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ABSTRACT

A study was made on the use of thorium in the PWR Angra dos Reis I cell and reactor calculations were made demonstrating that a reduction in uranium ore consumption of 30% is possible

1 – INTRODUCTION

Brazil has ordered a 600 MWe PWR for a site at the Atlantic coast near Angra dos Reis scheduled for operation in 1978

Recently a 1200 MWe unit of the Biblis class was ordered from KWU for the same site In the next few years it is planned to order a total of 8 PWR s

Last year a programm was started in our Institute to become familiar with the problems associated with physics calculations of PWR s We extended the scope of our calculations to include the thorium cycle as Brazil has large reserves of thorium and has yet to discover significant uranium deposits

Thorium utilization reduces the uranium ore consumption and might form a solution to efficient resources utilization in the case plutonium recycle being forbidden We were encouraged by the fact that some of the first LWR s – Indian Point(3) and ELK River (6) used thorium in their first core Also the work done by Zorzoli in Italy should be mentioned(7)

Reprocessing and refabrication of thorium fuel should not pose greater problems than those of plutonium fuel The radiation levels can be kept low provided the recycle U 233 is chemically cleaned just before fabrication of Th 228 whose daughters emit some high energetic γ s Babcox and Wilcock has demonstrated the fabrication of U 233 containing fuel on a pilot plant scale(2) Reprocessing would use a head end similar to that for LWR uranium fuel and the Thorex process as developped for HTGR s In Italy an integrated reprocessing and refabrication facility for thorium has been built(1)

2 – CELL CALCULATIONS

Initially we made a number of cell calculations for the thorium and uranium cycle with the same data and methods This was to minimize any systematic error In the calculations the uranium pins were substitued with equal diameter thorium pins We used the HAMMER Cell Code(5) modified to solve the burnup equations

A calculation of the Yankee Row PWR cell showed excelent agreement with the Pu production and Pu vector data as reported by Poncelet(4)

The cell dimensions are given in Figure 1 and the beginning of life zone concentrations in Table 1

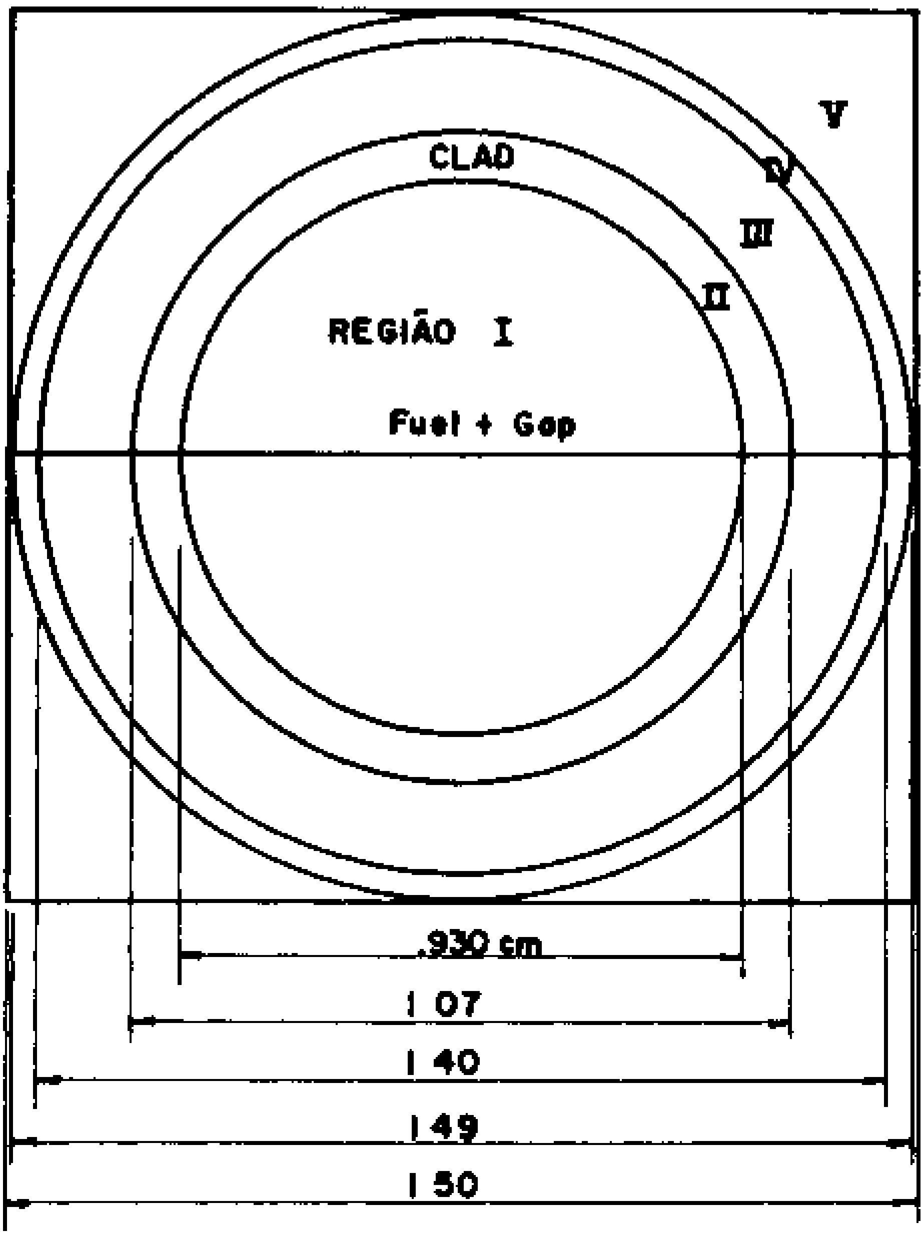

Figure 1 – Cell dimensions

Table I

BOL — Zone Concentrations

region		$^5UO_2+^5UO_2$	Net $PU+UO_2$	$^5UO_2+ThO_2$	$^3UO_2+ThO_2$	^5U+Th	^3U+Th
I Fuel	Th 232			0205	0200	0298	0291
	U 233		005	000002	000531	000003	000683
	U 235	000690	000156	0007		0009	
	U 238	0213	0218	00006		00007	
	Pu 239		00034				
	Pu 240		00018				
	Pu 241		000088				
	Pu 242		000067				
	O	0441	0440	0410	0410		
II Clad	Zr	0434 →					
	Fe	~ 10^{-7}→					
III e IV Water	H_2O	0249 →					
	Fe	00094 →					
	B 10		← 10^{-7} →				
IV control rod Eq	H_2O	0230 →					
	Fe	0075 →					
	B 10		← 10^{-7} →				

The initial enrichment of the fuel was so varied that at 15 MWd/Kg burnup keff was 1 00 Thus for these calculations leackage and control poison were neglected The results of the calculations are summarized in Table II The difference in the fast fission threshold and cross sections of Th 232 and U 238 is clearly shown in the fast fission factor ε About 30% of the fissions take place in bred material so that even for U 235 fueled reactors differences in $\bar{\eta}$ can be observed The differences in the beginning of life inventories result from the higher absorption cross section of Th and of the higher density of Th metal

The consumption and production of fissile material gives a indication of the ratio that can be maintained between U 235 fueled reactors and recycle reactors The plutonium production of two PWR is roughly equivalent to the consumption of one Pu fueled reactor One thorium oxide reactor produces sufficient fuel to sustain one U 233 ThO_2 reactor A U 235 Thorium Metal reactor can nearly sustain two U 235 Thorium metal reactors because the high U 235 loading reduces the burning of bred fuel in the U 235 Th reactor Using this ratio we can calculate the ore consumption and separative work requirements Table III For the uranium cycle it has been assumed that the discharged uranium will be reenriched Thus 20% of the discharged U 235 is lost in the tails of the enrichment plants Th cycle gives about 30% reduction in ore consumption and a 10% increase in enrichment The overall costs for fuel depletion are thus about 10% lower The slight increase in enrichment requirements is supprising since 95% enriched

U needs about two times more SWU *(1) per Kg U 235 than 3% enriched U This is partially compensated for by the lower U 235 consumption and by necessity to reenrich the used fuel

Table II

Results of Calculations

	REACTOR TYPE					
	$^{7}UO_2 - {}^{8}UO_2$	$Pu - UO_2$	$^{5}UO_2 - ThO_2$	$^{5}U - Th$	$^{3}UO_2 - ThO_2$	$^{3}U - Th$
Absorption						
Fissile	48	49	48	48	44	44
Fertile	33	38	34	35	37	38
Fission product	08	06	07	07	06	09
Structure mat.	02	02	03	02	03	03
H_2O	04	03	05	04	06	04
B 10	–	–	–	–	–	–
$\bar{\eta}$	1 93	1 87	2 05	2 05	2 22	2 24
ϵ	1 07	1 07	1 02	1 02	1 02	1 02
Conversion ratio	63	71	70	73	85	86
Inventory (kg)						
U 233	–	–	–	–	1130	1440
U 235*	1250	330	1480	1900	–	–
Pu 239	–	720	–	–	–	–
Pu 241	–	182	–	–	–	–
Consumption (kg/a)						
U 233	–	–	–172	–230	150	130
U 235*	330	83	370	460	–	–
Pu 239	–60	138	–	–	–	–
Pu 241	–16	14	–	–	–	–
Total	255	235	198	230	150	130

* Includes a 20% loss of U 235 due to rediffusion

Table III

Ore and Enrichment Consumption

	Fraction of U 235 reactors	U 235 consumption	Ore consumption	SWU consumption
U cycle	66	220 kg	50 000 kg	40 000 kg
ThO_2-cycle	50	185 kg	35 000 kg	45 000 kg
Th metal cycle	35	160 kg	30 000 kg	40 000 kg

3 – REACTOR CALCULATIONS

Full reactor calculations were made to include the effects of isotope buildup and control poison As a reference case we took the 600 MWe unit of Angra dos Reis We started with U 235 as fissil material After three cycles the bred fuel plus remeaning U 235 plus any other heavy isotopes were imideatedly recycled (Neptunium and Americium were not recycled) Sufficient U 235 was then added to obtain an excess reactivity needed for a run of 300 EFPD For the calculations we used a R Z reactor model (Figure 3) The incore fuel management was a strickt out in The power peaking factors were below 1 5 even though this refueling scheme is not optimal (Figure 4)

In a first run six cycles were calculated to obtain approximate equilibrium nuclide densities with BOL Cross Sections for U 235 fuel For these nuclide densities a new HAMMER run was made to generate two group cross sections With these then tweleve cycles were calculated Figure 5 Figure 6 The main fissile isotopes have reached equilibrium but some intermediate like U 234 U 236 are still increasing In Table IV the midcycle neutron balances are given

For a load factor of about 75% the U and Th cycles respectively consume 260 kg/a and 180 kg/a of U 235 The consumption of U 235 in the Th cycle is less than the neutron balances indicate as U 235 is being formed from captures in U 234

4 – COSTS

For the U cycle we assumed that the discharged fuel with a residual enrichment of 1 4% is reenched to 3 1% An second option is to replenish the fuel with highly enriched uranium A comparison of the depletion costs is given in Table V The thorium cycle offers an advantage over the uranium cycle on the depletion costs of 1 M$ for a 600 MWe reactor or 2 m$/KWh If a fabrication penalty due to alpha activity of 20% of t the fabrication costs or 30$/kg for the thorium fuel is included the cost advantage is reduced to about 5 M$/a or 1 m$/KWh

5 – SAFETY COEFFICIENTS

One of the concerns in the Th-cycle is the fact that U 233 like Pu possesses a βeff that is only 1/3 of that U 235 In Table VI an estimation is made of βeff The Th reactor has a βeff that is 10% lower than a Pu recycle reactor and 40% lower βeff than a standard PWR

We made some cell calculations to obtain the reactivity effect between the cold reactor and hot full power which are given in Table VII They indicate that at least 20 control rod drives are necessary to hold down the reactivity in the cold state Assuming that a control rod may only have a worth less than 1 The temperature coefficients will be negative

6 – OPTIMIZATION

We tried to find the optimum fuel to moderator ratio using two group theory The optimum with respect to conversion ratio is very broad for U 233 ThO_2 fuel Figure 7

To thus augment the conversion ratio we have to decrease the burnup there by increasing the fabrication and reprocessing costs Zorzoli(7) demonstrated that with Th metal fuel using a coextrusion process low fabrication costs are possible A reprocessing costs should also decrease due to a significant scale effect(8) We increased the fuel volume by about 100% by increasing the diameter of the fuel pins from 9 to 12 mm A cell calculation was made In Table VII the neutron balance is compared with a 9 mm fuel pin case It can be observed that the absorptions in H_2O and slowly saturating fission products are greatly reduced The resulting conversion ratio is than about 98

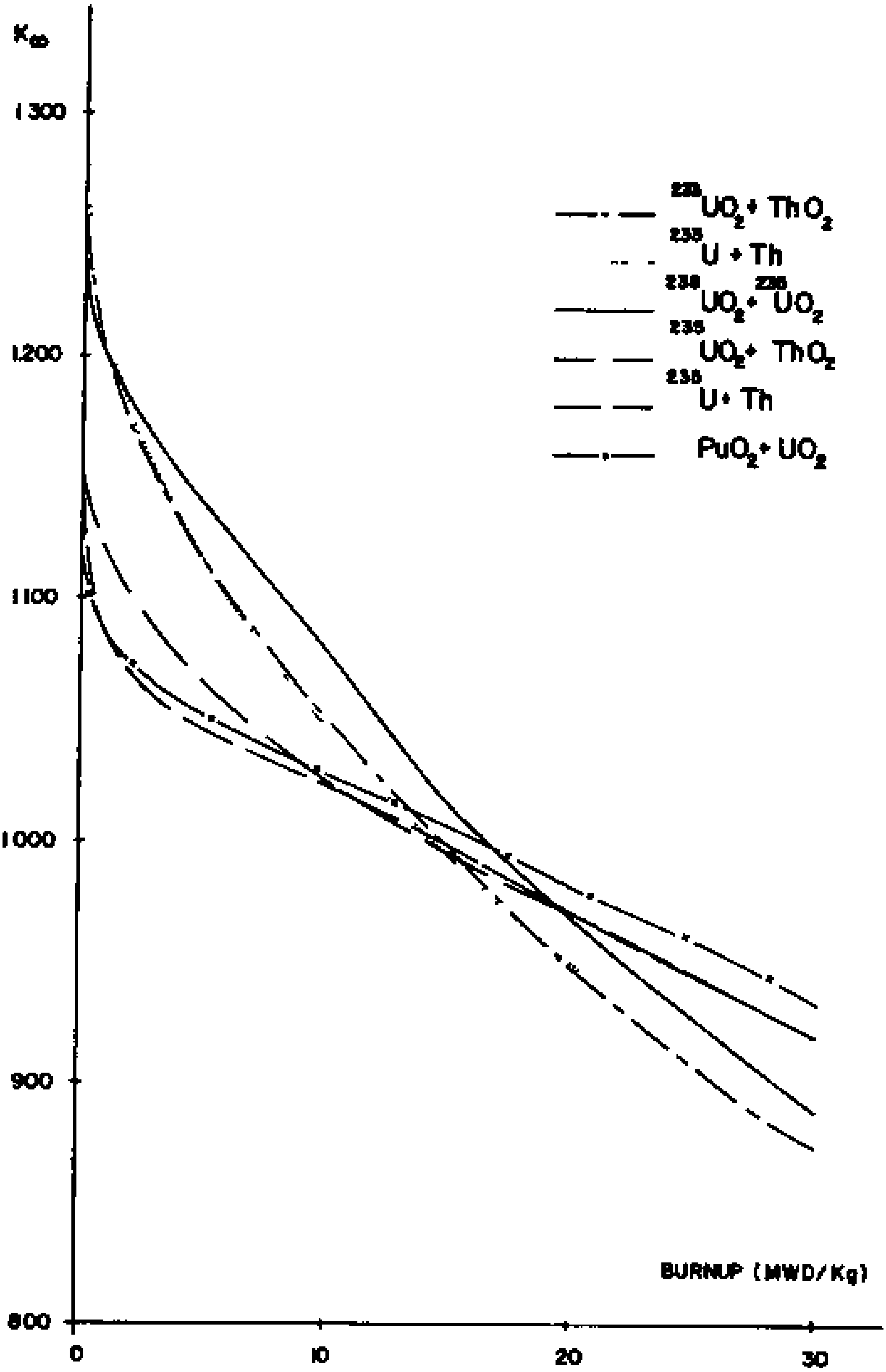

Figure 2 — K_∞ as a function of the Burnup

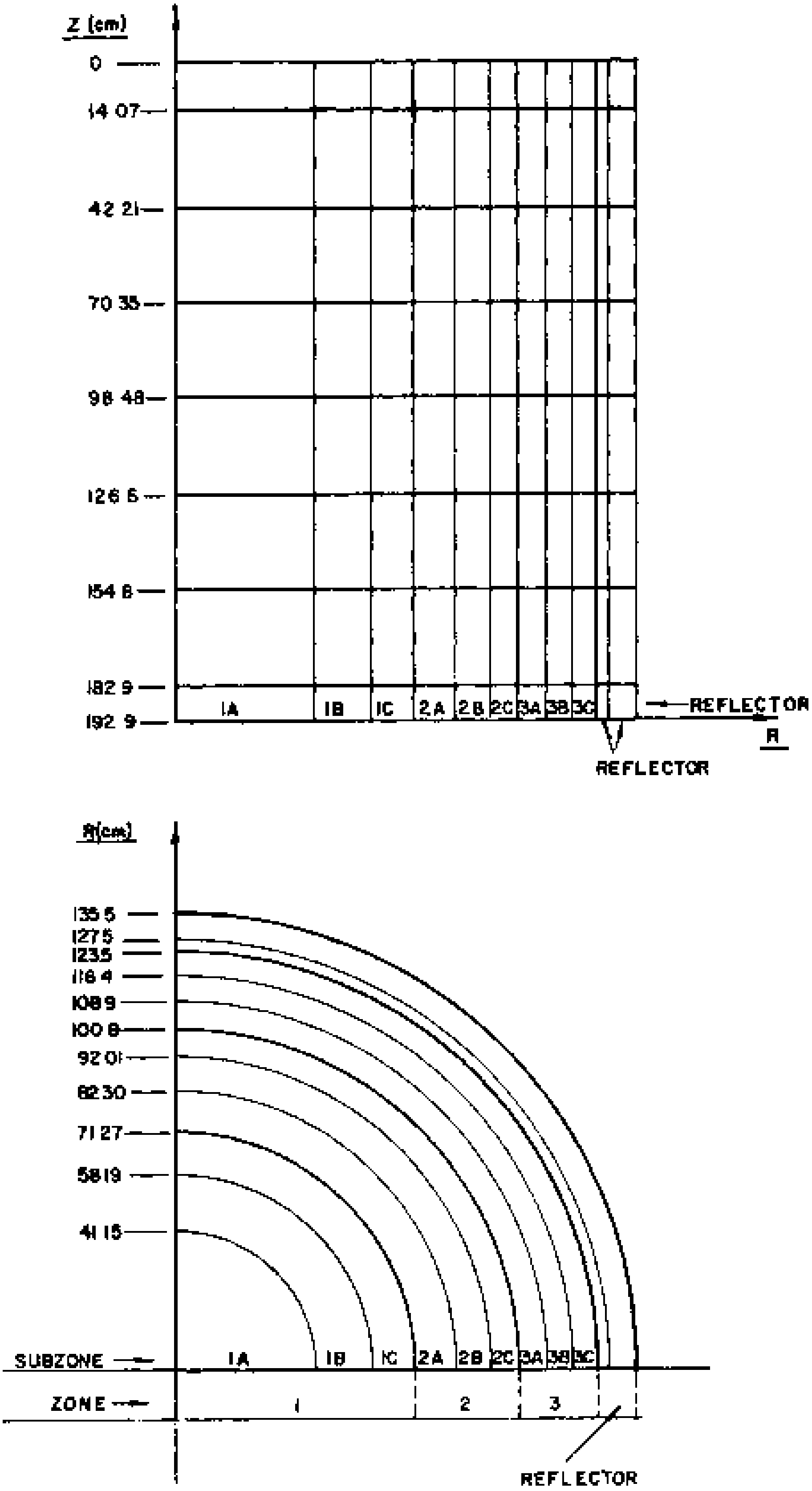

Figure 3 — R–Z model of angra core

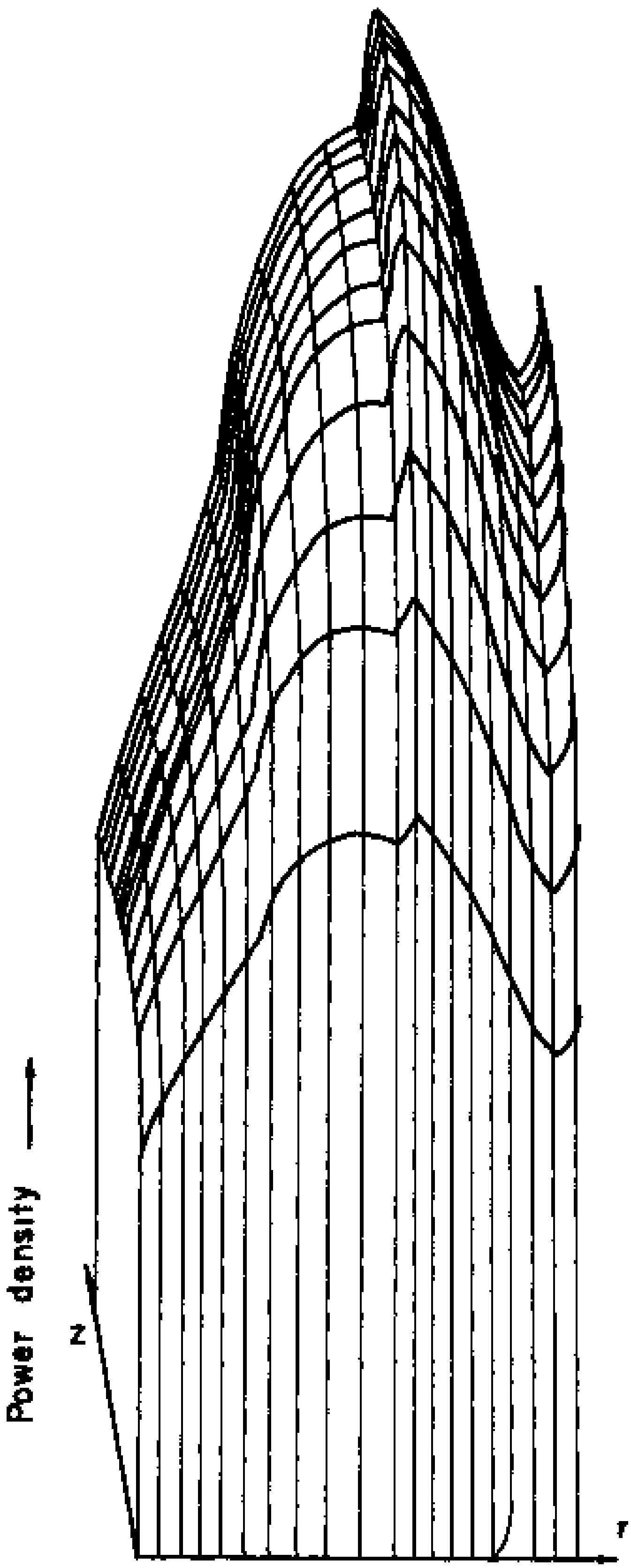

Figure 4 — Power distribution

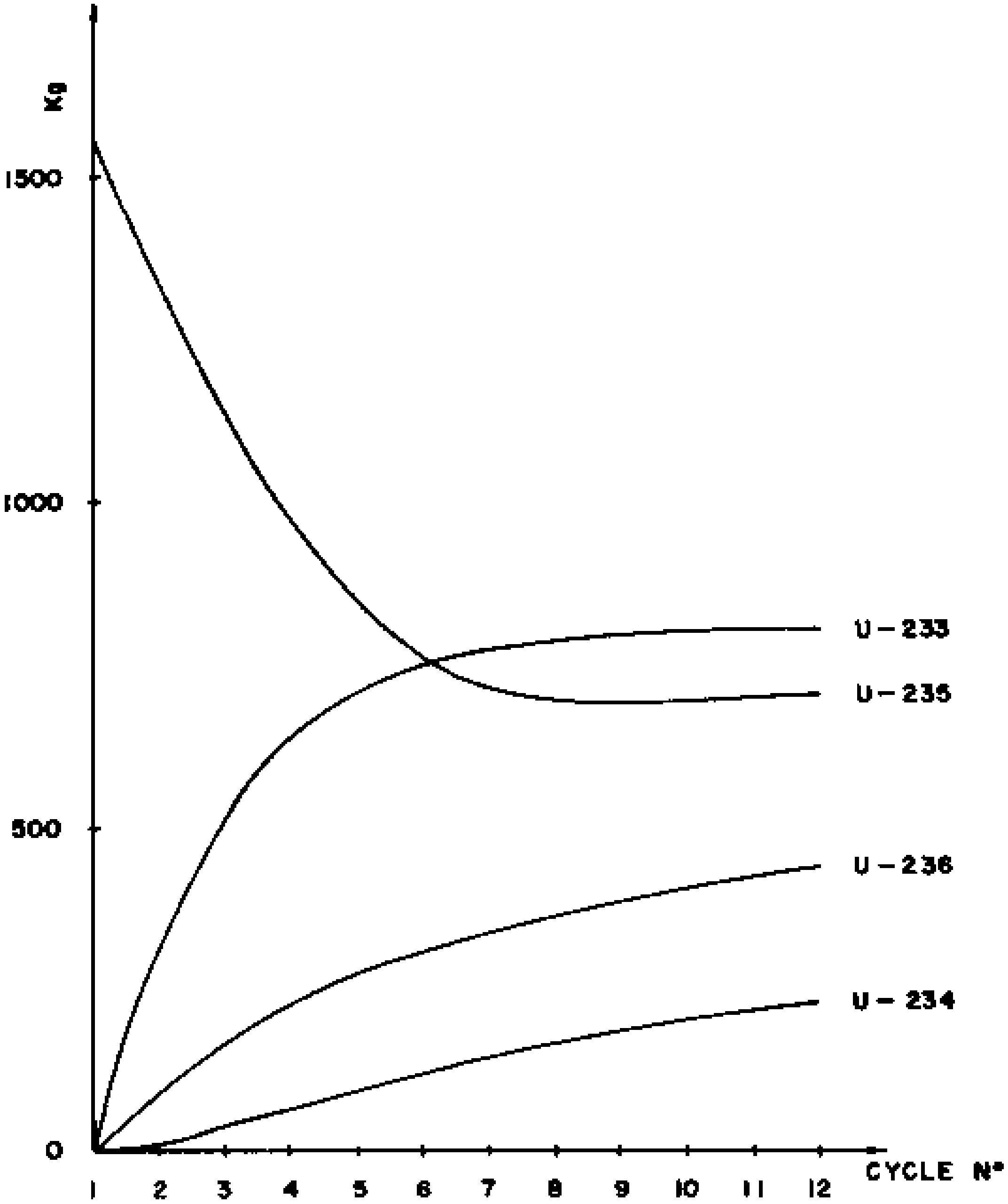

Figure 5 — Th–Cycle BOC inventories

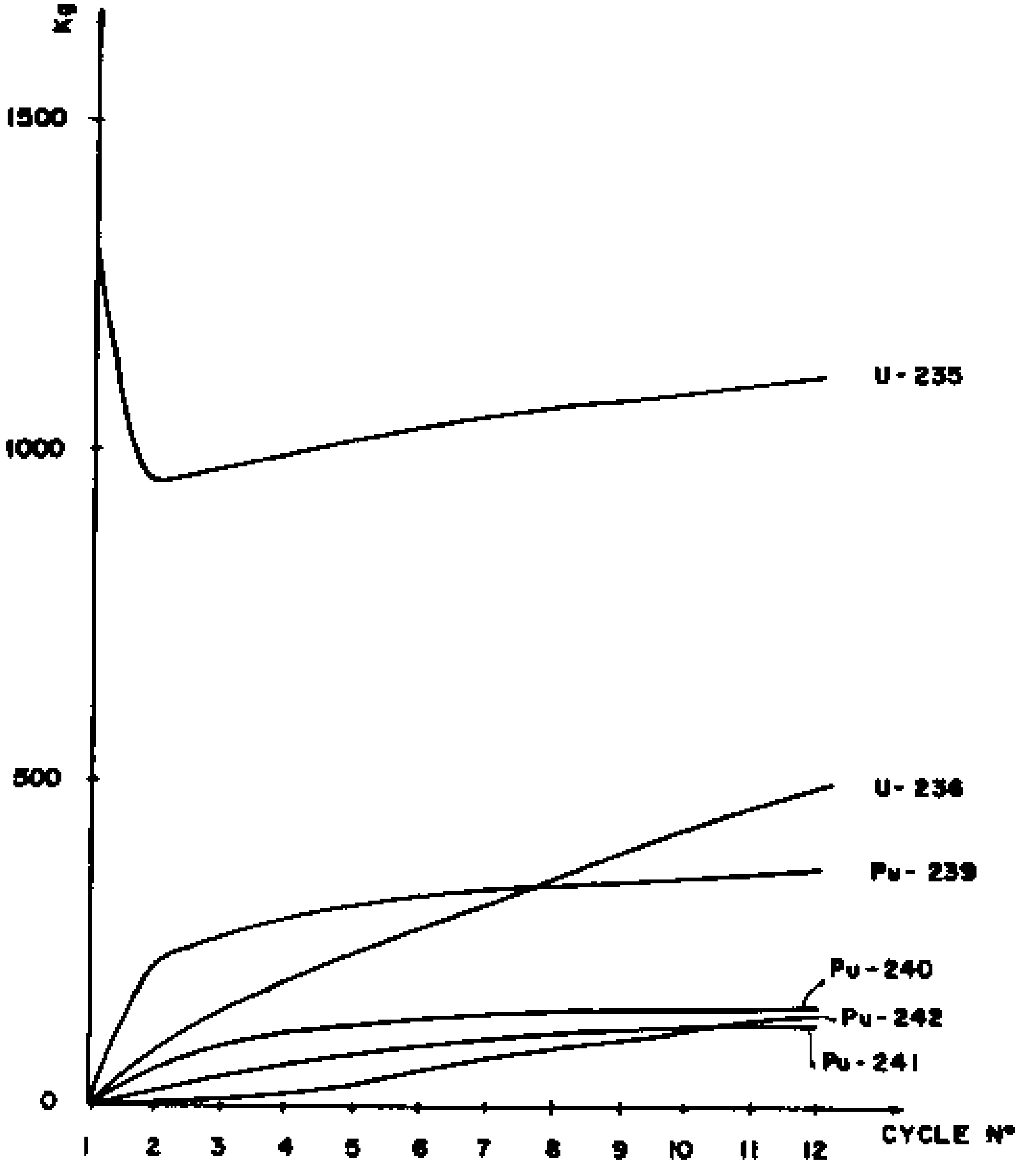

Figure 6 — U—Cycle BOC inventories

Table IV

Mid cycle Neutron Balances

	Th cycle			U cycle	
	Abs	Prod		Abs	Prod
Th 232	296	020	U 235	198	387
Pa 233	000		U 236	016	
U 233	287	634	Np 237	003	
U 234	024				
U 235	169	333	U 238	233	069
U 236	017		Pu 239	205	378
U 238	003		Pu 240	074	
O 16	003		Pu 241	072	152
Xe 135	023		Pu 242	015	
Sm 149	007		Am 243	004	
SS FP	041		Xe 135	018	
Zirc-4	009		Sm 149	011	
H	048		SS FP	034	
Fe	009		Zirc-4	009	
			H	039	
B 10	045		Fe	007	
Leack	002		B 10	039	
			Laack	020	
CR	690		CR	590	

Table V

Costs

	Enrichment		Feed		Total
	SWU*1000	Costs M$/a	Kg U nat *1000	Costs M$/a	M$/a
U cycle Redif+	54	2 5	52	1 8	4 3
U cycle MIx	67	3 2	52	1 8	5 0
Th-cycle	46	2 2	35	1 2	3 4

Table VI

βeff

	fractions of fissions	β	βeff
Th 232 U 233 U 235	02 634 333	0220 0027 0065	00044 00171 00216
Tot Th-cycle			00431
U cycle U 235 U 238 Pu 239 Pu 241	 387 069 378 152	 0065 0157 0021 0030	 0025 0011 0008 0004
Tot U-cycle			0048
U 235 U 238 Pu 239	6 1 3	0065 0157 0021	0040 0016 0007
Tot U-Standard			0063

Table VII

Reactivity Effects

	BOC	EOC
k∞ hot k∞ cold	1 043 1 082*	1 048 1 121*
Δ K	– 039	– 073

* Includes 023 as a result of the absence of Xe absorptions

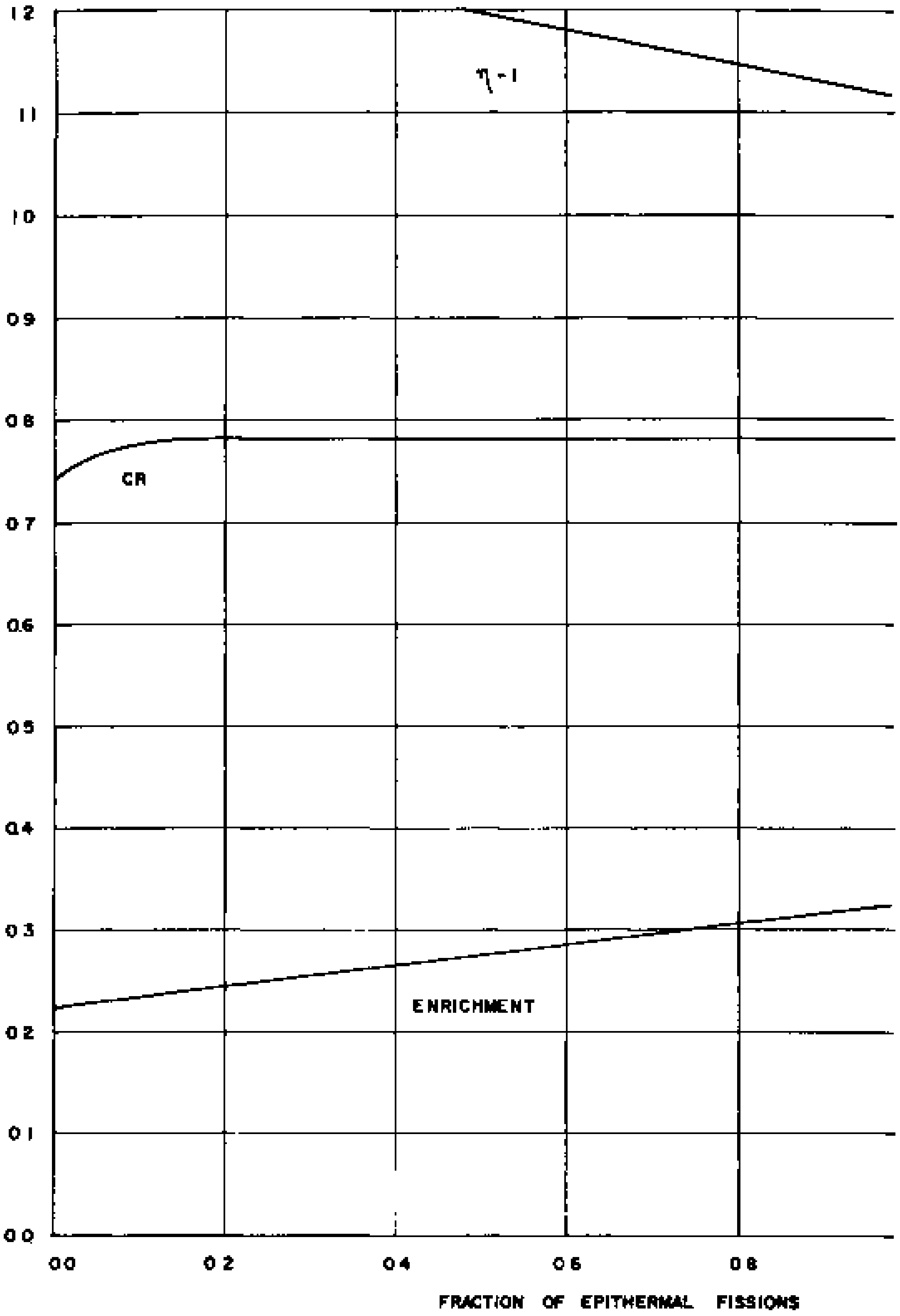

Figure 7 — Conversion rate optimization

Table VIII

Neutron Balance for Large Diameter

	9 mm		12 mm	
	Abs	Prod	Abs	Prod
Th 232	380	25	450	44
Pa 233	11		12	
U 233	435	965	439	951
U 234	12		9	
U 235	4	7	2	3
Xe-135	26		25	
Sm 149	4		4	
SS FP	56		28	
H_2O	44		9	
Fe	14		3	
Zirc 4	11		6	
CR	86		98	

7 – CONCLUSIONS

The use of thorium in light water reactors gives a reduction of 30% in uranium ore consumption and a saving of the order of 1 m$/KWh The shut down reactivity might pose some problems with respect to the number of control rod drives Large metallic fuel pins might lead to a low cost near breeder concept for the existing light water reactors

RESUMO

Estuda-se a utilização de tório no PWR de Angra dos Reis I Cálculos celulares e do reator demonstram que uma redução de até 30% no consumo de urânio é possível

RÉSUMÉ

On a étudié l utilisation du thorium dans le PWR d Angra dos Reis I Des calculs cellulaires ainsi que des calculs du réacteur ont montré qu une réduction de 30% de la consommation d uranium est possible

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