONIUM FUELLED FAST BREEDERS *

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D. Gupta
W. **Häfele**
P. Jansen
J. Seetzen

Institute for Applied Reactor Physics,
Kernforschungszentrum Karlsruhe,
Federal Republic of Germany

1. INTRODUCTION

The present stage of development of Pu fuelled fast breeder systems indicate, that they would enter large scale economic competition in the field of electrical power generation by the late seventies. This would mean that in most of the industrialized countries, such a system would be introduced into an already established nuclear industry based on converter type reactors, which have been producing different amounts of plutonium.

Under such a condition, the prospects of fast reactor systems can be assessed on the basis of a short-term and a long-term criteria. Under the short-term one, a fast breeder has to prove at first its technical maturity and that it can operate safely and soundly under industrial conditions. This will determine the time of its introduction into the existing nuclear system. At that time it must also be in a position to produce electricity at a lower cost than that from the existing converters.

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Under the long term criterion, a fast breeder besides being economic, should also be able to reduce the dependence of the nuclear system on fissile material and natural Uranium supply , and in the long run should also be able to make the system self-sufficient in its fissile material requirement. This would mean that the doubling time of the fast breeders should ultimately match with that of the nuclear system.

Fast breeders have the fundamental advantage of using plutonium more economically than the converters and as a result, can afford to pay a higher price i.e. about twice that which can be economically paid by the converters. Since they produce Pu in Situ, in excess of what they consume, from U-238, the waste material from the converters, their introduction in a converter based nuclear industry leads automatically to a reduction in natural Uranium consumption.

2. TYPES OF FAST BREEDER SYSTEMS

2.1. Technical and economic data

At present two fast breeder systems with plutonium appear to be able to meet the short term criterion. One is the steam cooled type with mixed oxide fuel [1] which will be named D-BRP and the other, the sodium cooled type with oxide fuel [2] named Na-BRO. Typical technical and economic data for these reactors [3] are shown in TABLE I. The fuel cycle economics of a sodium cooled reactor improves by more than 0.1 DPf/kwh if the oxide is replaced by mixed carbides [4]. The relevant data for such a system named Na-BRC are also included in TABLE I.

2.2. Technical and economic prospect

It is expected that the size of the major part of the nuclear reactors to be erected during the late seventies will be in the range of 1000 MWe. Data in TABLE I correspond to fast breeders of this size.

2.2.1. Doubling time

The doubling time $T_D[yrs]$ offers a good measure for assessing the prospects of fast breeders from the point of view of the long term criterion. The straight line doubling time STD[yrs], which gives the number of years required for a single reactor to produce a quantity of net excess fissile material equal to its initial inventory, is mainly a function of burnup, fuel rating, breeding ratio, out of pile inventory, Pu-losses in the fuel cycle, startup delay in the discharge of plutonium both from the core and the radial blanket and the number of fuel batches per core life time. It also depends on the thermal efficiency and the plant load factor. Following relation has been used for determining the STD.

$$\mathrm{STD}[yr] = \delta_{Pu} + \frac{\vartheta_o}{\Delta Pu} \cdot \frac{Z+1}{Z} - \frac{\delta_R}{Z} \qquad (1)$$

where

$$\delta_{Pu}[yr] = p \cdot \delta_R \left(\frac{pZ-1}{2\ pZ}\right) + \delta_W + \delta_F \qquad (1a)$$

$$\vartheta_o \; [\mathrm{t/GWe}] = \frac{\rho \cdot m \cdot x_o^{9+1}}{\eta \cdot r} \qquad (1b)$$

$$\Delta\mathrm{Pu} \; [\mathrm{t/GWe\ yr}] = \frac{365\,\kappa}{\eta \cdot a_{mav}} \left(-m \cdot x_o^{9+1} + \gamma \cdot \nu \cdot x_1^{9+1}\right) \qquad (1c)$$

$$\delta_R \; [\mathrm{yr}] = \frac{a_{mav}}{365 \cdot r \cdot \kappa} \qquad (1d)$$

The compound doubling time CTD, which gives the doubling time required if the excess plutonium is immediately cycled through other fast breeders in a nuclear system, is related to the STD by the following relation:

$$\mathrm{CTD} \; [\mathrm{yr}] = \ln 2 . \mathrm{STD} \qquad (2)$$

Symbols used above have the following meaning:

x_o^{9+1}, x_1^{9+1} [%]	Percentage of Pu-239+Pu-241 in the mixed Core + Bl. fuel at insertion (o) and at discharge (1)
η [1]	Thermal efficiency of the plant
r [MWt/kg mixed fuel]	Fuel rating averaged over core + ax.Bl. + rad.Bl./p
a_{mav} [MWd/kg mixed_fuel heavy metal]	Burnup averaged over core + ax.Bl. + rad.Bl./p
ρ [1]	excess element on reserve = 1,05
m [1]	fabrication loss factor = 1,01
ν [1]	reprocessing loss factor = 0,99
γ [1]	material used up in burnup = $1-1,05 \cdot a_{max} \cdot 10^{-3}$
κ [1]	plant load factor = 0,7
Z [1]	no. of batches in a core life time = 3
p [1]	ratio in-pile-time of radial blanket/core in-pile-time = 2
δ_W [yr]	cooling, reprocessing + transport time = 0,5
δ_F [yr]	fabrication time = 0,22
δ_R [yr]	in-pile time of core fuel

Fig.1 gives the relation between breeding ratio and the STD for different fissile rating. For the same reactor type, the doubling time can be varied over relatively large range (about 10 years) by simply changing the blanket thickness and also the core design. It may be mentioned in this connection that at the beginning, the doubling time for fast breeders would be considerably lower as a part of the plutonium would be supplied by the converters. As more and more converters are replaced by the breeders their doubling time would attain the value of CTD.

2.2.2. Steam cooled system

Technically steam cooled fast breeders can gain heavily from the vast industrial experience of light water type reactors in the field of steam cooling and oxide fuel technology. They might therefore, have the potential to be the first to attain technical maturity amongst the three reference reactors considered in TABLE I and would probably be ready for large scale application by 1978. Because of this possibility, the steam cooled system may bridge the gap between the existing converters and the sodium cooled system, in case the large scale application of the latter is delayed beyond the expected target date of 1980 on account of some unforseeable circumstances.

Economically, with their expected energy generation costs of 1,71 DPf/kwh they are lower than any of the known converters. These costs are, however, highest of the three reference fast reactors. Present investigations on steam cooled system, at the Karlsruhe center indicate, that there is room for improvement both in the capital investment and in the fuel cycle costs and the total energy generation costs from this system may be reduced to about 1,59 DPf/kwh (Figures in bracket under D-BRP). These costs, if attained, would make the steam cooled system economically **attractive**, even against advanced converters.

The straight line doubling time for D-BRP varies between 60-70 yrs and the CTD between 40-50 yrs. This means that the steam cooled fast breeder of current conception would not be able to meet the second criterion (long range self sufficiency in fissile material supply) unless the nuclear system in which it is introduced, also has doubling times of the same order of magnitude. In other words, it would always require a parallel line of converters to supply the rest of the plutonium. However, since it meets the first criterion and has the possibility of functioning as an intermediate generation of breeder, it can still reduce to a significant extent, the total energy generation costs and the natural uranium consumption of the whole system, as shown later. As such, the high doubling time in this particular case, in no way reduces the prospects of this system.

2.2.3. Sodium cooled oxide system

Technical: Like the steam cooled version, the sodium cooled oxide system can also gain considerably from the experience on oxide fuel technology from the existing converters. But the sodium technology and the safety requirements for sodium system have to be developed almost exclusively for the fast reactors. Although the intensive research and development activity in this field in many countries is quite evident and it is very probable that sodium cooled breeders will start producing electrical energy on an industrial scale by 1980 - the target date set for them, for the subsequent analysis, their introduction point has been conservatively taken to be 1985, mainly to account for any unforseeable set backs in their development.

Economics: Sodium cooled oxide breeders of the present conception with 1,65 DPf/kwh have the lowest energy generation costs of all the known and advanced converters /5/. They have possibilities of a further improvement to about 1,60 DPf/kwh.

Doubling time: An STD of 20 yrs and CTD of 15 yrs correspond to the normal long range doubling time of nuclear industries. This type of breeder system will therefore be able to make a nuclear energy system self sufficient in fissile material from the point of view of long range requirement, i.e. when the system is based solely on this type of breeders.

2.2.4. Sodium cooled carbide system

Technical: This system represents the advanced version of the previous type. A large amount of R+D work for the development of the carbide fuel would be necessary even after all the problems regarding sodium cooling have been solved. For the present study the introduction point of this type in a nuclear system has been conservatively taken to the 1995, although it might be reasonable to expect an earlier introduction.

Economics: The carbide breeders with their 1,54 DPf/kwh energy generation costs, are economically the most attractive of the three reference breeders considered. They are expected to retain their economic superiority over all the other reactor types over a relatively long period of time.

Doubling time: Mainly because of their high fissile rating and high breeding ratio, they have also the lowest STD (11 yrs) and CTD (7.6 yrs). On account of this, they can replace other reactors at a very rapid rate after their introduction in an existing nuclear system. If the doubling time of the existing system is greater than that for the carbide reactors, an excess of plutonium will be produced. By adjusting the breeding ratio in existing reactors or in those to be newly installed, the amount of this excess plutonium can be varied over a wide range.

3. MODEL OF A GROWING NUCLEAR SYSTEM WITH BREEDERS

The prospects of the three breeder systems can be illustrated in a somewhat more definite manner by assuming different models of growing converter based nuclear systems in which different types of breeders are introduced in a phased manner, and assessing the total accumulated energy generation costs and the total accumulated natural uranium requirements for the system upto a given time horizon. It should, however, be emphasized at this point that such an assessment is heuristic in principle and can only indicate relative trends which may be expected and the absolut values are of only secondary importance. These values are also rather sensitive to the initial assumptions made for the technical and economic characteristics and the time of introduction of the three fast breeder reactor systems. The sensitiveness of the results to input data has been analysed elsewhere /6/. On the other hand, such an analysis enables one to establish the general technical and economic target values, which have to be attained for different fast breeder systems to make them technically attractive and economically competitive.

3.1. Assumptions

1. The advanced data for the three Pu-fuelled fast reactors in TABLE I (Figures in bracket) form the basis of assessment.

2. The Pu-fuelled steam cooled reactor can also be operated with enriched uranium when necessary, without any change in the plant layout and reactor design. The relevant technical and economic data for this type of reactor called D-BRU are summarized in TABLE II. Such a reactor system produces electricity at a cost at least equal to that from a light water type converter. The D-BRU would produce 500 kg Pu-fissile/GWe yr as compared to 135 kg Pu-fissile/GWe yr from a LWR type.

3. The nuclear energy growth rate (refers to the Federal Republic of Germany) is given by Fig.2 [7]. The nuclear population starts with a light water enriched uranium reactor with technical and economic characteristics as shown in TABLE II. These reactors would produce 3.75 t Pu upto 1975 and 16 t of Pu upto 1980, if allowed to meet the nuclear energy growth alone.

4. The successive introduction dates of the different fast reactors would be:

1975	Steam cooled fast breeder with enriched uranium (in the form of oxides)
1978	Steam cooled fast breeder with Plutonium (in the form of mixed Pu+U oxides)
1985	Sodium cooled fast breeder with mixed Pu+U oxides
1995	Sodium cooled fast breeder with mixed Pu+U carbides

5. No plutonium would be obtained from an outside source.

6. All the reactors installed would have a life time of 25 yrs.

These dates may not necessarily be realistic but have been assumed to emphasize the salient features of this study.

3.2. Model of nuclear systems

Model I (Fig.2): The energy requirement is met solely by LWR-type. Plutonium produced in these reactors are desposed of without recycling it in these reactors.

Model Ia: Same as I, only the plutonium is recycled back into these reactors.

Model II (Fig.3): LWR are installed upto 1975 after which no new LWR would be introduced (Curve II) and the nuclear energy growth would be met with steam cooled breeder systems. The plutonium produced from the LWR would be used to install D-BRP (Curve IV) and the rest of the demand would be met by installing D-BRU reactors (Curve III).

Model III (Fig.4): Same as Model II upto 1985. From that time on only Na-BRO type breeders would be installed (Curve V). The D-BRP's would be operated from then on as D-BRU's and the plutonium from these reactors would be used to install additional Na-BRO's. Although D-BRP type breeders produce relatively small amounts of plutonium, they are ideally suited as an intermediate generation of reactors which can utilize the converter-produced plutonium in the most rational and economic manner until the Na-BRO's (which are a better producer of plutonium) attain technical maturity for large scale application. Although it is also possible to recycle the converter-produced plutonium back in the converters, it would be considerably uneconomic for them as the value of plutonium would be reduced by half. Besides that, since D-BRP's are expected to have significantly lower energy generation costs than the LWR type, their introduction in a nuclear system at the earliest possible date would reduce the total energy production costs of the whole system.

Model IV: Same as Model III upto 1995, after which no Na-BRO type would be installed and all the new installations would be of the Na-BRC type (Fig.5, Curve VI). In this case a part of the previously installed D-BRU's would be converted to D-BRP's from 1995 onwards (Fig.5, Curve VII), as it would be more economic to operate them for the rest of their life time as plutonium breeders and there would be enough excess plutonium from the Na-BRC to fuel them.

4. RESULTS

The accumulated natural uranium consumption and the total energy generation costs for all the models upto the year 2000 (i.e. 33 years from the present date) have been given in TABLE III. As a basis for further comparison, the accumulated natural uranium requirements upto 2040 have also been presented. Following points may be noted:

1. Light water reactors, if allowed to meet the nuclear energy growth curve alone, would have the highest accumulated natural uranium consumption and the highest total energy generation costs. The uranium consumption is reduced by recycling back the plutonium produced.
2. Any of the fast breeder combinations show a lower natural uranium consumption and lower generation costs over the LWR system alone. These savings increase continuously as the steam cooled systems are replaced by the sodium cooled versions.
3. Although the Na-BRO type has been taken to be slightly more expensive than the D-BRP type, the introduction of the former still shows a reduction in the total generation costs (Model III). This is mainly because of the reduced number of more expensive D-BRU reactors which are to be installed.
4. Although the Na-BRC are introduced into the system in 1995 and as such can influence the economics of the system for 5 years, the total reduction in production costs over Model III is still a significant value of $2.4 \cdot 10^9$ DM.
5. Model III and IV are only weakly dependent on an outside natural uranium supply.

5. CONCLUSIONS

Subject to the assumptions under 3.1. and the fact that the models are only heuristic in nature, the foregone analysis permit a number of generalized conclusions to be drawn.

5.1. The prospect of fast breeders should be evaluated only by considering them as part of a nuclear system and assessing the technical and economic advantages gained by the system as a whole, over a given period of time, through their introduction.

5.2. A nuclear system based on LWR type reactors alone has significantly higher uranium consumption and higher energy production costs than a system which is based on a combined LWR fast breeder combination. It is quite immaterial which of the three types of breeders considered in this study forms the partner.

5.3. Although steam cooled systems have low breeding ratio, high doubling time and can not make a nuclear system self-sufficient in fissile material requirement, a combination of D-BRU and D-BRP systems can reduce this requirement to a very large extent.

5.4. Pu-fuelled steam cooled breeders represent an ideal system as intermediate generation of fast reactors for economic utilization of converter-produced plutonium, incase the large-scale introduction of sodium cooled system is delayed beyond 1980. As such their development and application represent an insurance against any set-back in the sodium cooled breeder technology. If the suggested target for the steam cooled systems can be achieved, development of any other advanced converter type might become superfluous. The high doubling times of these reactors in no way reduce their economic prospects. However, to ensure favourable economics of the nuclear system, in which they are introduced, the steam cooled fast reactor with uranium must be able to produce electricity at a cost at least equal to that from the then operating light water reactors.

5.5. The steam cooled systemshave an inherent potential for economic improvement which has been amply demonstrated by the spectacular development of the LWR types in recent years. It is therefore quite probable that the steam cooled fast breeders would find large-scale application because of their favourable economics alone. The sodium cooled versions would then have to match their economics before finding large-scale application.

5.6. The assumed phased introduction of the steam cooled breeders followed by the sodium cooled oxide type and ultimately by the sodium cooled carbide type, appears plausible because of the varying degrees of problems associated with the respective systems. Since the overall nuclear energy system economics with these three types are reversed, being the best with carbides, followed by the sodium cooled oxide and finally by the steam cooled versions, simultaneous research and development work for all the three systems appear essential.

5.7. The cost savings, achieved with the steam cooled versions and with the sodium cooled breeders (even with very conservative dates for their introduction) over a LWR system, are high enough to warrant their development.

5.8. Natural uranium consumption in a LWR based nuclear system decreases as the overall economics of the system improves with the subsequent and consecutive introduction of the steam cooled, the sodium cooled oxide and the sodium cooled carbide type breeders.

5.9. Model analysis of the type carried out in the present study, assist in setting target values for the technical and economic parameters of fast breeder systems, which have to be attained either to permit their introduction or to improve their prospects in the field of competitive electrical generation. Such an analysis is not meant to predict the future in all details.

Acknowledgement

The authors would like to thank D.Faude for his assistance in preparing some of the tables and figures.

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TABLE I

Technical and Cost Data for the 1000 MWe Pu-fuelled Reference Fast Breeders D-BRP, Na-BRO, Na-BRC

Ref.Reactor Type	D-BRP Steam Cooled Oxide	Na-BRO Na-Cooled Oxide	Na-BRC Na-Cooled Carbide
Technical			
Core Vol.[ℓ]	8200	6570	3700
Core Diam.[cm]	263	293	241
Core Height [cm]	151	97.5	81
Fuel Pin Diam.[mm]	7	6.5	6.5
Critical Mass, Pu [t]	3.48(2.8)	2.68	1.7
Pu-Concentration [%]	11.9(10)	12.5	11.9
Ax.Bl.Mass [t]	17.6(17.6)	17.9	14.1
Rad.Bl.Mass [t]	32.2(32.2)	33.3	34.0
Breeding Ratio [1]	1.14(1.12)	1.37	1.50
Pu-Production [kg/yr]	80(55)	210	265
St.Line Doubl.Time [yr]	61(73)	22	11
Compound Doubl.Time [yr]	42(51)	15	7.6
Burnup in Core[MWd/kgheavy atom]	55(70)	80	80
Fissile Rating [MWth/kg Pu]	0.72(0.90)	0.87	1.33
Rod Power [Watt/cm]	326	460	920
Thermal Efficiency [1]	0.397	0.43	0.43
Load Factor [1]	0.7	0.7	0.7
Cost			
Total Capital Investment without First Core [DM/kwe]	560(510)	600	600
Specific Capital Costs[DPf/kwh]	1.07(0.97)	1.15	1.15
Operation Costs [DPf/kwh]	0.12(0.12)	0.12	0.12
Fuel Cycle Costs [DPf/kwh]	0.52(0.50)	0.38(0.34)	0.27
Total Energy Generation Costs [DPf/kwh]	1.71(1.59)	1.65(1.61)	1.54

TABLE II

Technical and Economic Data for Steam Cooled Fast Reactors
With Uranium (D-BRU) and LWR

	D-BRU		LWR[5]	
Technical				
Electrical Power [MWe]	1000		1000	
Thermal Efficiency [1]	0.397		0.345	
Critical Mass [t U-235]	3.5		3.43	
U-235 Concentration in Core [%]	12.0		3.0	
Ax.Blanket [t heavy metal]	17.6		-	
Rad.Blanket [t heavy metal]	32.2		-	
Economics				
Total Capital Investment [DM/kwe]	510		516	
Energy Generation Costs [DPf/kwh]				
Capital Charges		0.97		0.99
Fabrication Costs	0.17		0.17	
Reprocessing Costs	0.12		0.06	
Burnup Charges	0.75		0.52	
Pu-Credit	-0.35		-0.08	
Total Fuel Cycle Costs		0.69		0.67
Operation Costs		0.12		0.12
Total Energy Costs		1.78		1.78
Pu-produced [kg/yr] at a load factor of 0.7	500		135	

Note: The D-BRU data are in some respects optimistic. However, they can be obtained if the present investigations on this system being carried out at the Karlsruhe Research Center turn out to be favourable.

TABLE III

Accumulated Natural Uranium Requirement and Total Energy Generation Costs for the Four Models of Nuclear Systems with Different Fast Breeder Types

No Model Type	Accumulated nat. U Requirement 10^3t		Total Energy Costs upto the yr 2000 10^9DM	Difference from Model I 10^9DM
	2000	2040		
I. Only LWR without Pu recycle	360	2300	213.6	-
Ia. Only LWR with Pu recycle	310	1800	213.6	-
II. LWR, (D-BRU+D-BRP)	290	720	204.4	- 9.2
III. LWR, (D-BRU+D-BRP), Na-BRO	170	200	203.2	-10.4
IV. LWR, (D-BRU+D-BRP), Na-BRO, Na-BRC	160	170	200.8	-12.8

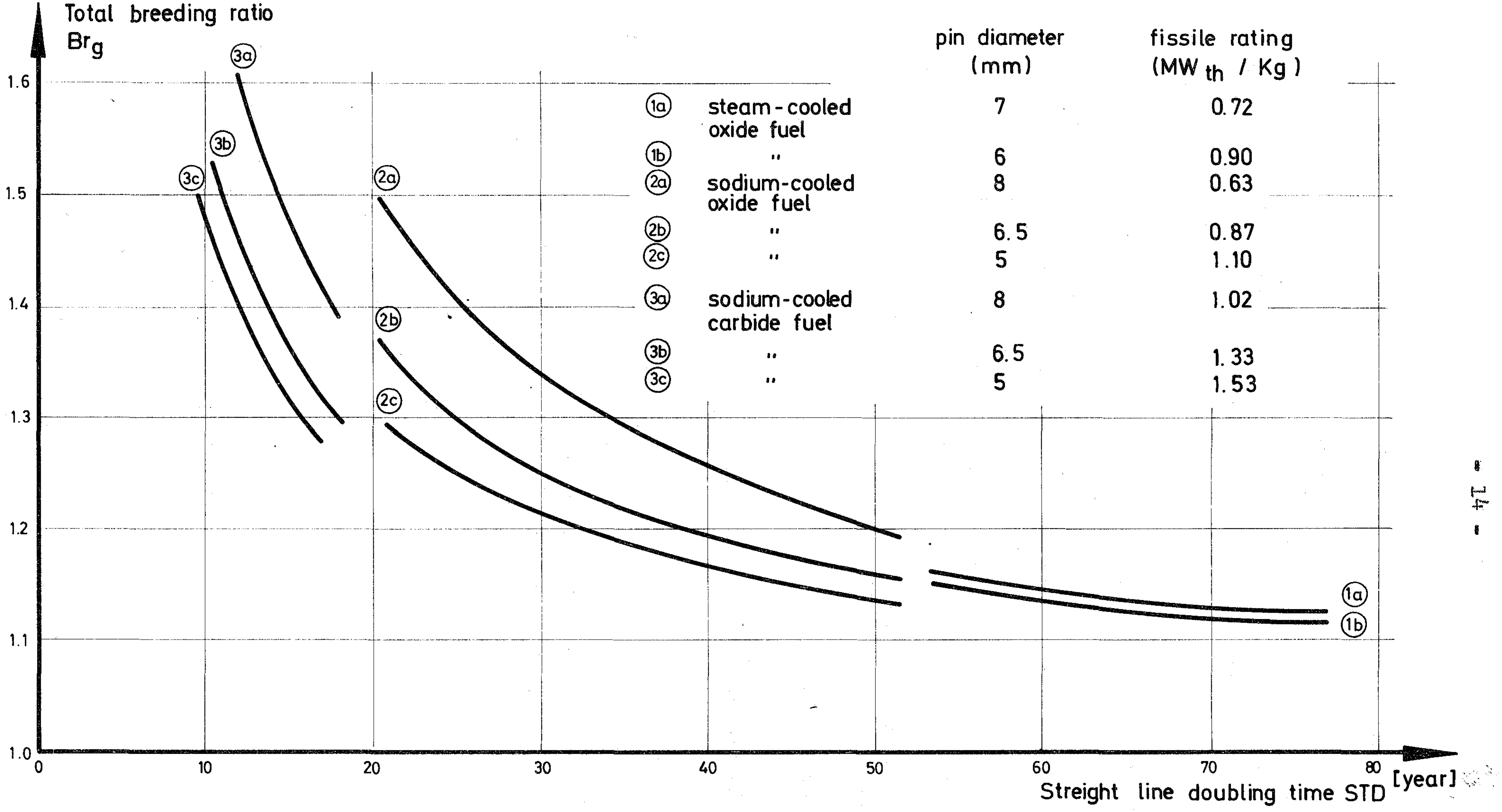
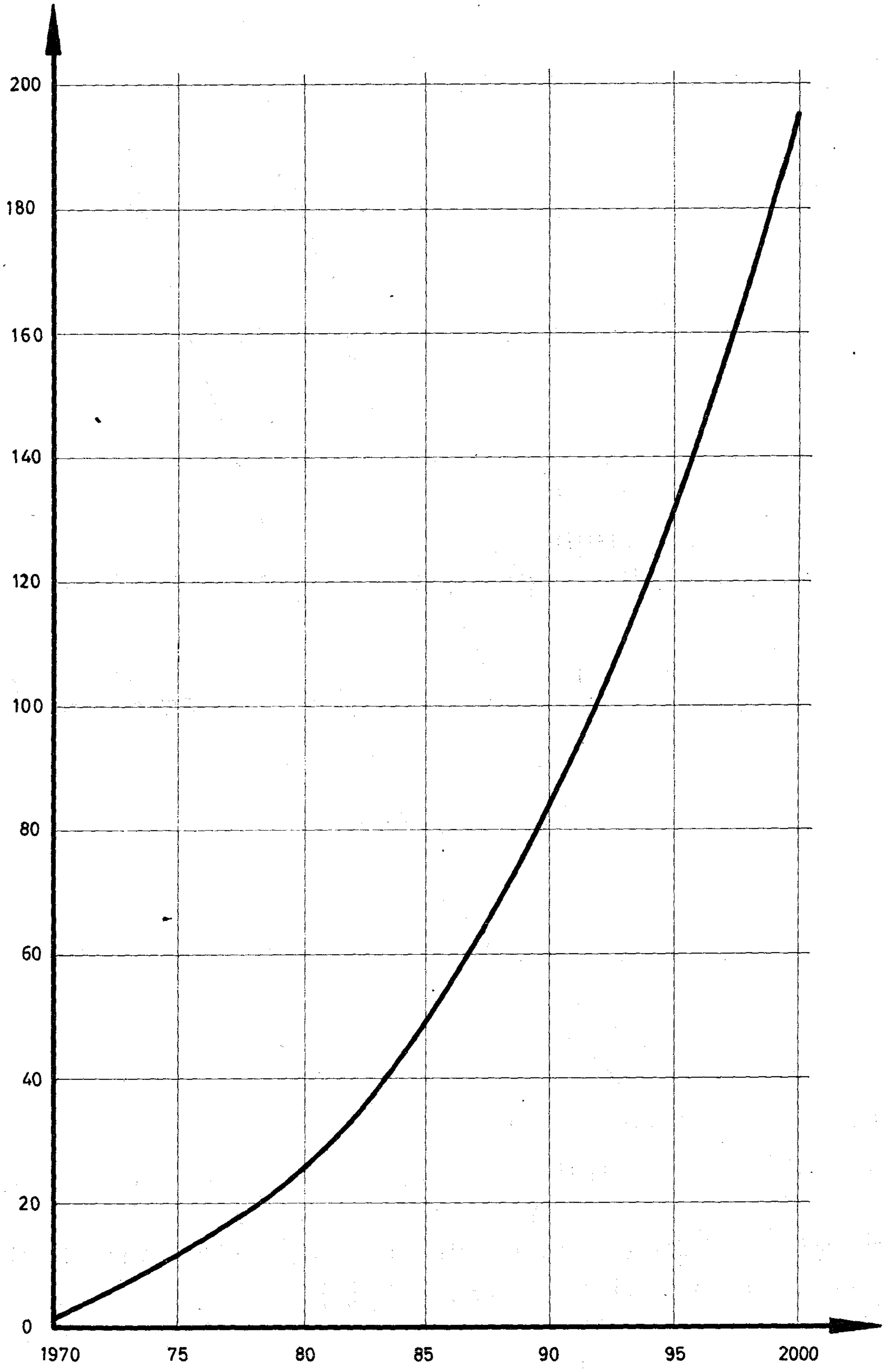


Fig.1 Streight line doubling time as a function of breeding ratio with fissile rating as parameter, for three reference reactors

Fig.2 Nuclear energy growth curve for the Federal Republic of Germany [7]



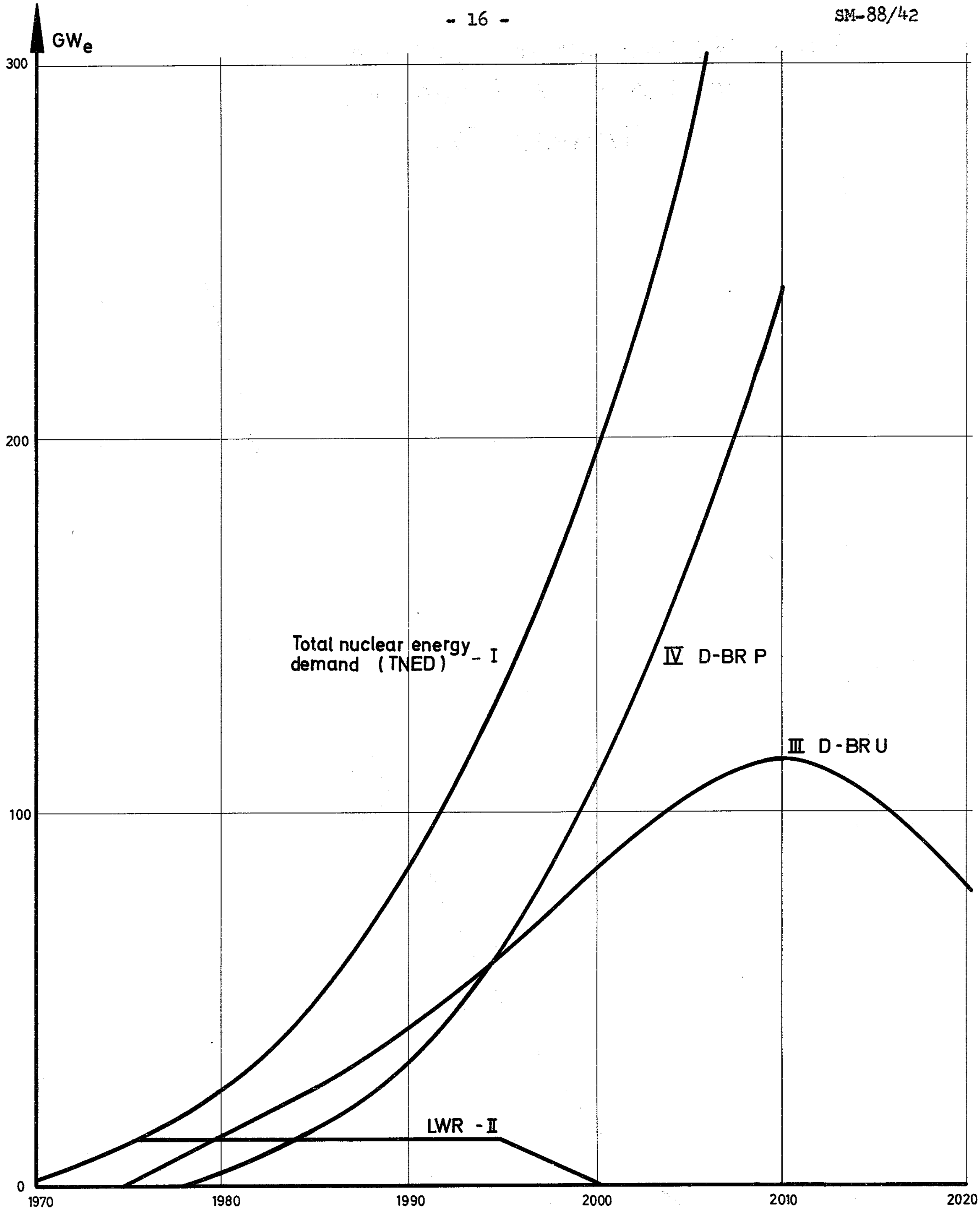


Fig. 3 Model II. Reactor combinations with LWR (1970–75). D-BR U + D-BR P (1975-2000)

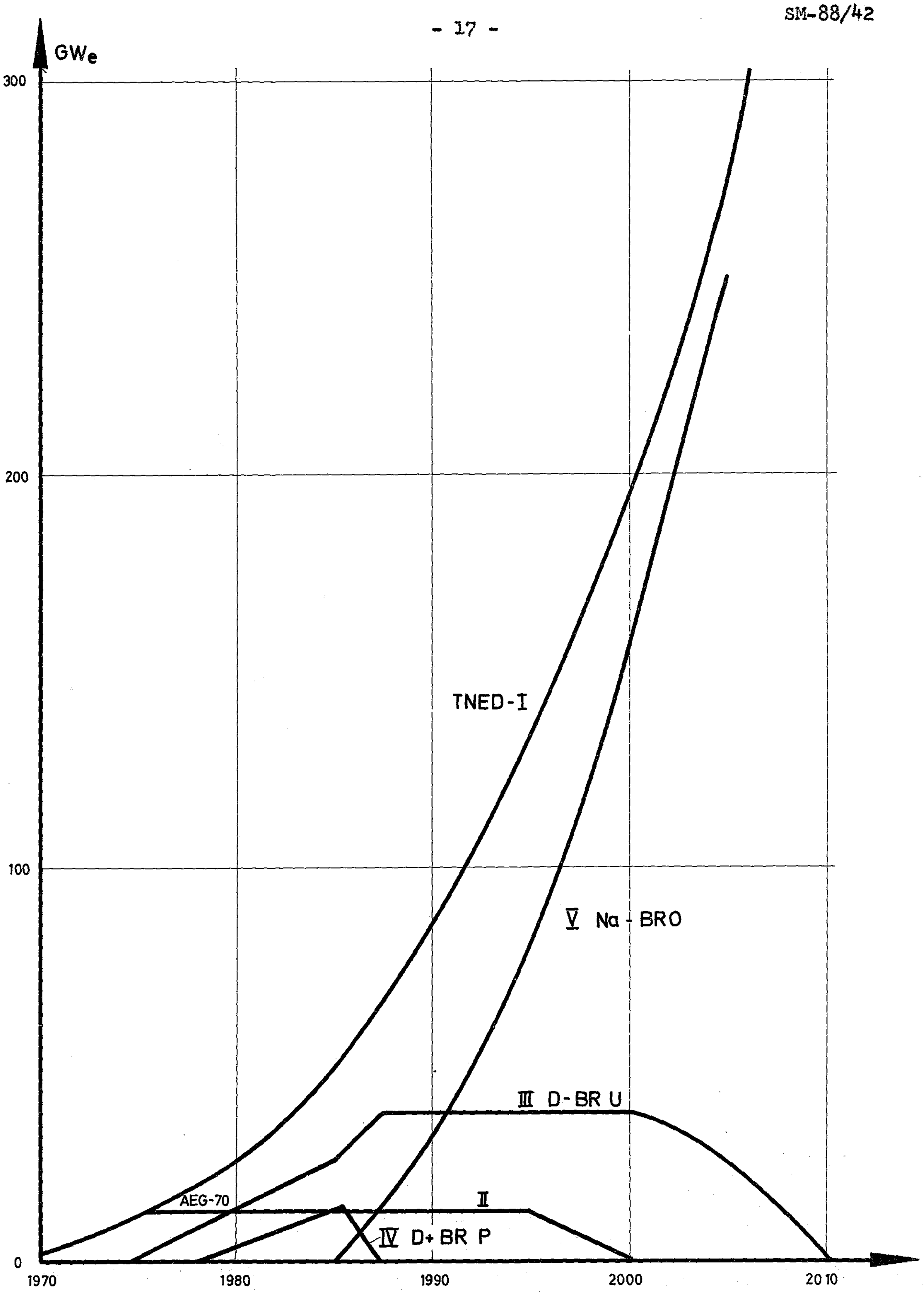


Fig. 4 Model III. Reactor combinations with LWR (1970-75), D-BR U + D-BR P (1975-85), Na-BR O (1985 onwards)

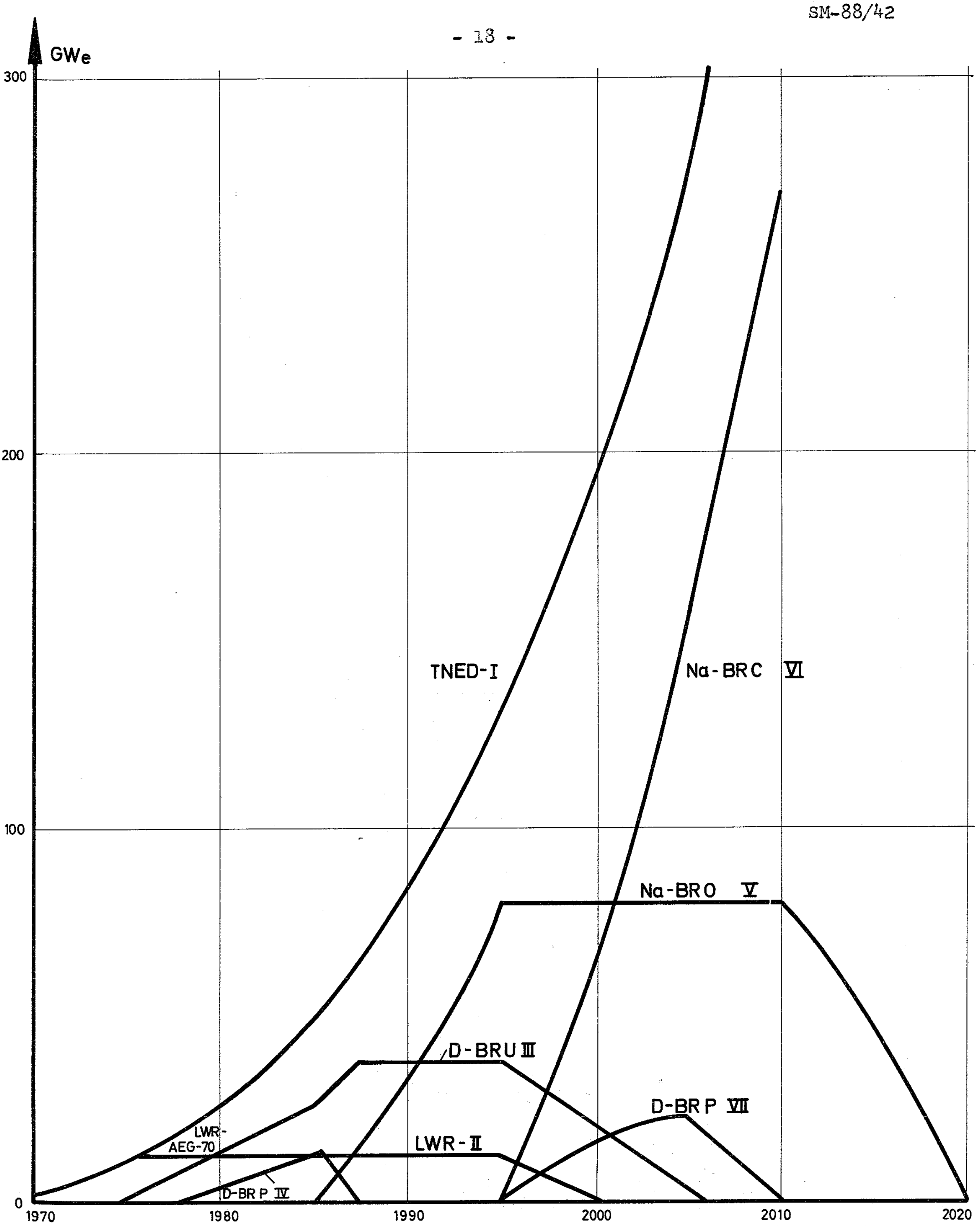


Fig. 5 Model IV. Reactor combinations with LWR (1970 -75). D-BR U + D-BR P (1975-85). Na-BRO (1985 -95). Na-BRC (1985 onwards)