	Technische Mitteilung	TM-HL-261
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Betrifft: Very high breeding ratio in the molten chloride fast power reactor with external cooling.		Datum: 28.7.75 26 Seiten Zeichnungen

Introduction

In the recent time the discussion about the breeding efficiency of fast breeders is dealing with the difficulties of obtaining a reasonable doubling time for nuclear power.

In this paper the search for a significant improvement of both of these parameters, and therefore of the doubling time, is aimed to a design of a molten chloride fast breeder reactor, with as good as possible doubling time characteristics.

This can be achieved by rather trivial improvements. But here it must be stressed that most of these improvements can be realised only in a fast reactor with liquid fuel and especially in molten plutonium chlorides.

1) The breeding gain is very sensitive to the hardness of the neutron spectrum in the core. Because in the molten fuel reactor it is possible to use fissile material also with elimination of fertile material, the spectrum can be rather hard.

Verteiler

Abteilung	Name	Expl.	Abteilung	Name	Expl.
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	Dr. M. Furrer	1		S. Kypreos	1
IN	P. Moser	1	DO	Bibliothek	3
	K.H. Bucher	1		Reserve	15
ME	G. Ullrich	1			
PH	Dr. J. Brunner	1			
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	E. Ottewitte	1			

The impact of elimination of the fertile nuclide from the core e.g. on the Doppler-effect will be discussed later.

2. Because of hard spectrum the bonus of fast fission in fertile nuclides is high, which improves the breeding gain.

3. The elimination of structural material from the core in case of out-of-core cooling improves the neutron balance.

4. Decrease of the fission products concentration because of continous reprocessing, improves the neutron balance.

5. Doubling time, more than breeding gain characterises the efficiency of breeding process or for linear increasing power system the conservation coefficient which equals

$$\text{Gain x (Specific Power)}^2$$

The specific power in a liquid fuel reactor can be achieved on a level lower than 1 kg Pu tot/MWther, for the whole system: core + external heat exchanger + reprocessing plant.

This preliminary report gives some selected datas about such a type of power reactor.

This datas are calculated on the following basis:

- ANISN reactor code
- 23 neutron groups taken from GGC-3 condensed from ENDF/B III
- 7 zones with 110 intervals
- fourth order of quadrature, S_4
- anisotropy by first order Legendre expansion, P_1
- instead of F.P. cross sections, here the datas for Cs-133, have been used.

The reference reactor: core

The reference reactor is characterised on (see fig. 1) fig. 2. Short description of his properties:

Total thermal power:	6000 MWth
Central zone:	Molten chlorides of uranium-238 diluted by sodium chloride as internal breeding zone. Also some amounts of Pu-239 from the breeding process are here present. Small amounts of fission products are present Radius of this zone 110 cm
Wall:	Material: iron with layer of molybdenum Width: 3 cm
Fuel zone:	Molten chlorides of plutonium Pu-composition: 0,7 Pu-239, 0,2 Pu-240 0,1 Pu-241 diluted by sodium chloride. Significant amounts of uranium-238 (as chlorides) are present for achieving an internal breeding ratio of 0.22 Width of zone 18 cm Specific power ~ 1 KW/cm^3 Flux total $\sim 1 \cdot 10^{16}$ n cm^{-2}s^{-1}
Wall:	Material: iron/molybdenum Width 3 cm
External zone:	The same as central breeding zone Width in all cases 100 cm
Reflector:	Material: iron only Width in all cases 40 cm

(see table 1)

Table 1 CORE 200/C

Thermal power 6 GWth

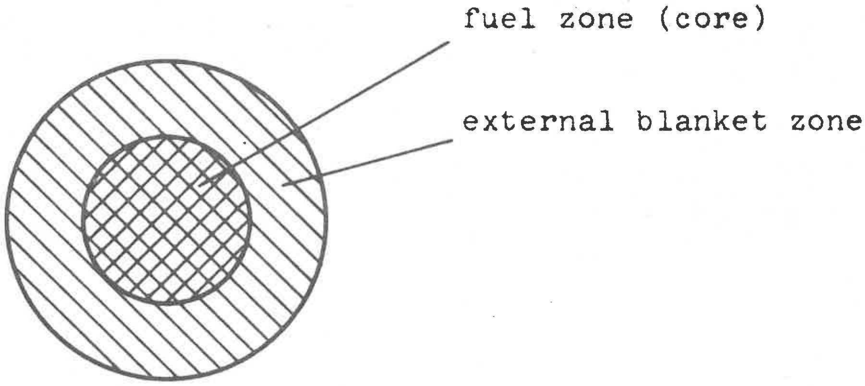
Breeding ratio 1,75

Specific power in fuel 1,1 KW/cm^3

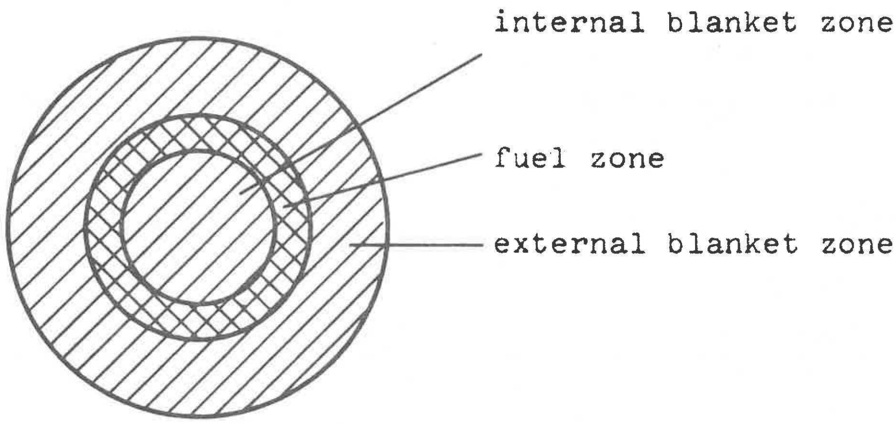
Radius cm	Width of zone cm	Zone	Composition atoms/10^{24} cm^3	Flux thermal/total Breeding ratio	Specific power KW/cm^3 temperature
0	110,0	I Central breeding zone	U-238 $6{,}4\cdot10^{-3}$ Pu-239 $6{,}0\cdot10^{-5}$ F.P. $2{,}0\cdot10^{-5}$ Na $3{,}4\cdot10^{-3}$ Cl $2{,}27\cdot10^{-3}$	$\frac{1{,}05\cdot10^{16}}{3{,}7\cdot10^{8}}$ 0,490	T_{inlet} 700°C T_{outlet} 800°C
110,0	3,0	II Wall	Fe $7\cdot10^{-2}$ Mo $1\cdot10^{-2}$	$\frac{1{,}15\cdot10^{16}}{9\cdot10^{7}}$	~850°C
113,0	17,9	III Fuel zone	Pu-239 $1{,}4\cdot10^{-3}$ Pu-240 $4{,}2\cdot10^{-4}$ Pu-241 $2{,}1\cdot10^{-4}$ U-238 $4{,}2\cdot10^{-3}$ F.P. $2{,}0\cdot10^{-5}$ Na $3{,}4\cdot10^{-3}$ Cl $2{,}6\cdot10^{-2}$	$\frac{1{,}02\cdot10^{16}}{6{,}6\cdot10^{7}}$ 0,22	1,1 KW/cm^3 T_{inlet} 750°C T_{outlet} 1050°C
130,9	3,0	IV Wall	Fe $7{,}0\cdot10^{-2}$ Mo $1{,}0\cdot10^{-2}$	$\frac{8{,}24\cdot10^{15}}{2{,}5\cdot10^{8}}$	~850°C
133,9	100,0	V External breeding zone	the same as central breeding zone I	$\frac{3{,}9\cdot10^{14}}{1{,}9\cdot10^{9}}$ 1,040	T_{inlet} 700°C T_{outlet} 800°C
233,9	40	VI Reflector	Fe $8{,}0\cdot10^{-2}$	$\frac{5{,}2\cdot10^{12}}{5\cdot10^{4}}$	
273,9					

Fig. 1 Peculiarity of the Reference Reactor Design

"Classical" fast breeder reactor with external blanket only



This reference reactor Blanket-Core-Blanket



for impact of internal breeding zone (see also DUCAT, MIT, 1974)

Fig. 2 Power Reactor 6 GWth

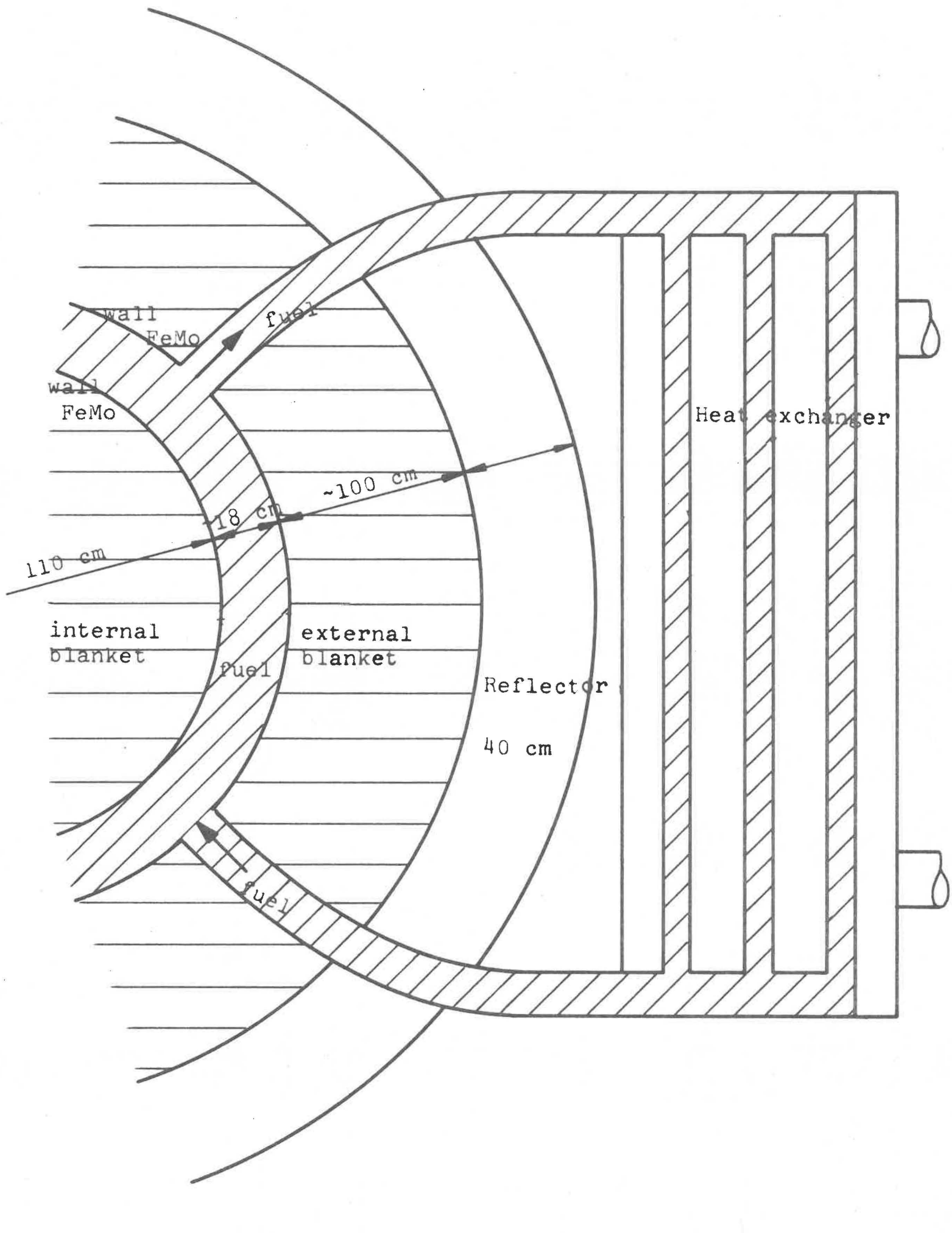


Fig. 3 Neutron Flux in Reference Reactor

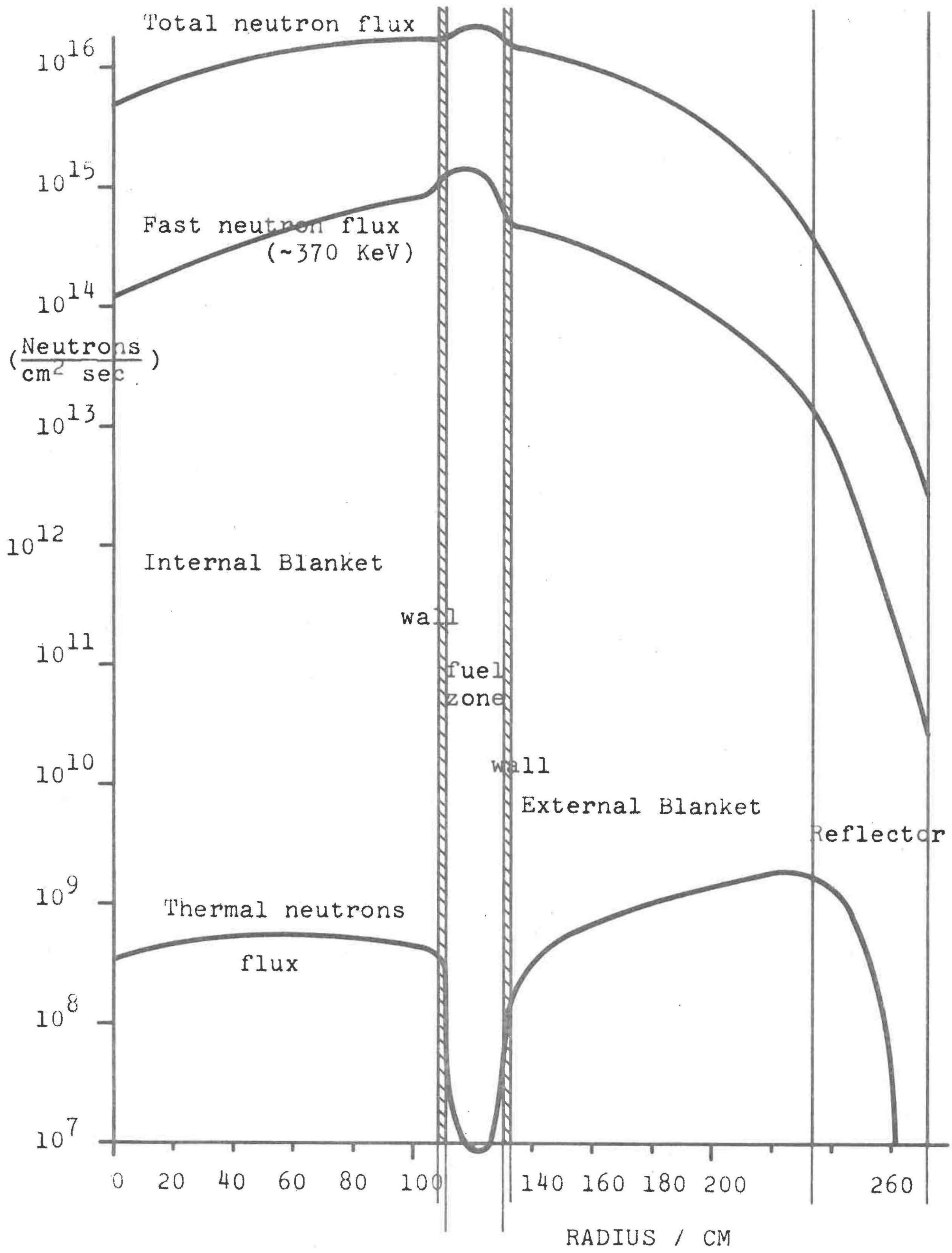
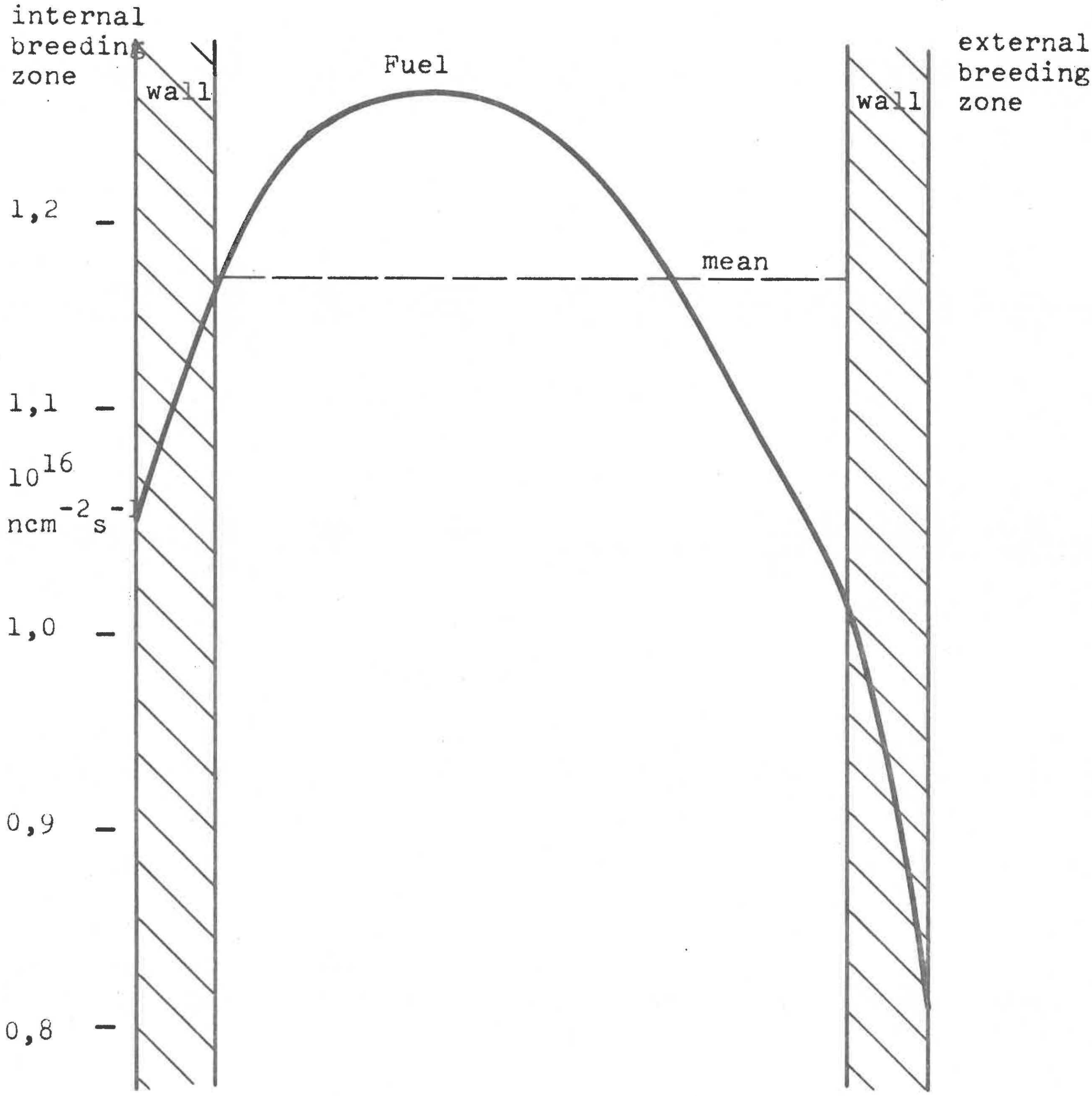


Fig. 3' Total Flux in the Fuel Zone



The neutron flux in the reference reactor is shown in fig. 3, 3' and 4.

The thermal flux in all three zones, external breeding zone, fuel and external breeding zone is only 10^{-8} of the total flux and only in external blanket zone arrives 10^{-6}.

The total flux is relatively smoth distributed and also in the fuel zone the maximum to the mean value of the flux achieves approx 1,13 (fig. 3').

The neutron flux is rather hard and the median energy of neutrons (here estimated as that to the left and to the right of this value the number of fission is equal) is approximately ~370 KeV (see fig. 4). In a typical liquid metal fast breeder and in gas cooled fast breeder this value equals: 120 KeV and 176 KeV respectively.

As a good illustration of the impact of the most important parameters on the value of breeding ratio a simplified calculation is given on the table 2. The discrepancy between this calculations and the computer output is of 8%.

Fig. 4 Spectrum in Fuel Zone

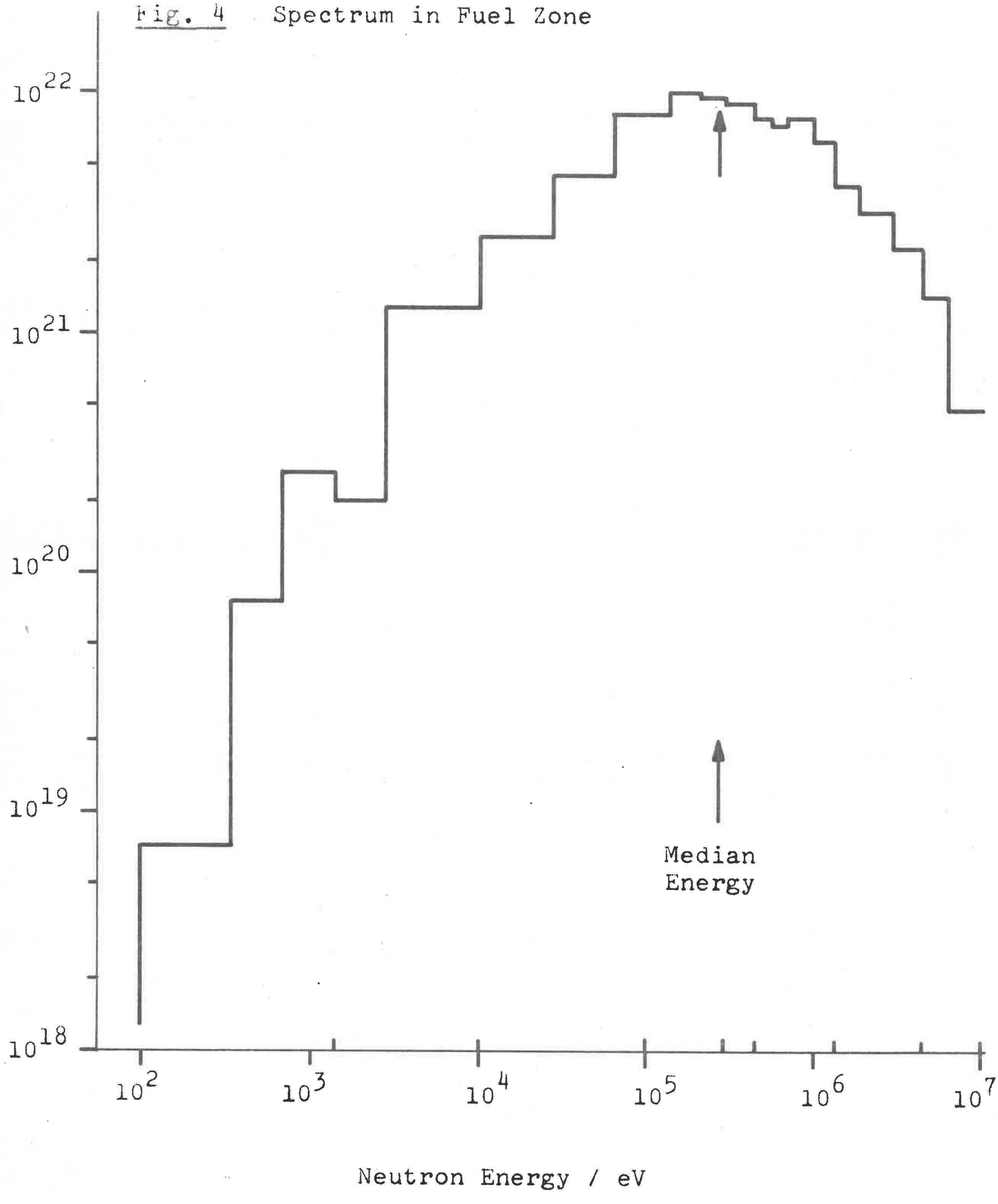


Tabelle 2 Simplified calculation of breeding ratio and neutron balance

Median energy (10/11 group)		370 KeV	
Pu-238	σf	1.83 barn	
(from computer output)	σc	0.180	
	ν	~2.95	
	α	0.0984	
	$\eta - 1$	1.6857	
δ: fertile/fissile fission		0.37	
Bonus $\frac{(\nu' - 1)\delta}{1+\alpha}$		0.539	
Total positive			2.225
Losses			
FP, Cl, Na,			
Mo, Fe		0.160	
Leakage (arbitr.)		0.10	
$\frac{\text{Losses} + \alpha}{1+\alpha}$		0.32	
Calculated BR			1.890
Computed BR			1.752

Impact of the plutonium contents in the fuel

One of the most important problems in achieving a high breeding ratio seems to be the hardness of the neutron flux, this is strongly influenced by the composition of the fuel.

In this case the fuel has been postulated to be a mixture of

$$a\ PuCl_3 \cdot b\ NaCl \cdot c\ UCl_3$$

a = 0,1 - 0,2 b = 0,7 - 0,8 c = 0,1 - 0,2

Unfortunately not all datas for this system are available (fig. 5).

The rough calculation of the changing concentration of $PuCl_3$ in the melt with NaCl (fig. 6) shows a rather sharp decrease of breeding gain BG for decreasing plutonium concentration, especially when the plutonium molar ratio to the sodium is lower than 0,25.

In spite of these uncertainties of the $PuCl_3$-NaCl-UCl_3 system here has been calculated the impact of uranium-238 in the fuel. For a constant $PuCl_3$ concentration, with simplified correction of NaCl concentration, the results are given on the fig. 7.

For the increasing ratio of uranium to plutonium in fuel from 0 to 3 the total breeding gain increases from 0,65 to 0,95. It is a rather clear situation; and therefore the reference reactor includes uranium in fuel in a ratio of 2:1 to the plutonium.

Fig. 5 The System $PuCl_3$-NaCl-UCl_3

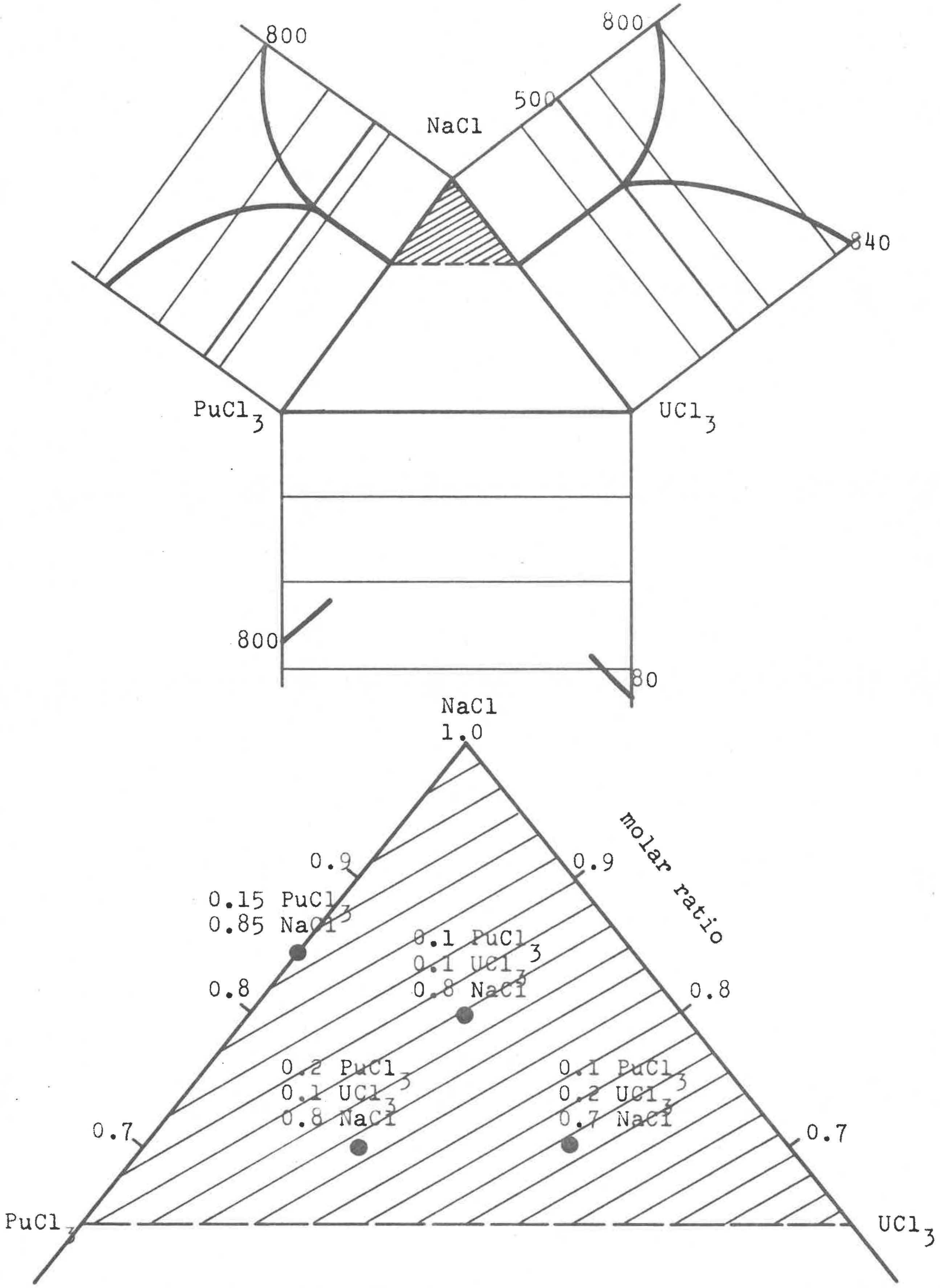


Fig. 6 Plutonium Concentration

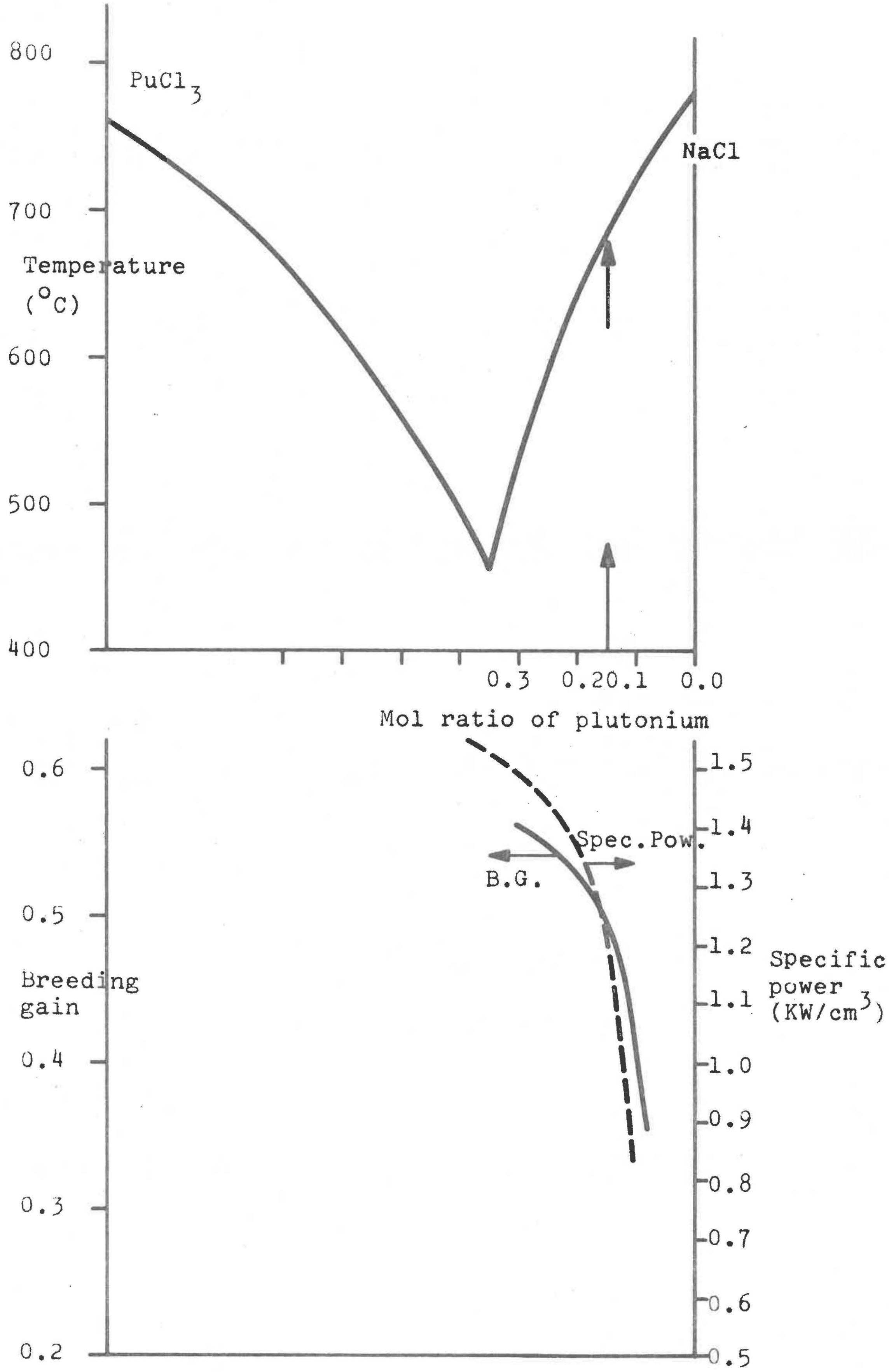


Fig. 7 Impact of U-238 Concentration in the Fuel
Pu-Concentration: $0.0021 \cdot 10^{24}$ atom/cm^3

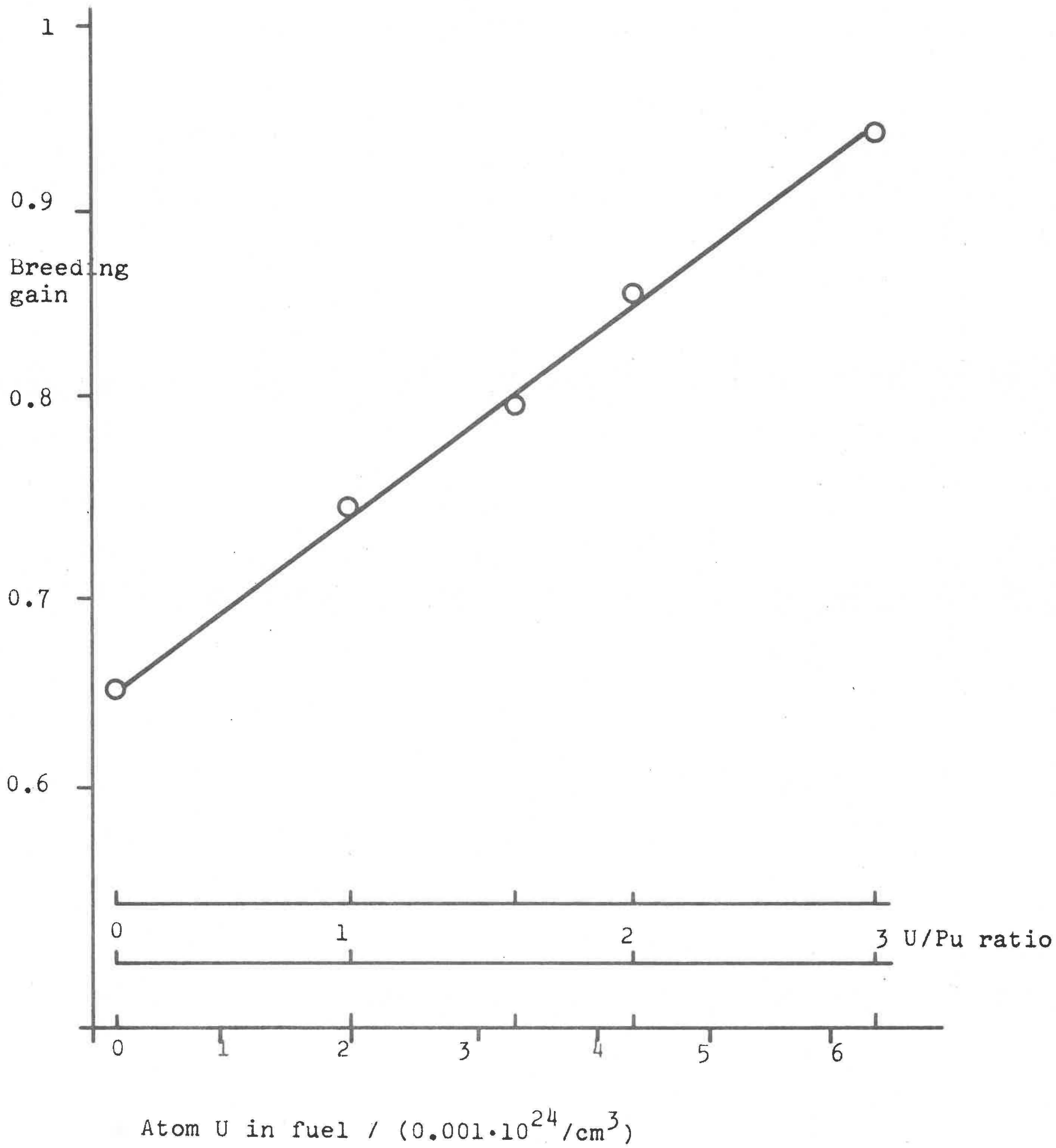
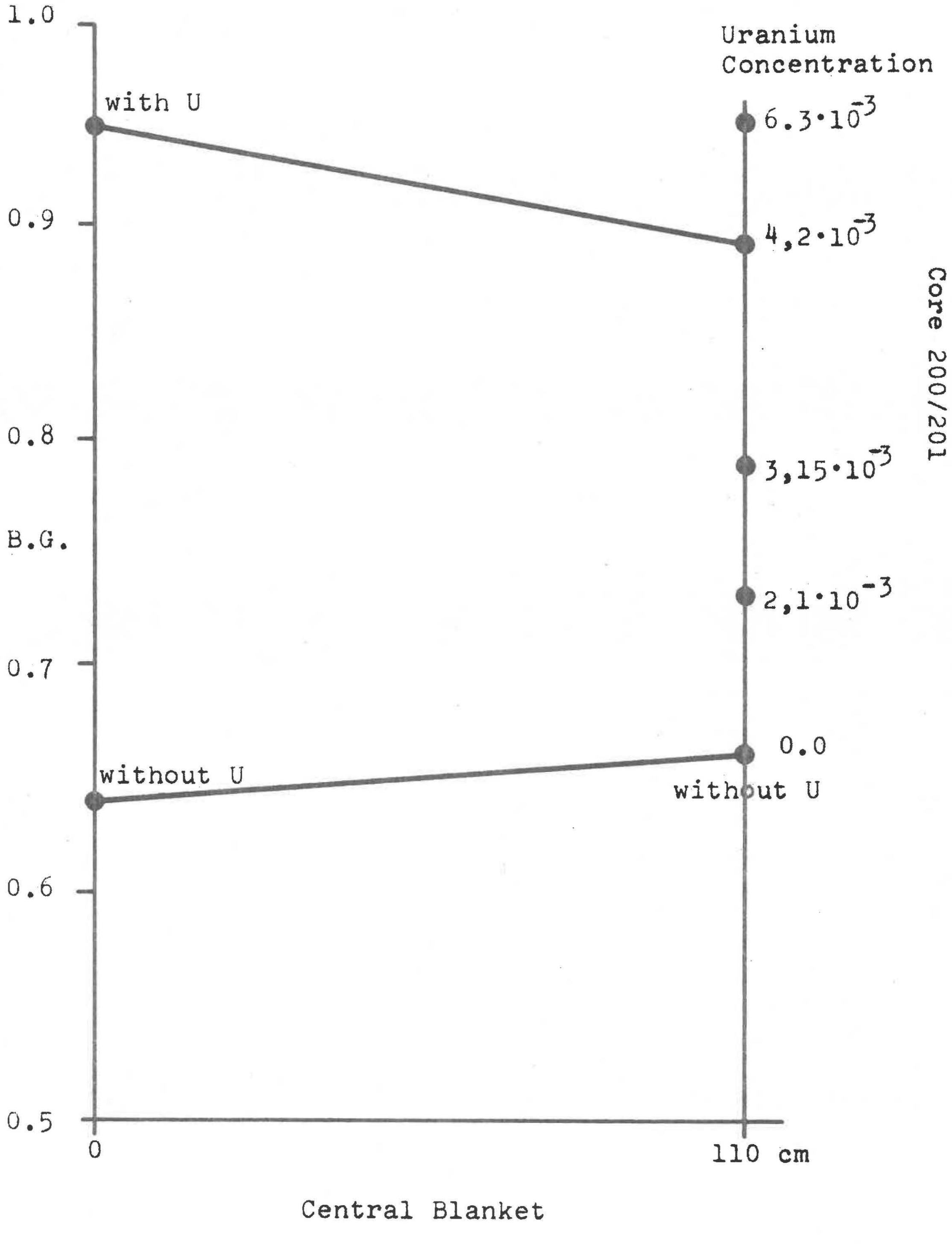


Fig. 8 Impact of Uranium Concentration in the Fuel



Problem of geometry:

Central breeding zone versus central fuel zone

The reference reactor is a rather nonconventional one because of three zones structure:

- internal blanket zone
- fuel zone
- external blanket zone

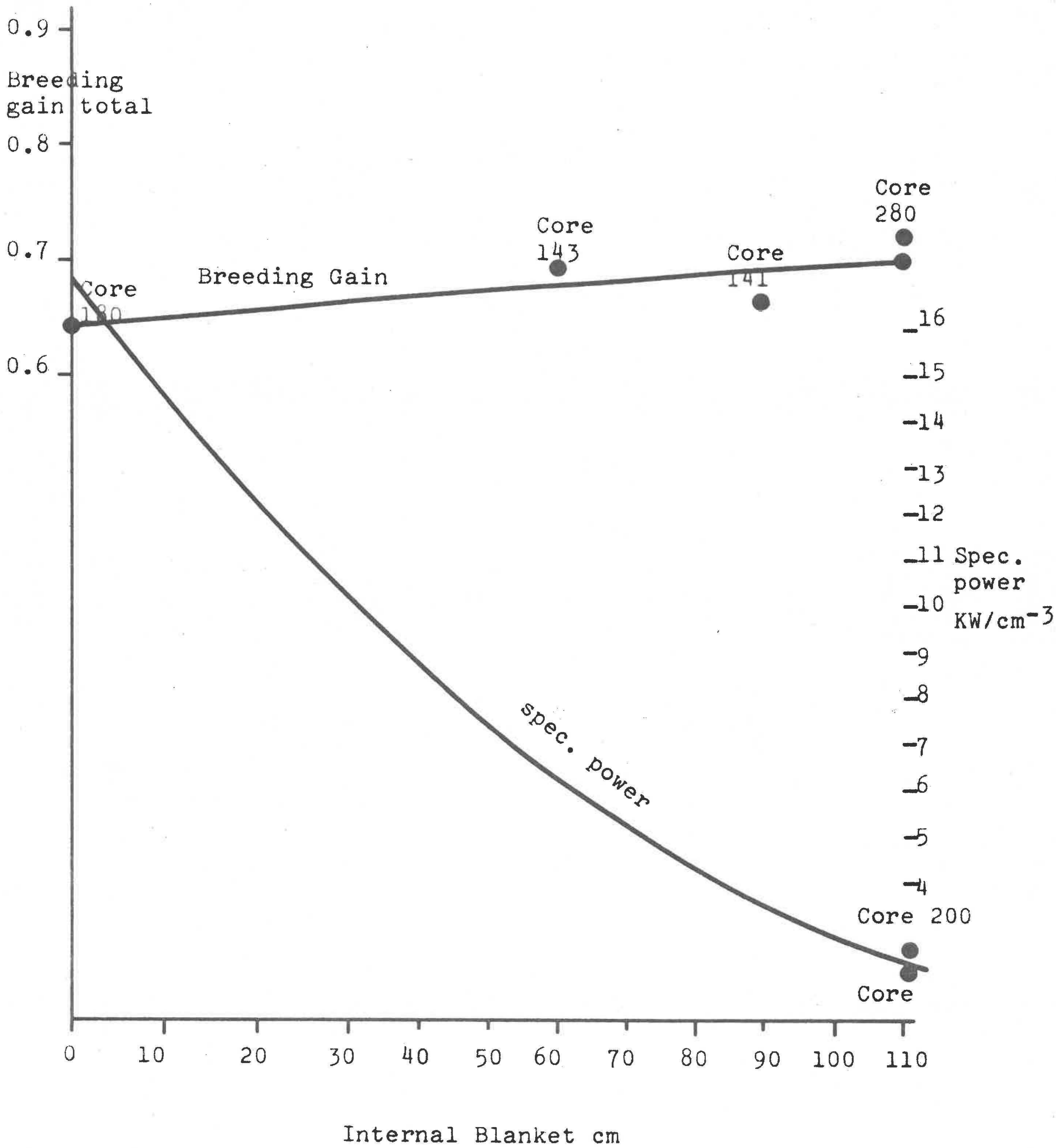
This type of reactor has been checked with the conventional type (table 2). For all other more or less constant parameters, inclusive total power, the obtained results for breeding gain are equal. But the difference is to see in the specific power changes more than one order of magnitude, being higher in the "conventional" central fuel zone reactor. It is trivial that also the mean neutron flux increases from $1{,}2 \cdot 10^{16}$ n $cm^{-2} s^{-1}$ for nonconventional central blanket zone to approx $2 \cdot 10^{17}$ n $cm^{-2} s^{-1}$ for the conventional central fuel zone.

Because the specific power and intensity of neutron flux is doubtless a very serious problem from point of view of ingeneering design of the reactor (cooling, radiation damage of structural material and fuel) the both systems that is without internal blanket zone and with radius up to 110 cm have been calculated. The results are given on fig. 8 for fuel without uranium and with uranium in fuel for both extrem cases; no internal blanket zone and by internal blanket zone.

Table 2 Fuel in central zone versus fuel in middle zone
6 GWth "Chlorophil"

Core (number of case)		conventional (180)	nonconventional (200)
Geometry	Central Middle Outer	Fuel ---- Blanket >100 cm	Blanket 110 cm Fuel ~18 cm Blanket 100 cm
Pu/FP		$2,1\cdot10^{-3}/2\cdot10^{-5}$	$2,1\cdot10^{-3}/2\cdot10^{-5}$
Spec. power KW/cm^3		17,7	1,41
Power in fuel %		90,9 %	76,2 %
Flux total in fuel left) right)	boundary	$2,04\cdot10^{17}$ $1,15\cdot10^{17}$	$1,2\cdot10^{16}$ $1,08\cdot10^{16}$
Flux in outer blanket left)) right)	boundary	$8,99\cdot10^{16}$ $2,16\cdot10^{15}$	$9,7\cdot10^{15}$ $2,5\cdot10^{14}$
Breeding gain		0,63	0,70
Median energy (group)		9 1/2	10

Fig. 9 Impact of Internal Radius
(No U in Fuel)



On the fig. 9 and 10 are given some results of different radii of the central breeding zone.

Also the simplified calculation of internal zone breeding ratio, breeding ratio in fuel and external zone breeding ratio is shown on table 3.

From all these datas the following conclusions can be obtained:

- increase of the internal breeding zone from zero up to 110 cm increases the breeding gain for given type of fuel, wall and fertile material only unsignificant, less than 10% relative.

- the specific power increases dramatically and makes the solution of in the design very difficult.

- the increase of U/Pu ratio from 2 up to 3,6 does not influence the total breeding gain (see fig. 10).

Table 3 (in arbitrary units)

Case number	Internal zone			Fuel		Outer zone			Total Breeding Ratio
	Pu-239 $\sigma x \nu$	U_{fis} $\sigma x \nu$	U_{cap}	$Pu\text{-}239_f$ $\sigma x \nu$	$Pu\text{-}241_f$ $\sigma x \nu$	$Pu\text{-}239_f$ $\sigma x \nu$	U_{fis} $\sigma x \nu$	U_{cap}	
*) 200	0,14	0,308	0,8	3,05	0,351	0,30	0,47	1,83	1,70
**) 180				3,63	0,367	0,04	0,46	2,50	1,63

*) nonconventional

**) conventional

Fig. 10 Breeding Ratio Versus Radius of Internal Fertile Zone

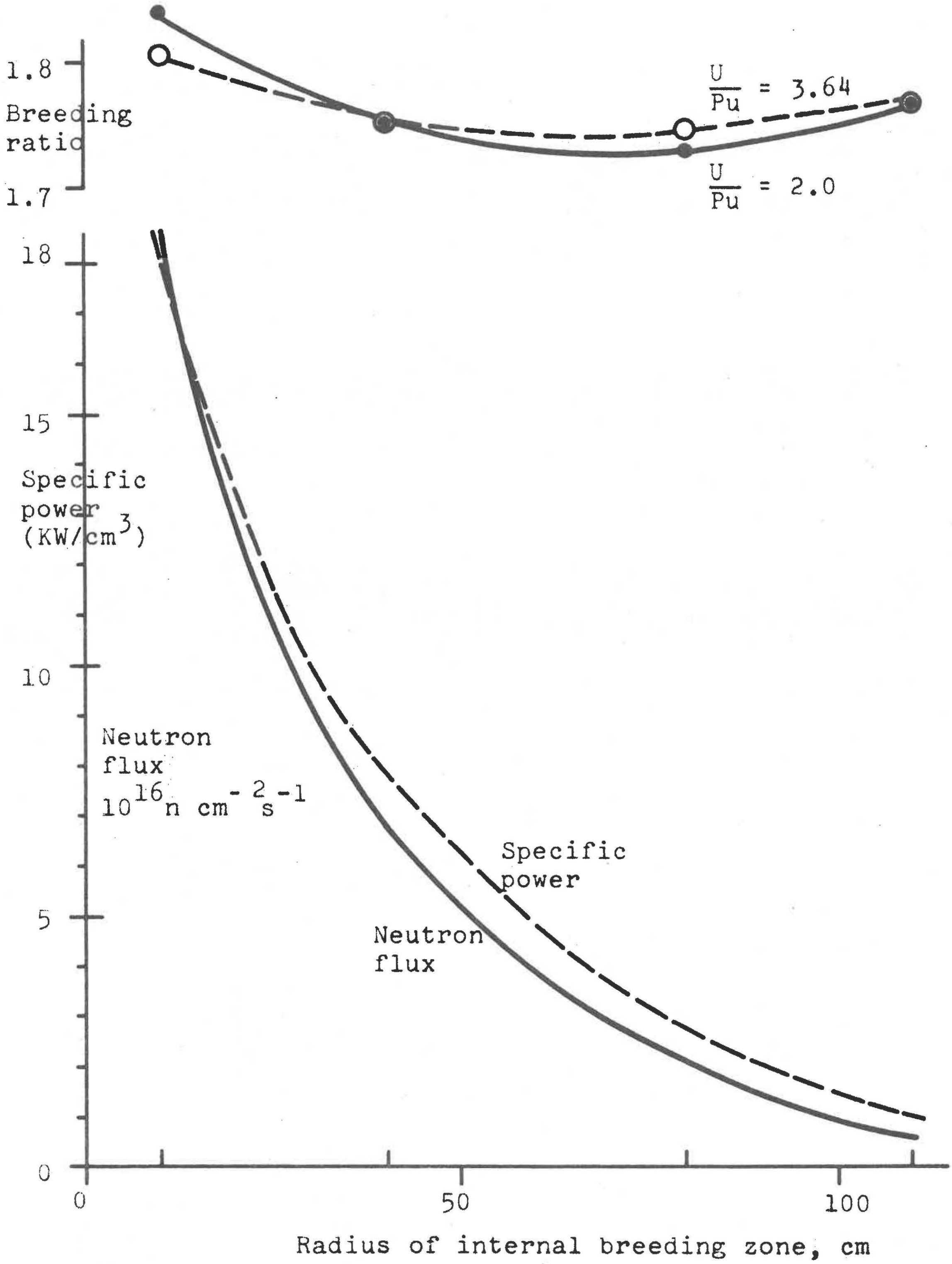
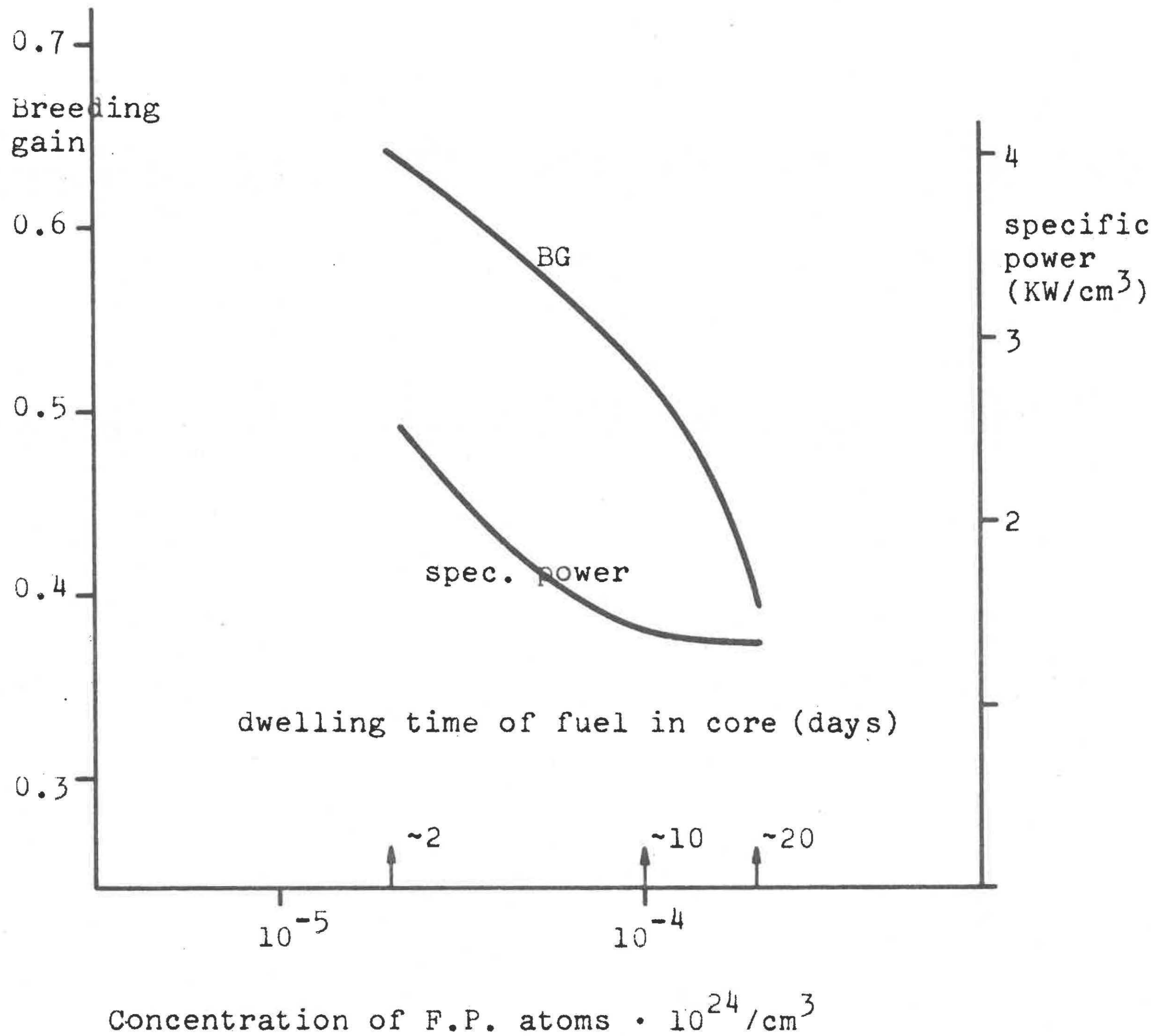


Fig. 11 Impact of Fission Products Concentration in Fuel
(very simplified, from different calculations)



Impact of reflector

The impact of the 40 cm with reflector, when changing from iron to lead is rather unsignificant as is to see from table 4.

Impact of F.P. concentration

This parameter play a very important role. For given reactor design and given fuel and fertile composition the increase the concentration of F.P. (here simulated by Cs-133 only) from $2 \cdot 10^{-5}$ to $2 \cdot 10^{-4}$ (in $10^{24}/cm^3$) decrease the breeding gain from 0,65 up to 0,38, when specific power decreases less than twice.

In steady state reactor a concentration of $2 \cdot 10^{-5}$ atoms F.P. $10^{24}/cm^3$ for a fuel with $2{,}1 \cdot 10^{-3}$ atoms Pu$\cdot 10^{24}/cm^3$ is to achieve for a specific power of 2 KW/cm^3 after a time period of

$$t = \frac{2 \cdot 10^{-5} \cdot 10^{24}}{2 \cdot 10^{3} \cdot 3{,}1 \cdot 10^{10} \cdot 2} = 1{,}61 \cdot 10^{5} \text{ sec}$$

that is after 1,87 days. The higher value of F.P. concentration that is $2 \cdot 10^{-4}$ corresponds to 18,7 days of mean dwelling time of fuel in reactor.

Table 4 Central fuel (Core 18)
(wall 2,5 cm; Pu = $2,1 \cdot 10^{-3}$ at/10^{24} cm^3)

Case	A	B	C
U in fuel	no	yes $4,2 \cdot 10^{-3}$	no
Reflector 40 cm	Fe	Fe	Pb
Volume fuel $\cdot 10^5 cm^3$	2,95	2,40	2,97
% power in fuel %	90,6	92,1	90,8
spec. power in fuel KW/cm^3	18,4	23,0	18,3
BR tot	1,64	1,94	1,66
Flux total right bound zone 3	$1,18 \cdot 10^{17}$	$1,25 \cdot 10^{17}$	$1,187 \cdot 10^{17}$

Impact of chlor-37 separation a separated chlorine Cl-37 which has much lower absorption cross section than Cl-35. The impact of each adsorber on the breeding ratio is given by:

$$\Delta B = \frac{A+D+L+\alpha}{1+\alpha}$$

ΔB = decrement of breeding ratio

A = absorption rate in given absorber

D = absorption rate in rest of absorbers

L = leakage

α = $\sigma c/\sigma f$

Because in typical case for strong absorber in hard spectrum fast core

$$A \cong (D + L) \cong \alpha = 0.15$$

The relativ impact on the rather high breeding ratio of B = 1,6 results in a case when the "profit" of the separation factor will be e.g. 0,9 A, than

$$\Delta B = \frac{0{,}9 \cdot 0{,}15}{1{,}15} = 0{,}12$$

and in relation to breeding gain

$$\Delta G = \frac{0{,}12}{0{,}6} = 0{,}20$$

doubling time $\frac{T'_2}{T_2} = \frac{G}{G+\Delta G} = 0{,}83$

Acknowledgment

All the results have been achieved in close cooperation with J. Ligou. The best thanks for the help of E. Ottewitte (nuclear datas and ANISN-code management) and S. Padiyath for computer technique help.

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