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FUEL CYCLE ECONOMICS OF FAST BREEDERS WITH PLUTONIUM *

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1. INTRODUCTION

It is now an accepted fact that large size fast breeders with plutonium would be in a position to produce power at lower costs than those from presently known converters. The low costs are mainly because of their attractive fuel cycle economics /1,2,3/. A careful balancing of sometimes conflicting technical and economic parameters is however, necessary to attain low fuel cycle costs.

2. GENERAL

2.1. Reactor system

Typical current designs /4,5/ of plutonium fueled fast reactor systems consist of a core of moderately enriched fuel surrounded both radially and axially by fertile blanket material. The core fuel is normally distributed

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in small diameter pins to attain high fuel rating. The axial blanket fuel elements form a part of the core elements whereas, the fuel elements for radial blankets may have larger diameter and form a separate entity. Although a number of coolants have been considered, the present study is limited to fast reactor systems with sodium as coolant. Since the fuel cycle costs are also influenced by the chemical composition of the fuel used, two types of fuels i.e. mixed uranium and plutonium oxides and uranium and plutonium carbides have been considered.

Reactor data

1000 MWe size fast reactors have been used for the analysis of fuel cycle costs. During early eighties, when fast breeders are expected to enter the field of electrical generation, reactors in this capacity range would form the major part of the units to be installed. All the relevant technical data used for the reference reactors are summarized in TABLE I. For subsequent variations in reactor parameters, the height to diameter ratio for the core, the pressure drop and the temperature increase in the coolant accross the core were kept constant so that the capital investments for the reactor systems could be assumed to be the same as those for the respective reference systems. Although mixed carbides have about 5 times the thermal conductivity of that of the mixed oxides [6], it was taken conservatively to be only twice that of the oxides for the reference design.

2.2. Fuel cycle industry

Fabrication and reprocessing plants, the two important branches of the fuel cycle industry, are characterised by their relatively low plant scale-up factors. Therefore, the specific fabrication and reprocessing costs decrease significantly with increasing size of these plants. By the time fast breeders would start penetrating nuclear energy production, a considerable volume of fabrication and reprocessing capacities would be in operation based on converter type reactors [11]. It would be more economic for both the converter and breeder type reactors to expand the existing fuel cycle industry, carry out fabrication and reprocessing steps in centrally located multipurpose plants and take advantage of the low specific costs than to build a marginal size fuel cycle industry for the fast breeder system alone. The present analysis is based on a combined fuel cycle industry.

3. FUEL CYCLE COSTS - INTERDEPENDENCE OF REACTOR AND COST PARAMETERS

The fuel cycle costs for fast breeders can be divided into three main categories:

1. Fabrication costs
2. Reprocessing costs
3. Plutonium interest minus plutonium credit

These costs have been calculated according to a present worth method discussed in detail elsewhere [7,8].

An analysis of these costs indicates some interdependence between the cost parameters and the reactor parameters and are discussed below.

3.1. Cost parameters

3.1.1. Specific fabrication costs in DM/kg

As mentioned earlier the fuel elements for the core and the axial blanket material form a single unit and are fabricated together. Fabrication of elements for the radial blanket can be carried out separately and is based on the same technology as that for the known converter elements. The specific fabrication costs for the core, the axial blanket and the radial blanket can be treated individually. For the core material, the specific fabrication costs K_K in DM/kg heavy metal are mainly a function of plant throughput D_F [t U+Pu/yr], pin diameter d in mm and the length L_K in mm [9]. In a somewhat simplified form the cost relationship may be expressed as follows:
(Symbols not defined in TABLE I, are explained in the text).

$$K_K(\text{DM/kg Core fuel}) = 100+381 \left[\frac{12,50}{d} + \frac{7,70}{d^2}\right] \left(1- \frac{L_K}{2780}\right) \left(\frac{D_{oF}}{D_F}\right)^{0,4} \quad \ldots \quad (1)$$

For a given throughput and length, the fabrication costs per pin, K_{pin} [DM/fuel pin], increase approximately linearly with the pin diameter in the range of 5-9 mm according to the following relation:

$$K_{pin} = 31,4\ d \quad \ldots . \qquad (2)$$

The specific fabrication costs for the axial part of the core elements K_{AB} [DM/kg ax.Bl.fuel], may also be expressed as a function of plant throughput and core pin diameter:

$$K_{AB} = 20 + \frac{656}{d} + \frac{420}{d^2} \left(\frac{D_{oF}}{D_F}\right)^{0,4} \ldots \qquad (3)$$

The fabrication costs for the radial blanket elements have been taken to be a constant at DM 200/kg radial blanket material. For calculating the fuel cycle costs according to [7,8] the weighted average of fabrication costs, K_{AV} for the core, the axial blanket and the radial blanket material has to be taken. The burnup has also to be averaged (a_{mav}) over the same amounts of material.

The throughput of a plant for the fabrication of fast breeder core elements is a function of the installed reactor capacity P(GWe), the burnup a_m and the thermal efficiancy η of the reactor population. In an expanding nuclear industry, the capacity is also a function of the fuel rating, as the first core elements for the new reactors to be installed have also to be fabricated in a year along with the running requirement of the existing reactors in the same year [10,11]. However, since the fabrication capacity required for the first cores is small compared to the running requirement, the fabrication capacity D_F at a given time t may be taken to be as:

$$D_F \simeq \frac{365\ \kappa\ m}{\eta\ a_m} \cdot P(t+\delta F) \ldots \qquad (4)$$

where m is the fabrication loss factor (1,01) and δ_F [yr] is the time required for fabrication.

For a given reactor system and installed power, the variation in the fuel pin costs for the core part of the element may be expressed by combining eqs. 1,2,4 as follows:

$$K_{pin} = (31{,}4d)\left(\frac{a_m}{a_{m_o}}\right)^{0{,}4} \quad \ldots \qquad (5)$$

where, for the present study

a_{m_o} = 80,000 MWd/t core fuel, for the reference plant.

Capacity of the reference plant

D_{oF} = 88 t U+Pu/yr or 100 t UO_2+PuO_2/yr.

3.1.2. Fabrication costs K_{FK} in Dpf/kWh

On the basis of the above cost considerations and the method discussed in /1/ it can be shown that the fabrication costs for the core elements are a function of the following reactor parameters:

$$K_{FK} \propto \frac{1}{\eta\, a_m^{0{,}6}}\left(\frac{1}{X(1+y)}\right)^{0{,}5} \ldots \qquad (6)$$

$$\text{or} \quad \propto \frac{1}{\eta\, a_m^{0{,}6}\, d} \quad \ldots. \qquad (6a)$$

when specific pin costs are considered, and

$$K_{FK} \propto \frac{1}{\eta\, a_m^{0{,}6}} \quad \ldots. \qquad (7)$$

when specific costs in DM/kg (eq.1) are considered.

Eqs. 6 and 7 show that with increasing burnup the fabrication costs for the core fuel do not decrease as a_m^{-1} but at a slower rate of $a_m^{0{,}6}$ if the other reactor parameters are kept constant. The fabrication costs for the axial blanket elements are relatively small. Although they have been included in the final FC-costs, they have not been considered for parameter dependence.

3.2. Specific reprocessing costs in DM/kg

The reprocessing of fast breeder fuel elements can be conveniently carried out in large centrally located multipurpose plants. The main difference between the fast breeder core elements and those from well known converters (for example light water reactor type) lies in the higher plutonium concentration and higher burnup of the former. Both of them can be reduced considerably by discharging a part of the radial blanket elements (which have a low burnup and low plutonium concentration) simultaneously with the core elements and reprocessing them together. The average plutonium concentration of the breeder fuel can be further reduced by processing them along with elements from the light water reactors. Since the current high burnup LWR types discharge their fuel at less than 0.6% U-235, a mixing with fast breeder fuel which may contain waste uranium would not cause a significant reduction in the rest value of LWR fuels. The Pu-240 content in high burnup LWR fuels is in the same range as that in the equilibrium plutonium from a mixed core+blanket fast breeder fuel (TABLE II), so that no significant isotopic swing is expected through such mixing.

In a centrally located plant which has been built for a specific fissile material concentration and yearly throughput, the specific reprocessing costs for fast breeder fuels K_R in DM/kg mixed fuel would normally be a function of plutonium concentration in the irradiated fuel elements and their batch-size.

The following relation has been used /12,13/:

$$K_R = 100 \, \frac{x_1^{Pu}}{x_o^{Pu}} + \frac{T \, D_R}{B} \quad \ldots \qquad (8)$$

where x_o^{Pu} is the Pu-design concentration; x_1^{Pu}, the averaged Pu-conc. in the mixed fuel of fast breeder; T, the turn around time in days; D_R, the plant throughput in t U+Pu/day, and B/ t / the batch-size of the fuel elements to be reprocessed. In the present study:

$$x_o^{Pu} = 0{,}04$$

$$T = 7$$

$$D_R = 1$$

$$B = \frac{N_{th} \, 365.\kappa}{a_{mav}}$$

The base costs of 100 DM/kg correspond to a 1 t/day plant and decrease with increasing throughput of the plant according to the approximate analytical expression /13/:

$$K_R(D_R) = 103{,}3 \, D_R^{-0{,}74} \quad \ldots \qquad (8a)$$

For calculating the Pu concentration x_1^{Pu}, the weighted average of the Pu concentration in the core, the axial and the radial blanket elements have to be taken. Similarly the burnup has also to be averaged (a_{mav}) over the same amount of materials. The averaged transport costs for the mixed fuel have been taken to be DM 20/kg and have to be added to the reprocessing costs.

3.2.1. Reprocessing costs K_A in Dpf/kWh

The reprocessing costs for the mixed core and blanket elements show the following dependence on burnup if eq. 8 and the method in /1/ are considered:

$$K_A \propto \frac{C_1}{\eta a_{mav}} + \frac{1}{\eta} \qquad (9)$$

where C_1 is a constant.

Here also the a_m^{-1} dependence is significantly reduced because of the batch-size factor.

3.3. Plutonium interest and plutonium credit

3.3.1. Plutonium interest K_{int} in Dpf/kWh

Interest charges have to be paid for the plutonium produced or bound in the fuel cycle for both the in-pile and the out-of-pile time. Normally three categories of interest charges are considered during one cycle time.

1. Interest charges for the first inventory plutonium during the in-pile time. These are proportional to:

$$K_{int(in\text{-}pile)} \infty \frac{\alpha\, m\, R}{b\, K\, \eta} \quad \ldots \qquad (10)$$

where R is the sum of the interest and tax rate.

2. Interest charges for the first inventory plutonium during the out-of-pile time which are proportional to:

$$K_{int(out\text{-}of\text{-}pile)} \infty \frac{\alpha\, m\, R\, t_w}{a_m\, \eta(1+y)} \quad \ldots \qquad (10a)$$

t_w represents the total out-of-pile time.

3. Interest charges for the excess plutonium bred in the radial blanket during the in-pile time of the radial blanket. They are a function of the following reactor parameters:

$$K_{int(rad)} \infty \frac{p\, \alpha\, R\, a_m (1+y)(Br_g - 1)}{b\, \kappa\, \eta} \quad \ldots \qquad (10b)$$

The in-pile time for the radial blanket elements can be different from that for the core and axial blanket elements. p represents the ratio of the radial blanket in-pile time to the core in-pile time. A long in-pile time for the radial blanket would mean less frequent discharge and hence low reprocessing cost contribution to the total fuel cycle costs but at the same time would mean a higher interest charge for the plutonium produced in it. The optimum in-pile time can be estimated by balancing the interest charges against the reprocessing costs /1/.

3.3.2 Plutonium credit, $K_{Pu\,Cr}$ in Dpf/kWh

The sum of the three interest charges under 3.1 is reduced by the credit value of plutonium produced in excess in the blankets. This value is proportional to

$$K_{Pu\,Cr} \infty \frac{\alpha(\nu Br_g - 1)}{\eta} \quad \ldots \qquad (11)$$

where ν is the reprocessing loss factor (0,99).

When the credit value equals the interest charges, the fuel cycle costs become independent of plutonium price. For a given set of reactor parameters and plutonium price, these relations give the breeding ratio or the interest rate which would make the fuel cycle costs independent of the plutonium price. If the technically attainable breeding ratio is lower than this value for a given interest rate, the fuel cycle costs would rise with increasing plutonium price.

The plutonium price cannot however, rise or fall indefinitely. The lowest value of plutonium for a fast reactor system would be given by the reprocessing costs. For specific reprocessing costs of about 200 DM/kg mixed fuel, this would come to about 5 DM/g Pu-fissile. The upper limit is given by the fact that 1 g Pu corresponds to about 1.5 g U-235 on the reactivity scale in fast breeders. Fast breeders can therefore afford to pay 1.5 times the prevailing price of U-235, for Pu. At present U-235 has a value of 48 DM/g (for $ 8/lb U_3O_8). Therefore, plutonium for fast breeders can have a price of 72 DM/g. This would mean the upper limit for plutonium price. For a higher price it would be more economic to use U-235 in fast breeders.

3.4. Reactor parameter

The reactor parameters which influence the fuel cycle costs are summarised in TABLE III. The fuel cycle costs for the two reference reactors Na-BRO and Na-BRC are also included there. The cost relations indicate that the reactor parameters η, a_m, b, χ, y and Br_g influence the fuel cycle economics in a relatively intricate manner. However, it is possible to discuss some generally discernable trends.

1. Thermal efficiency η:
   All the cost items are inversely proportional to the thermal efficiency and decrease monotonously with an increase in its value.

2. Burnup a_m:
   An increase in burnup reduces the fabrication and reprocessing costs (eqs. 7,9), the interest charges for the out-of-pile inventory (10a) and increases the interest charges for the excess plutonium (10b). In canned fuel, for high burnups above 100.000 MWd/t, the core fuel density has to be reduced considerably below 85 % of the theoretical value to accomodate for the swelling of fuel /14/. A reduced fuel density reduces the internal as well as the total breeding ratio and decreases the fissile rating. Besides that, because of higher fission product poisoning, a higher excess reactivity is necessary to keep the reactor critical over its core lifetime, which also causes a decrease in the fissile rating. All these tend to increase the interest charges for plutonium. These two influences working in opposite direction cause the fuel cycle costs to go through a minimum when the burnup is increased continuously.

3. Fissile rating b:
   The fabrication costs (6) increase with b at the rate of $b^{0,5}$; the interest charges for the in-pile plutonium inventory and for the excess plutonium in blanket decrease at the rate of b^{-1}. For a given fuel type and rod power, the fertile to fissile material ratio y decreases with increasing b as shown in Fig. 1. The decreasing interest charges and the increasing fabrication costs cause the fuel cycle costs to go through a minimum with increasing b.

4. Rod power χ:
   Although fabrication costs are inversely proportional to the rod power (9), it is not an independent variable and is related to

the other reactor parameters through the relation:

$$\frac{\pi d^2}{4} = \frac{\chi(1+y)}{b\ p_F\ 10^3} \qquad (12)$$

where p_F is the density of fuel.

The fertile to fissile ratio y decreases with increasing χ (Fig. 1) so that the fabrication cost advantage with higher χ (for a given fuel), is partly compensated by the reduced value of y.

5. Fertile to fissile material ratio y:
Inverse of the term (1+y) gives the fissile material concentration in core. Explicitely, the fabrication costs (6) and the interest charges for the out-of-pile inventory (10a) are inversely proportional and the interest charges for the excess plutonium in radial blankets (10b) are directly proportional to this term. But, because of the fact that y decreases with an increase in both fissile rating and rod power (Fig.1), it influences and tends to increase the fuel cycle costs in an implicit manner also. Besides, a reduced value of y means a higher concentration of plutonium in core and necessarily a lower concentration of U-238, which in its turn means a lower internal breeding ratio and consequently a lower total breeding ratio. This tends to increase the fuel cycle costs further.

6. Breeding ratio Br_g:
For a given fast breeder system the breeding ratio is mainly a function of heavy metal density (referred to the reactor volume) and the hardness of neutron energy spectrum. Therefore, the carbide fuel, which has a higher density and gives a harder spectrum has also a higher breeding ratio than the oxide fuel. The breeding ratio in existing reactors can be varied within a wide range (for example, for the oxide system between 1,1-1,4 for the carbide system from 1,1-1,5) by changing the thickness and the height of fuel in the radial and the axial blanket respectively.

4. COMPARISON WITH FUEL CYCLE COSTS OF KNOWN CONVERTERS

In TABLE IV typical fuel cycle costs for a light water reactor and a heavy water natural uranium reactor /8/ are compared with those for the reference fast breeder reactor Na-BRO. The relevant technical and cost data are also included in that table. Although the specific fabrication costs in DM/kg fuel are higher for the averaged fast breeder fuel than those for the LWR or the HWR, the fabrication costs in Dpf/kWh are lower than either of the two. This is because of the higher thermal efficiency of the breeder than the LWR and higher thermal efficiency and higher burnup than the HWR. This is also true for the reprocessing costs. However, the major difference in costs between the LWR and the Na-BRO lies in the burnup charges and the Pu-interest. In spite of the relatively high interest charges for the Pu-inventory which have to be paid by the oxide type of fast breeder, the total costs on account of this item are considerably lower (by 0,28 Dpf/kWh) than the burnup charges (minus the Pu-credit) to be paid by the LWR. Fast breeders will always have an advantage over the LWR for this cost item as they do not have any burnup charges.

5. EXAMPLES ON THE INFLUENCE OF TECHNICAL AND COST PARAMETERS ON FUEL CYCLE COSTS

TABLE V summarises the reactor and the cost parameters which have been varied. It also includes the basic fuel cycle data. Every time a reactor parameter was changed the reactor was made critical anew. The height to diameter ratio for the core, the pressure drop and the temperature difference of the cooling medium accross the core were kept always the same. The main purpose of these variations is rather to understand general trends than to determine the fuel cycle costs with great accuracy.

5.1 Fuel cycle costs vs. burnup, TABLE VI, Fig. 3

According to TABLE VI fuel cycle costs increase from 0.38 to 0.43 Dpf/kWh when the burnup is increased from 80.000 to 160.000 MWd/t. In Fig. 3 fuel cycle costs show a minimum for both oxide and carbide fuel. The FC-costs reduce for a given burnup when the rod power is increased from 230 to 460 watt/cm for oxide type fuel. For the same pin diameter the rod power with carbide fuel is twice that of the oxide fuel. For 80.000 MWd/t burnup the FC-costs for the carbide fuel are 0.27 Dpf/kWh compared to 0.38 Dpf/kWh for the oxide fuel.

5.2 FC-costs vs. fissile material rating, Fig. 2

In all the four cases shown in Fig. 2, the FC-costs go through a minimum with increasing rating in the range of 5 - 8 mm pin diameter. For a given rating the FC-costs are always lower for carbides than for oxides.

5.3 FC-costs vs. rod power and critical mass, Fig. 4

The optimised fuel cycle costs (with optimum b and p) decrease relatively slowly with increasing rod power for oxide fuel. With a four time increase in χ from 230 to 920 watt/cm the FC-costs decrease from 0.42 to 0.33 Dpf/kWh i.e. by about 20%. The initial plutonium inventory on the other hand, reduces at a faster rate. For the same increase in rod power it decreases by a factor of 2,4.

5.4 FC-costs vs. breeding ratio, Fig.5, and Pu price, Fig.6

For a plutonium price of zero, FC-costs tend to decrease with decreasing breeding ratio (Fig.5), as fabrication and reprocessing costs for the radial blanket become an unnecessary economic burden. For higher plutonium prices, the FC-costs show a minimum for a specific breeding ratio for both the oxide and the carbide fuel. The higher fabrication and reprocessing costs for the increased amount of radial blanket outweighs the plutonium credit above a certain breeding ratio. Because of their lower breeding ratio the oxide fuel shows a stronger dependence on plutonium price than the carbide fuel (Fig.5,6). For oxide fuel for example, the FC-costs increase from 0.38 to 0.53 Dpf/kWh when the Pu price is increased from 40 to 80 DM/g. For the same increase, the FC-costs for the carbide fuel go up from 0.27 to 0.35 Dpf/kWh.

5.5 FC-costs vs. fabrication costs, TABLE VII, and reprocessing costs, TABLE VIII

The effect of a change in average fabrication costs on the total FC-costs for the reference reactors Na-BRO and Na-BRC are shown in TABLE VI. The FC-costs reduce from 0.4 to 0.25 Dpf/kWh for the oxide and from 0.36 to 0.17 Dpf/kWh for the carbide when the average specific fabrication costs are decreased from 500 to 100 DM/kg, i.e. by a factor of 5. The effect of changing reprocessing costs on the FC-costs is considerably lower (TABLE 7).

6. CONCLUSIONS

The validity and accuracy of any analysis on fuel cycle economics of fast breeder systems is limited by the fact that such an analysis has to be a projection in the future, as economic fast breeders would probably come into operation about a decade from now. Besides, in carrying out the present analysis some plant variables have been kept constant which may be changed at a later stage. In spite of these drawbacks, the foregone analyses permit a number of generalised conclusions to be drawn, which more or less characterise some of the inherent properties of fast breeder systems and the dynamically growing nuclear industry, which the fast reactors will form a part of.

6.1 In an expanding nuclear energy system all the cost parameters used for deriving the fuel cycle costs of fast breeders (excepting the interest rate), will be to a large extent influenced by the existing converter reactors in the foreseeable future. The specific fabrication and reprocessing costs for fast breeder fuel elements are likely to decrease with time because of large size plants and improved technology whereas, the Pu price would have a tendency to rise so long as the fast breeders are to depend on plutonium produced in the converters.

6.2 The burnup influences mainly the fabrication and reprocessing costs. It is better to reduce these costs by improving the technology or improving the thermal efficiency than by increasing the burnup. Since the fabrication costs have larger effect on FC-costs than the reprocessing costs, it would be economically advantageous to put more effort on the reduction of fabrication costs than on the improvement of reprocessing technology. Because of the first core requirements for the newly installed reactor, the capacity of the fabrication industry always leads that of the reprocessing industry by 3-4 yrs.

6.3 Fast reactor systems with oxide fuel are more sensitive to Pu-price than those with carbide fuel. Even so, the FC-costs for oxide breeders remain considerably below those for light water reactors even with a Pu-price of 80 DM/g.

6.4 The oxide breeders have a cost advantage of about 0.3 Dpf/kWh and the carbide about 0.4 Dpf/kWh in the fuel cycle costs over the presently known converters.

6.5 An oxide or a carbide reactor system with approximately the same capital investment can be designed for a wide range of reactor parameters which influence the FC-costs (Oxide: burnup 40.000 - 100.000 MWd/t, fissile rating 0,5 - 1,1 MW_{th}/kg Pu, rod power 230 - 500 watt/cm, breeding ratio 1,1 - 1,37; Carbide: burnup up to 100.000 MWd/t, fissile rating 1,0 - 2,5 MW_{th}/kg Pu, rod power 500 - 1.500 watt/cm, breeding ratio 1,2 - 1,5). They can always be designed for the prevailing economic conditions in such a way that the fuel cycle costs remain well below those from any of the known converter systems.

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TABLE I

Technical and cost data for the reference reactors Na-BRO and Na-BRC

	Symbol	Unit	Reactor type	
			Na-BRO Na-cooled mixed oxide	Na-BRC Na-cooled mixed carbide
Geometry				
Core volume		1	6.570	3.700
Core height		cm	97,5	81
Core diameter		cm	293,0	241
Axial blanket hight		cm	40	40
Radial blanket thickness		cm	45	45
Fuel pin diameter Core + Ax.Bl.	d	mm	6,5	6,5
Radial Blanket		mm	12,5	12,5
Reactor-physical				
Thermal power	N_{th}	MWe	2.333	2.333
Electrical power		MWe	1.000	1.000
Thermal efficiency	η	1	0,43	0,43
Max. Rad. power	χ	Watt/cm core fuel	460	920
Fissile rating	b	MW_{th}/kg Pu-fissile	0,87	1,33
Burnup in Core	a_m	MWd/t heavy metal	80.000	80.000
Ratio fertile/Fissile in Core Ar	y	1	7,0	7,4
Breeding ratio				
Internal	Br_i	1	0,94	0,95
Axial	Br_a	1	0,24	0,28
Radial	Br_r	1	0,19	0,27
Total	Br_g	1	1,37	1,50
Plant load factor	κ	1	0,7	0,7
Reactor-Thermydynamics				
In core:				
Fuel fraction	ω	%	40,4	35,5
Struct.mat.fraction	β	%	19,4	18,1
Coolant fraction	α_c	%	40,2	46,4
Temp. increase in coolant	A_T	°C	200	200
Pressure drop in coolant	ΔP	Atm	3	3
Cost data				
Spec. Fabrication				
Core	K_K	DM/kg heavy metal	619	614
Axial blanket	K_{AB}	DM/kg heavy metal	130	115
radial blanket	K_{RC}	DM/kg heavy metal	200	200
Av.Core + Ax.Bl.+Rad.Bl.	K_{AV}	DM/kg heavy met.mixed	384	315
Spec.Reprocessing + transport	K_R	DM/kg heavy metal in mixed core + Ax, Bl.+Rad.Blanket	210	175
Plutonium price	α	DM/g Pu-fissile	40	40

TABLE II

Composition of Plutonium from high burn-up LWRs and Fast Breeder Reactors

Pu-Isotope	LWR [°/o]	Fast Breeder [°/o]
239	55-60	60-75
240	20-25	22-30
241	10-15	2,5-5
242	5-10	0,5-2,5

TABLE III

Dependence of fuel cycle cost items on reactor parameters, Pu-price and interest rate; FC-costs for Na-BRO and Na-BRC

Cost items in Dpf/kWh	Parameter dependence	Eq.	Fuel cycle costs Dpf/kWh		
				Na-BRO	Na-BRC
1. Core fabrication	$\eta^{-1} \cdot a_m^{-0{,}6} \cdot b^{-0{,}5} \cdot \chi^{-0{,}5} \cdot$		Fabrication costs for		
	$\cdot (1+y)^{-0{,}5}$ or	6	Core + Ax. Bl. + Rad. Bl.	0,13	0,15
	$\eta^{-1} \cdot a_m^{-0{,}6} \cdot d^{-1}$ or	6a			
	$\eta^{-1} \cdot a_m^{-0{,}6}$	7			
2. Reprocessing for mixed fuel (Core + Ax.Bl. + Rad. Bl.)	$C_1 \cdot \eta^{-1} \cdot a_{mav}^{-1} + \eta^{-1}$	9	Reprocessing + Transport costs	0,06	0,06
3. Pu-Interest-Pu-Credit			Pu-Int-Pu-Credit	0,19	0,06
(a) Pu-Int. for in-pile inventory	$\alpha . m . R . b^{-1} . k^{-1} . \eta^{-1}$	10	Pu-Int. in-pile	0,257	0,184
(b) Pu-Int. for out-of-pile inventory	$\alpha . m . R . t_w . a_m^{-1} . \eta^{-1} . (1+y)^{-1}$	10a	Pu-Int. out-of-pile	0,048	0,046
(c) Pu-Int. for excess Pu produced in Rad. Bl.	$\alpha . R . p . a_m (1+y)(Br_g - 1) .$ $. b^{-1} . k^{-1} . \eta^{-1}$	10b	Pu-Int. Rad. Bl.	0,030	0,030
(d) Pu-Credit	$\alpha (\upsilon Br_g - 1) \eta^{-1}$	11	Pu-Credit	-0,145	-0,200
			Total FC-costs	0,38	0,27

TABLE IV

Fuel cycle costs for LWR /8/, HWR /3/ and the Reference fast breeder Na-BRO

Cost item	Symbol	Unit	LWR	HWR	Na-BRO
Fabrication	K_F	Dpf/kWh	0,17	0,34	0,13
Reprocessing	K_A	Dpf/kWh	0,06	- (Throw away cycle)	0,06
Burnup-charges	K_B	Dpf/kWh	0,52	0,20	-
Interest charges on plutonium	K_{int}	Dpf/kWh	Incl. in $K_{Pu\,Cr}$	-	0,34
Plutonium credit	$K_{Pu\,Cr}$	Dpf/kWh	-0,08	-	-0,15
Total fuel cycle costs	K_{FC}	Dpf/kWh	0,67	0,54	0,38
Spec. Fab. Costs	K_{AV}	DM/kg	250	200	384
Spec. Repro. Costs (incl. Transport)	K_R	DM/kg	140	-	210
Thermal efficiency	η	1	0,345	0,33	0,43
Burnup (average)	a_{mav}	MWd/t mixed fuel	27500	9000	30000

TABLE V

Parameter variation and reference data for fuel cycle cost calculations.

	Na-BRO			Na-BRC
Burnup MWd/t · 10^3	40 80 110 160			40 80 110
Rod power, watt/cm	230	460	920	920
Fissile rating, MW_{Th}/kg Pu	0,75 0,54 0,41	1,1 0,87 0,63	1,72 1,27 1,03	1,58 1,33 1,02
Fuel pin diameter, mm	5,0 6,5 8,0	5,0 6,5 8,0	5,0 6,5 8,0	5,0 6,5 8,0
Rad. bl. thickness, cm	15 30 45			15 30 45
Ax. bl. height (at the top and bottom of core fuel) cm	25 30 35 40			25 30 35 40
<u>Base fuel cycle data</u>				
Specific fabrication costs				
Core fuel	Eq. (1)			same after making correction for density
Ax. Bl. fuel	Eq. (3)			
Rad. Bl. fuel, DM/kg	200			200
Plutonium price, DM/g	40			40
Interest rate %/a	7			7
Taxes %/a	2,7			2,7
Life time for reactor, yr	25			25
Fabrication time, yr	0,22			0,22
Reprocessing time (including cooling and transport)	0,50			0,50
Total out-of-pile time (tw) yr	0,72			0,72
Excess requirement of material in Fabrication (m)	1,01			1,01
Material obtained from reprocessing (υ)	0,99			0,99

TABLE VI

Technical and Fuel Cycle Cost Data for the Reference Reactor Na-BRO with 80.000 and 160.000 MWd/t burn-up

Burn-up	[MWd/t Core fuel]	80.000	160.000
Critical Mass	[kg Pu-f]	2.682	3.364
Fissile Rating	[MWth/kg Pu-f]	0,87	0,69
y	[1]	7,0	4,04
Pu fissile concentration in Core	[°/o]	12,5	19,8
Real smeared density of heavy metal	[°/o of theoretical]	0,85	0,72
Breeding Ratio	[1]		
Internal		0,94	0,74
Axial		0,24	0,24
Radial		0,19	0,19
Total		1,37	1,19
Fuel Cycle Costs	[Dpf/kWh]		
Fabrication		0,13	0,10
Reprocessing + Transport		0,06	0,05
Pu-Interest - Pu-Credit		0,19	0,28
Total		0,38	0,43

TABLE VII

Fuel Cycle Costs for Na-BRO and Na-BRC with different specific fabrication costs for mixed Core + Blanket Fuel

Spec. Fabrication Costs ⎡DM/kg mixed fuel⎦	0	100	200	300	400	500
Fuel Cycle Costs ⎡Dpf/kWh⎦						
Na-BRO	0,25	0,28	0,32	0,35	0,39	0,42
Na-BRC	0,12	0,17	0,21	0,26	0,31	0,36

TABLE VIII

Fuel Cycle Costs for Na-BRO and Na-BRC with different specific reprocessing costs for mixed Core + Blanket Fuel

Spec. Reprocessing Costs ⎡DM/kg mixed fuel⎦	0	50	150	250	350	450
Fuel Cycle Costs ⎡Dpf/kWh⎦						
Na-BRO	0,32	0,33	0,36	0,38	0,40	0,43
Na-BRC	0,21	0,23	0,27	0,31	0,34	0,38

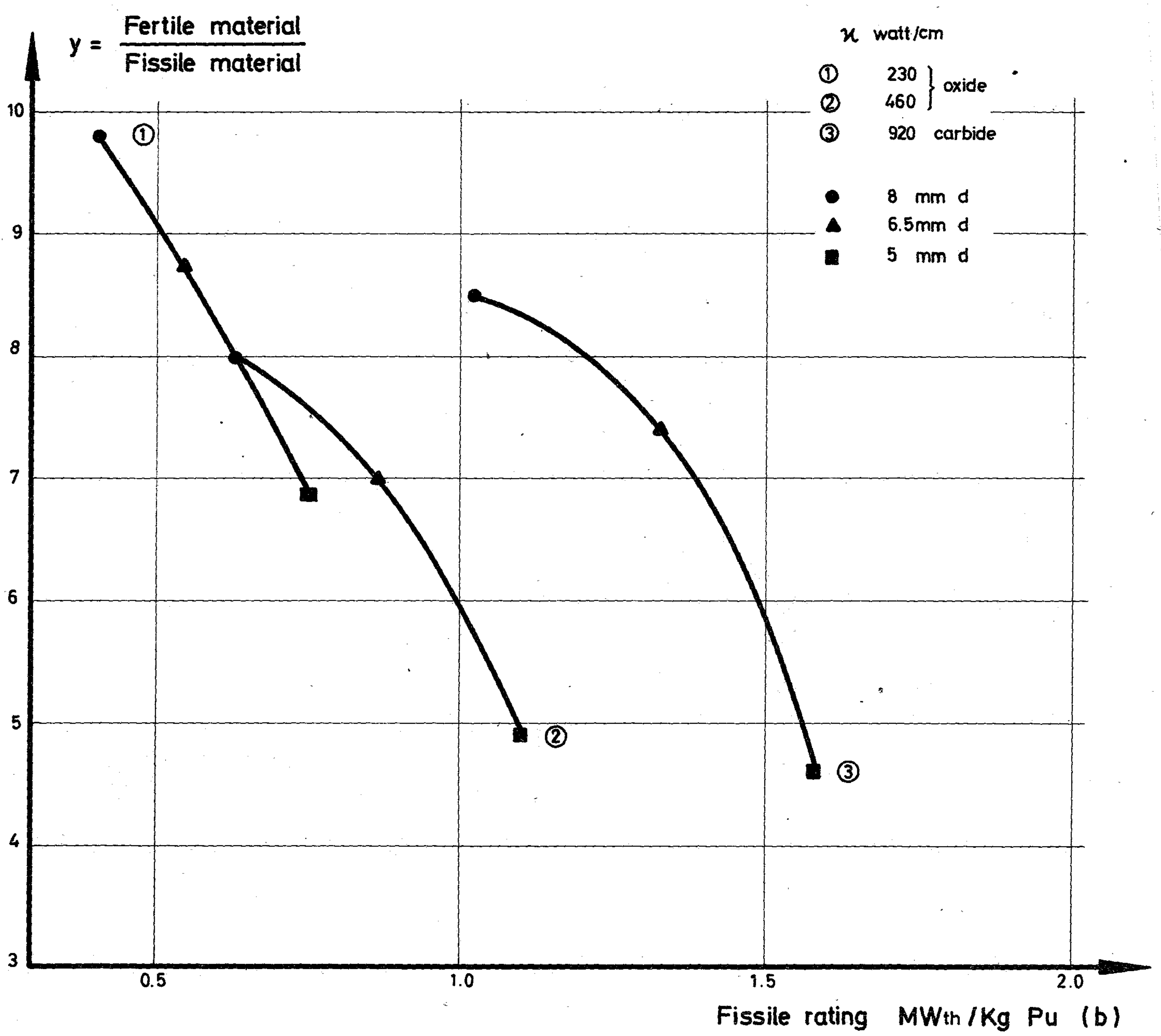
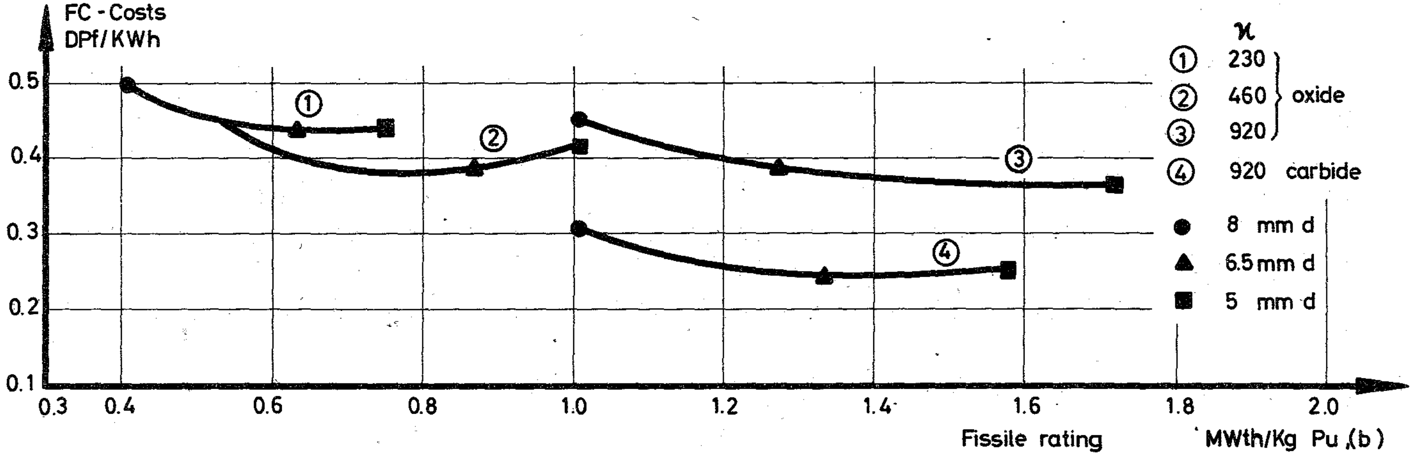


Fig. 1 Dependence of y on fissile rating (b) for the oxide type and the carbide type fuel, with rod power (ϰ) as parameter

Fig. 2 Fuel cycle costs vs fissile rating with ϰ as parameter
a_m = 80.000 MWd/t



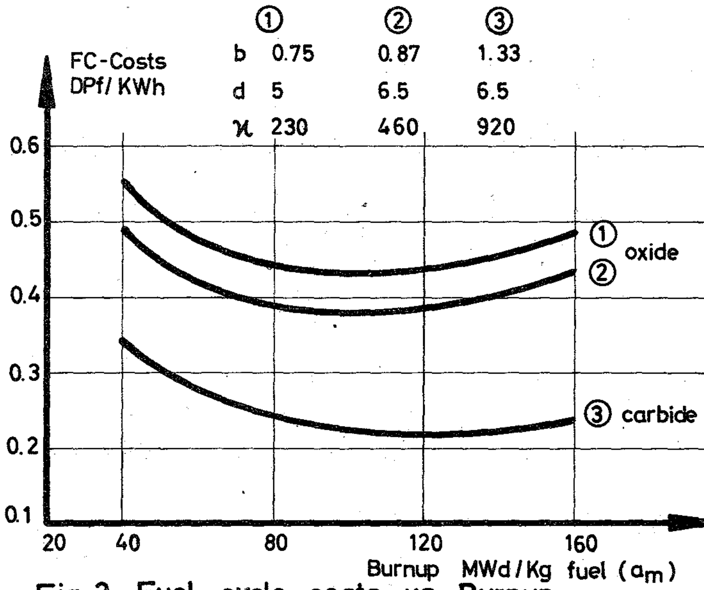


Fig. 3 Fuel cycle costs vs Burnup
with ϰ as parameter

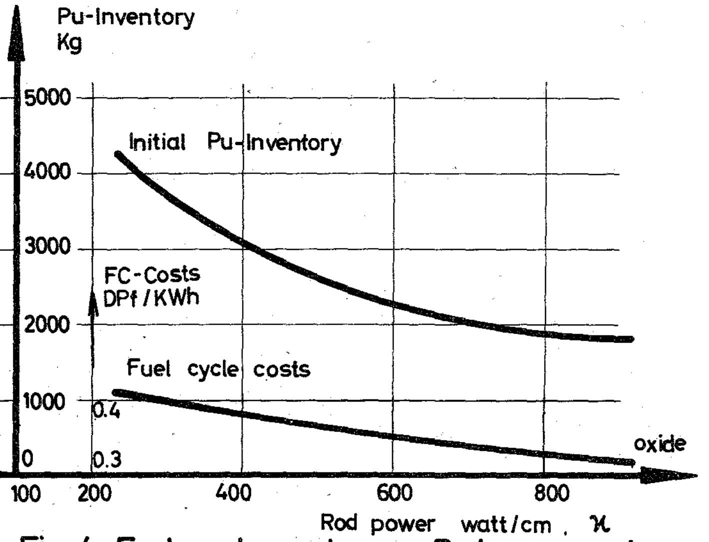
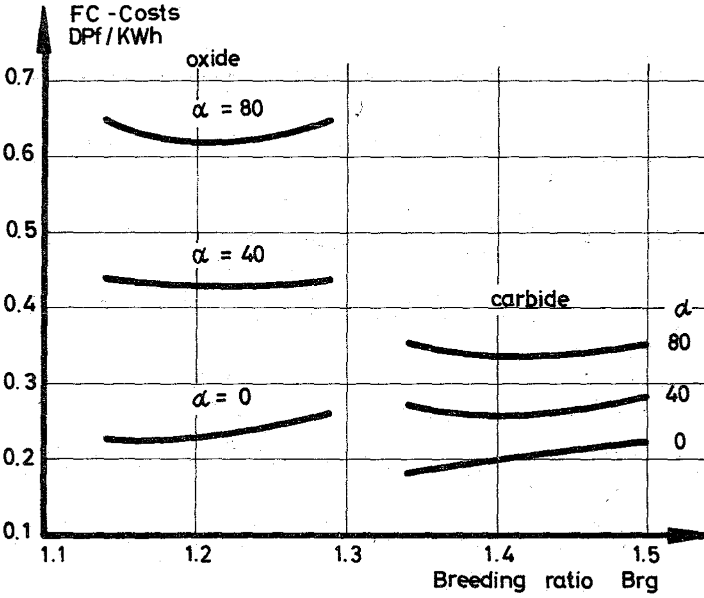


Fig. 4 Fuel cycle costs vs Rodpower and initial Pu-Inventory (oxide)
a_m = 80.000 MWd/t



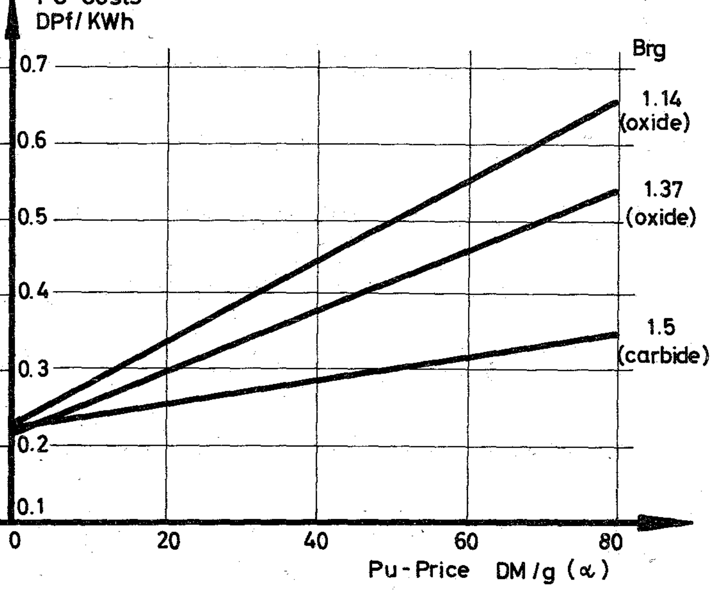


Fig. 5 Fuel cycle costs vs Breeding ratio with Pu-Price as parameter

Fig. 6 Fuel cycle costs vs Pu - Price with Breeding ratio as parameter