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PLUTONIUM AS A MAKE-UP IN THE THORIUM INTEGRAL BLOCK HTR FUEL ELEMENT

by

G. GRAZIANI, C. RINALDINI (Euratom)
H. BAIRIOT and E. TRAUWAERT (BelgoNucléaire, Bruxelles)

1973

Joint Nuclear Research Centre
Ispra Establishment - Italy

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The following economical hypotheses were also parametrically varied : the U-233 credit, the Pu price and the fabrication cost.

The calculations showed that it is possible to design integral block fuel cycles in which plutonium is the feed fuel. If not exceeding the reference age-factor of the uranium-thorium cycle is assumed as feasibility criterion, only once-through cycles will economically be acceptable (with a U^{233} credit of 14 \$/gr). By parametrically changing the value of the fissile plutonium and imposing the fuel cycle costs to be equal to the cost of the reference uranium-thorium cycle, an equivalent plutonium value was deduced. The fissile value was found to be in the range between 8.4 and 9.5 \$/gr, depending on the values adopted for the fabrication cost corresponding to the different degrees of plutonium dilution in the kernels. These values are almost independent of the burn-up and of the U^{233} credit value.

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ABSTRACT

An analysis was performed in order to investigate the perspectives of using Plutonium as a make-up instead of U-235 for a Thorium cycle in a High Temperature Gas Cooled Reactor. A number of physical and economical parameters were varied. In particular : — type of fuel particles (three degree of dilution of Pu into the graphite within the fuel kernels); — heavy metal density in the fuel pin; — Pu enrichment of the fresh fuel or, alternatively, the fuel discharge burn-up (between 40 and 100 GWD/t). Two types of fuel-cycle scheme, namely once-through and recycle of the bred fuel were considered.

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KEYWORDS

HTGR
FUEL ELEMENTS
PLUTONIUM
FUEL CYCLE
ECONOMICS

INTRODUCTION

A considerable irradiation and operation experience in power reactors is going to be built up in the next future for the integral block HTGR fuel element of GGA. This block has been optimised for a reference U235 - Th cycle.

However, as highly enriched uranium is an expensive material, an alternative feed material might be provided by the plutonium that will become available from the light water reactors and which is not yet used in fast reactors.

To investigate the performance of a fuel cycle with plutonium feed, a physics and an economical analysis is needed that would allow the reoptimisation of the fuel element, taking into account the characteristics of the four isotopes contained in the plutonium.

However, as the experience gained with the integral block design is limited to one fixed geometry, it was felt that changing some dimensions of the block could jeopardize the confidence in this design. Hence it was decided to freeze it to the geometry of Fort St Vrain. The only possible variations left are thus at the fuel pin level.

But even these variations could bring some changes in the temperature behaviour of the fuel element. It was therefore thought that for a constant power density (8 MW/m^3) the age factor should be restrained beneath a maximum value. This value was determined by a reference U235 - Thorium physics calculation for a cycle that was known to be feasible and which was more or less optimum. These calculations were completed by economics calculation in comparison of which it was then possible to determine the equivalence plutonium value for the optimum plutonium thorium cycle.

2. CALCULATION METHOD

The physics calculations for the survey were performed with a 20 group, zero dimension scheme, taking the leakage into account with a group independent buckling. One dimensional details of power and burn-up distribution should not change the conclusions of the comparison of different types of cycle. The same can be said for the loading scheme : a continuous charge-discharge equilibrium cycle was considered, taking into account-by poison (Boron) absorption - the loss of neutrons due to control rods inserted into the core for full Xe-override requirements. For the spectrum, the fuel evolution, the reactivity calculations and the search for the equilibrium conditions the programme MOGA was used (Ref. 1).

The calculation of the multigroup cross sections and of the resonance integral were performed employing the General Atomic Cross-section library and the codes GAM II and GATHER II (Ref. 2).

The effects of heterogeneity on the effective cross-sections are taken into account by means of self-shielding factors, which are previously fitted to the average cell macroscopic cross-section. The self-shielding factors were evaluated by DSN method, using the programme WRETCH (Ref. 3).

This method can lead to a certain error when Plutonium fuel is fed into the core, as this fuel is heavily absorbing and the macroscopic cross-sections can perceptibly change during the life. In order to assess the magnitude of this error, a typical case with high initial Pu feed has been chosen and a multi-step burn-up calculation was performed. For each step of burn-up the fuel burns with its average spectrum and the self-shielding are calculated with the average composition of the step considered. The result of this calculation has been compared with the usual one-step calculation, where the average core spectrum and average self-shielding constant during the life are employed. The difference between the two types of calculations exaggerates the error introduced, as the real situation lies somewhere in between. A fuel element, in fact, will burn with a spectrum which is intermediate between the average core spectrum and its own spectrum.

It has been found that the discrepancy in the average core reactivity due to the two types of approach is acceptable for values of burn-up up to 80 MWd/kg (fig 1).

The error introduced in our calculation tends to reduce the average core reactivity and then to enhance the fissile requirements, at least in the range of low moderation ratios, where the Plutonium feed is very high and the heterogeneity effects are more remarkable.

As for the economical assessment, the method employed was the one followed by the code COFFEE (Ref. 4).

As the approach to equilibrium period is not known, the assumption made in this code is that the capital invested in building up the equilibrium charge of the core can be assessed as a "core value", attributing to each fuel element a worth equal to the average between the fresh and the spent fuel.

MAIN REACTOR AND FUEL CHARACTERISTICS

The main reactor physics characteristics that have been kept constant in all the calculations are given in table 1. Table 2 is a compilation of the most relevant data with regard to the fuel elements for the different cycles considered. The different sets of economical data are given in table 3.

Table 1

MAIN REACTOR AND PHYSICS CHARACTERISTICS

1. Electrical power :	1000 MW
2. Thermal efficiency :	0.40
3. Power density :	8 W/cc
4. Buckling :	$5.57.10^{-5}$ cm^{-2}
5. Control rod investment :	100% Xe override requirement
6. Type of refuelling :	continuous
7. Feed plutonium composition :	Magnox or first charge LWR discharge Pu i.e. 73 % Pu 239 15 % Pu 240 12 % Pu 241

Table 2

FUEL CHARACTERISTICS

1° Kernels

a. Uranium - thorium cycles

thorium particles : diameter : 0.4 mm
carbide density : 8.55 g/cc

U235 particles : diameter : 0.1 mm
oxide density : 9.86 g/cc

b. Plutonium - thorium cycles

thorium particles : diameter : 0.8 mm
oxide density : 10 g/cc

plutonium particles : three types of particles are considered differentiated by the ratio of the number of atoms of Pu versus graphite in the kernels :

C/Pu	5	10	20
diameter [mm]	0.5	0.5	0.5
oxide density [g/cc]	4.54	2.91	1.70
graphite density [g/cc]	1.004	1.289	1.502

2° Coating

a. Uranium - thorium cycles (for all particles)

layers	thickness [10^{-3} mm]	density [g/cc]
buffer	50	1.1
PyC	20	1.84
SiC	20	3.0
PyC	50	1.84
	140	

b. Plutonium - thorium cycles (for all particles)

layers	thickness [10^{-3} mm]	density [g/cc]
buffer	35	1.0
seal	20	1.5
PyC	30	1.7
SiC	35	3.2
PyC	30	1.7
	150	

° Fuel pins

Rod diameter : 12.7 mm
Length : 36.5 cm
Number of rods per block channel : 2
Height of channel plugs : 3 cm
Heavy metal loading : variable
Graphite matrix density : 1.7 g/cc.

° Hexagonal block

Graphite density : 1.8 g/cc
Distance across flats : 360 mm
Height : 790 mm
Fuel holes : number : 210
diameter : 12.7 mm
Coolant holes : number : 108
diameter : 15.9 mm
Burnable poison holes: number : 6
diameter : 12.7 mm
Block handling hole: length : 395 mm
equivalent diameter : 50 mm

Table 3

ECONOMIC DATA

(The data in brackets are variants to the standard data)

Interest rate	: 11 %	
U233 value	: 14 $/g	(16 $/g)
Pu fiss. value	: 10 $/g	(8 $/g)
U235 (93 % enriched)	: 12 $/g	
Thorium value	: 30 $/kg	
Fabrication delay	:180 days	
Reprocessing delay	:360 days	
Load factor	:0.75	
Reprocessing cost	:	
uranium	:100 $/kg HM	
all other HM	:120 $/kg HM	

Fabrication cost

Class	"Standard"	"Low"	"High"
thorium or uranium [$/kg HM]	150	125	150
plutonium C/Pu = 5	160	133.33	400
[$/kg Pu fiss.] 10	180	150	750
20	200	166.67	1200
interest on fissile hold up during fabrication [%]	7	5.83	7
graphite cost [$/kg gr.]	9	7.5	9

4. URANIUM - THORIUM REFERENCE CYCLES

4.1. Specific fuel cycle characteristics

The geometry of the fuel element was in all points similar to the current GGA design (see table 2 and ref 5). The thorium loading was chosen to be 0.48 gr/cc. This leads to a moderation ratio of 226 (NC/Nth).

Considering the questionableness of an early reprocessing of U233, three different cycles have been calculated, all of the segregated type :

1° once through cycles,

2° cycles with recycling of the bred fuel in the breed particles,

3° cycles with recycling of the bred fuel in the feed particles.

The irradiation time for all these cycles was identical and fixed at 1050 full power days.

4.2. Physics results

The resonance integral was calculated to be 48 barns. Considering the different cycles and particles the following enrichments *, burn-ups, conversion ratios and age factors have been calculated (Table 4).

Table 4

Type of cycle	BU [GWD/t]	Enrichment * [%]				Conversion ratio	Age factor
		initial		final			
		Feed	Breed	Feed	Breed		
Once through	67.8	5.65	-	0.65	2.31	0.685	1.372
Recycling into breed part.	68.2	2.29	2.85	0.30	2.90	0.766	1.336
Recycling into feed part.	68.4	4.86	-	0.55	2.32	0.760	1.387

* The enrichment is defined as the percent ratio of the weight of the fissile content to the total weight of the initial heavy metal.

4.3. Cost calculation results

With the standard cost assumptions of table 3 the fuel cycle costs have been calculated as follows for two values of U233 and of the fabrication cost (Table 5).

Table 5

URANIUM THORIUM FUEL CYCLE COST [MILLS/kWh]

Fabrication cost (see table 3)	U_{233} value [$/g]	Type of cycle		
		Once through	Recycling into the breed fuel	Recycling into the feed fuel
"Standard"	14	1.648	1.575	1.546
"	16	1.589	1.616	1.575
"Low"	14	1.553	1.481	1.453
"	16	1.494	1.523	1.482

As a general result we see that it is more economic to recycle the bred fuel in the feed particles than in the breed particles. This is mainly due to a slightly worse neutronic performance of the latter cycle resulting from the build up of U_{236} in the continuously recycled bred uranium. This economic advantage is however obtained at the cost of a somewhat higher age factor (Table 4).

Considering the influence of the cost of U_{233} we see that an increase in this cost influences differently the once through cycles and the recycle cycles. The equivalence value of U_{233} for both types of recycling are given in the table below (Table 6) :

Table 6

U_{233} EQUIVALENCE VALUE [$/gr]

Type of cycle \ Fabrication cost	"High"	"Low"
Once through versus recycling in breed part	15.46	15.43
Once through versus recycling in feed part	16.31	16.26

As the fuel cycle cost for the case with recycling in the feed particle is lower than for the case with recycling in the breed particle, it is obvious that the equivalence U_{233} value must be lower for the latter than for the former. No wonder either that the equivalence value is only slightly influenced by the variation in fabrication cost : it results from the very small part taken by the fabrication cost in the difference between the once through and the recycle fuel cycle cost.

PLUTONIUM - THORIUM CYCLES

5.1. Degrees of freedom for the survey

With a given reactor and fuel element geometry and with a fixed power, the freedom for optimisation of the fuel cycle is reduced to the following parameters :

1° the type of fuel particles

2° the amount of heavy metal in a fuel pin

3° the relative amount of plutonium in a fresh fuel element.

These elements are shortly described below.

5.1.1. Type of fuel particles

As can be seen from the data in table 2, three different plutonium particles have been considered according to the degree of dilution of the plutonium into the graphite within the fuel kernels. A high degree of dilution may be desirable to withstand high internal stresses due to solid swelling and fission gas pressure after irradiation. On the other hand it is clear that at constant kernel diameter the fabrication cost per unit amount of plutonium will be higher for the more diluted particles, due to the higher number of particles needed to contain the same amount of plutonium.

From neutronics point of view one will also note a difference in behaviour with the degree of dilution as the self shielding of the plutonium increases when the dilution decreases. This effect was taken into account by the use of different self shielding factors for the three types of particles as illustrated by Table 7 and fig 2.

Table 7

Pu_{240} SELF SHIELDING FACTOR IN ENERGY GROUP 10 (1.09 TO 1.025 eV) AS A FUNCTION OF THE MACROSCOPIC ABSORPTION CROSS SECTION

C/Pu \ $\Sigma_{ab.}$ [cm^{-1}]	0	0.2	0.4	0.6	0.8	1.0
5	0.358	0.343	0.330	0.318	0.308	0.298
10	0.965	0.597	0.469	0.399	0.353	0.320
20	1.031	0.602	0.467	0.395	0.348	0.316

These self shielding factors have been calculated in the thermal energy groups. They are the smallest (highest self shielding effect) in the energy group around 1.06 eV i.e. around the resonance absorption peak of Pu_{240}. There is a marked difference between the self shielding factors of the more diluted (C/Pu = 20,10) and of the less diluted kernels (C/Pu = 5). In the first case the self shielding varies considerably with the macroscopic absorption cross section whereas in the second case the self shielding factor is about constant, but lower.

5.1.2. Thorium loading

In a fuel pin the heavy metal particles are dispersed in a matrix of graphite. For a block of fixed geometry and graphite density a higher heavy metal loading in the fuel pins corresponds to a lower moderation ratio of the core and vice-versa. The heavy metal loading is also related to the packing fraction, i.e. the relative volume occupied by the fuel particles compared with the total volume of a pin. Table 8 gives the relations between the thorium loadings (ThL), the packing fractions (Pf) and the moderation ratios (NC/Nth).

Table 8

ThL [gr/cc]	0.486	0.539	0.569	0.604	0.688	0.799
Pf	0.1328	0.1473	0.1557	0.1652	0.1882	0.2185
NC/Nth	250	225	212.5	200	175	150

5.1.3. Plutonium enrichment* and burn-up

A certain amount of fissile isotopes is needed to maintain the reactor critical up to a given burn-up or during a given time. The determination of the actual values of the Pu enrichment as a function of the burn-up is the object of the physics calculations and will be reported below.

*Let the enrichment here be defined as the weight proportion of fissile plutonium (Pu 239 and Pu 241) to the total amount of heavy metal.

The burn-ups considered in these calculations range between 40 and 100 GWD/tHM. No higher values have been adopted as it is felt that, with the present fuel characteristics, 100 GWD/tHM is approximatively an upper confidence limit. However no attempt has been made so far to relate this limit to the type of fuel nor to the moderation ratio, although one knows that these parameters are linked.

5.2. Further fuel cycle characteristics

As in the uranium - thorium case different types of cycles have been considered according to the use of the irradiated fuel. However in order to reduce the amount of calculations, only two types of cycles were initially considered for the whole survey :

1° the once through cycle ;

2° the cycle with recycling of the bred fuel in the breed particles.

As all the cycles of this second type appeared to have a very high age factor one physical calculation has also been performed for a cycle with recycling of the bred fuel in the feed particles, but the results have not been much more encouraging and this calculation was not extended to the rest of the survey.

5.3. Physics results

The resonance integral of the thorium has been calculated for the different moderation ratio and are reported in Table 9.

Table 9

RESONANCE INTEGRAL

NC /Nth	150	200	250
Ri [barns]	39.8	42.7	44.7

Taking account of these values the enrichments and age factors have been calculated for all combinations of the above discussed parameters. Their values are given in Tables 10, 11, 12, 15 and 16 and plotted in fig 3 and 4.

5.3.1. Once through cycles (Tables 10, 11 and 12)

Considering the initial enrichments there is a marked difference between the lower and higher moderation ratio. At high moderation ratio (NC/Nth = 250) the enrichment is in the order of 6 to 8 percent and is increasing with increasing burn-up as in the uranium cycle.

For low moderation ratio (less than 200) the enrichments are markedly higher and they decrease with increasing burn-up. The higher enrichment level is due to the shift in spectrum towards the epithermal energies. This shift increases the resonance absorption in Pu_{240}. This resonance absorption decreases the efficiency of the Pu as a fissile make-up, therefore calling for higher feed enrichments. This trend towards higher feed enrichments is somewhat moderated by an increasing self shielding of the fuel and by a higher Pu_{241} production.

The self shielding mainly reduces the influence of Pu_{240} as it is in its 1.06 eV resonance energy group that the self shielding coefficients are the smallest. Moreover the self shielding is different for the different Pu particles. With the lowest C/Pu in the kernel (C/Pu = 5) the self shielding coefficient in the 1.06 eV group is very low (0.35) and only slightly influenced by the macroscopic absorption cross section (fig 2). For the higher C/Pu (10 to 20) the self shielding coefficients of the same energy group are higher and very sensitive to the macroscopic cross section. This explains the trend towards higher enrichments-and thus higher macroscopic absorption cross sections - for the Pu particles with C/Pu = 10.20 than for C/Pu = 5.

The higher Pu 241 production of the less moderated fuel cycle increases the reactivity of the averaged burnt Pu. As this Pu 241 production reaches its full importance only after some burn-up of the fuel, it will influence slightly more the cycles with higher burn-up (Table 13). However the variation of feed enrichment with increasing burn-up results even more from the shift of the average flux towards the softer spectra. This trend is indicated by the decrease in average Pu 240 density which is one of the factors determining the thermal spectrum. As can be seen from Table 14, this density variation is characteristic of the less moderated cycle and explains the decrease in feed enrichment with increasing burn-up (fig 3, 4).

Table 10

Pu/Thorium cycles

1° C/Pu internal = 5

Once through cycles

NC/NTh	BU GWd/tHM	Initial enr. Pu fiss.	Final enr. Pu fiss.	Final enr. U_{233}	Convers. ratio	Age factor
150	49.48	14.87	10.30	2.51	0.809	
	66.50	14.32	8.37	3.08	0.800	
	83.45	14.07	6.88	3.53	0.790	
175	41.60	14.28	10.43	2.11	0.802	1.041
	50.47	13.49	8.92	2.45	0.797	1.046
	59.51	12.74	7.45	2.75	0.791	1.055
	68.56	12.15	6.18	3.02	0.784	1.070
	86.13	11.78	4.51	3.44	0.770	1.125
200	53.04	9.87	5.11	2.50	0.773	1.119
	71.26	9.33	3.15	2.99	0.757	1.252
	88.36	9.94	2.50	3.33	0.744	1.335
212.5	45.16	8.22	4.06	2.20	0.763	1.178
	54.36	7.98	3.10	2.48	0.756	1.262
	63.30	8.13	2.58	2.72	0.750	1.330
	72.07	8.42	2.22	2.92	0.744	1.389
	89.09	9.27	1.83	3.24	0.731	1.473
225	54.98	7.12	2.19	2.44	0.744	1.396
	72.58	7.89	1.66	2.85	0.732	1.524
	89.55	8.89	1.42	3.16	0.720	1.606
250	55.50	6.36	1.38	2.36	0.725	1.622
	73.05	7.36	1.10	2.73	0.714	1.759
	90.01	8.47	0.95	3.01	0.701	1.850

Table 11

2° C/Pu internal = 10
Once through cycles

MC/MTh	BU GWd/tHM	Initial enr. Pu fiss.	Final enr. Pu fiss.	Final enr. U_{33}	Convers. ratio	Age factor
150	49.01	15.51	10.98	2.48	0.813	
	65.85	15.02	9.13	3.05	0.806	
	82.73	14.67	7.55	3.50	0.796	
175	40.77	15.68	11.94	2.04	0.810	1.025
	49.35	15.09	10.65	2.37	0.806	1.028
	67.07	13.73	7.92	2.96	0.795	1.040
	85.15	12.62	5.47	3.42	0.784	1.075
200	50.16	13.96	9.57	2.33	0.797	1.039
	70.11	10.54	4.53	2.97	0.773	1.139
	88.10	10.17	2.79	3.35	0.752	1.278
212.5	41.49	14.46	10.78	1.95	0.798	1.032
	51.40	12.17	7.67	2.34	0.787	1.051
	62.33	9.31	3.91	2.70	0.767	1.187
	71.67	8.85	2.74	2.93	0.754	1.295
	89.06	9.29	1.90	3.26	0.737	1.430
225	54.17	8.26	3.49	2.43	0.762	1.226
	72.45	8.02	1.86	2.87	0.740	1.452
	89.55	8.89	1.46	3.18	0.725	1.564
250	55.38	6.53	1.63	2.37	0.736	1.519
	73.09	7.33	1.11	2.74	0.720	1.711
	90.10	8.40	0.89	3.03	0.705	1.826

Table 12

3° C/Pu internal = 20
Once through cycles

MC/MTh	BU GWd/tHM	Initial enr. Pu fiss.	Final enr. Pu fiss.	U_{33}	Convers. ratio	Age factor
150	49.03	15.51	10.98	2.48	0.813	1.024
	65.87	14.97	9.14	3.05	0.805	1.029
	82.74	14.67	7.55	3.50	0.796	1.039
200	50.14	14.02	9.57	2.33	0.797	1.034
	70.06	10.62	4.60	2.96	0.773	1.134
	88.10	10.17	2.79	3.35	0.752	1.275
225	54.05	8.42	3.66	2.42	0.763	1.210
	72.45	8.02	1.87	2.87	0.741	1.447
	89.55	8.88	1.44	3.18	0.725	1.560
250	55.37	6.54	1.64	2.37	0.737	1.513
	73.09	7.32	1.11	2.74	0.720	1.707
	90.10	8.39	0.89	3.03	0.705	1.822

Other important results of the physics calculation are the age factors (tables 10, 11 and 12). They are always increasing with increasing burn-ups, either because the initial fissile content is increasing (for higher moderation ratios) or because the average fissile content is decreasing (for the lower moderation ratios) (Table 14). The age factors are also increasing with increasing moderation ratio : this is due to the reduction in average fissile content for the softer spectra. Comparing the age factors for the different plutonium dilution degrees, the cycle most submitted to self shielding (C/Pu = 5) has the highest relative power variation. This also results from the lower average fissile content as a consequence of the lower resonance absorption in the better shielded Pu 240 (Table 14).

If we consider the age factor of the reference uranium - thorium cycle (1.372) as an upper limit, we see that only the cycles with a low moderation ratio are acceptable, the limit being between the values 200 and 225 depending on the burn-up and the type of fuel particles (fig 3, 4).

Table 13. FRACTIONAL ABSORPTIONS IN SOME HEAVY ISOTOPES

Once through plutonium - thorium cycles

	BU [GWd/tHM]	PU239 [%]	Pu240 [%]	Pu241 [%]	Pu242 [%]	U233 [%]
1° NC/Nth = 175	41.60	37.4	21.0	11.3	0.5	4.3
C/Pu = 5	50.47	35.8	20.2	11.7	0.6	5.3
	59.51	34.1	19.3	12.1	0.8	6.3
	68.56	32.5	18.5	12.4	0.9	7.3
	86.13	29.9	17.1	13.0	1.2	8.9
2° NC/Nth = 175	40.77	37.6	21.9	11.4	0.5	4.0
C/Pu = 10	49.35	36.1	21.3	11.8	0.6	4.8
	67.07	33.1	19.8	12.4	0.8	6.6
	85.15	30.3	18.1	13.0	1.1	8.4
3° NC/Nth = 250	55.38	30.4	17.0	15.1	1.1	6.9
C/Pu = 10	73.09	27.5	15.8	15.8	1.6	8.6
	90.10	26.1	15.2	16.0	1.9	9.5

Table 14

Once through plutonium thorium cycle

Average atomic densities

NC/NTh	C/Pu/k	BU [GWd/tU]	Pu239 [10^{-8}at/cc]	Pu240 [10^{18}at/cc]	Pu241 [10^{18}at/cc]	Pu242 [10^{18}at/cc]	U233 [10^{18}at/cc]
175	5	41.60	44.3	9.68	11.8	0.68	4.9
		50.47	38.7	8.60	11.4	0.7	5.8
		59.51	33.3	7.61	11.0	0.8	6.6
		68.56	28.8	6.80	10.6	1.0	7.4
		86.13	23.6	5.92	10.2	1.3	8.7
175	10	40.77	51.1	10.77	13.04	0.6	4.8
		49.35	46.2	9.72	12.92	0.7	5.7
		67.07	36.1	7.53	12.32	1.0	7.3
		85.15	27.5	5.78	11.46	1.2	8.7
250	10	55.38	6.33	2.15	3.86	0.8	3.6
		73.09	5.65	2.01	4.01	1.2	4.4
		90.10	5.77	2.02	4.34	1.5	5.7

5.3.2. Cycles with recycling of the bred fuel

When the bred fuel (mainly U233) is recycled in breed particles, the plutonium make-up is very much reduced (1.5 to 4 % enrichment) (Table 15). We see that the plutonium enrichment increases with increasing moderation ratio as there is less neutron absorption by the thorium in a softer spectrum and hence less U233 production. The enrichment is also increasing with increasing burn-up but this is coherent with the low enrichment cycles and with the once through plutonium cycles with high moderation ratios.

The reason why the enrichment was never decreasing with increasing burn-up, as for the low moderation ratios of the once through plutonium cycles is to be found in the small amount of Pu involved in these cycles, thus leaving the flux spectrum almost unaffected. Similarly there was practically no influence of the type of Pu-particle on the physics results.

The major drawback for this type of cycle are the high age factors. In fact when comparing with the corresponding reference uranium - thorium cycle, all the considered cycles have a higher age factor and should therefore be discarded according to the above used criterion.

An attempt to reduce the age factor by recycling the bred fuel in the feed particles was not more successful as can be seen from Table 16.

The only way to reduce the age factor in these types of fuel cycles with recycling of the bred fuel is to go to even lower moderation ratios. However with a fixed geometry this means going to a very high heavy metal investment. This is the reason why it was not considered.

Table 15

Main physics results of Pu - thorium cycles
with recycling of bred fuel in breed particles
(for all Pu dilution degrees)

C/Th	BU [GWd/tHM]	Init. enr. [Pu fiss]	Final enr. [Pu fiss]	Final enr. [U33]	Convers. ratio	Age factor
150	56.74	1.46	0.08	3.76	0.835	1.476
	76.66	2.26	0.10	4.10	0.804	1.580
	91.88	3.19	0.13	4.47	0.779	1.625
200	56.86	1.74	0.06	3.28	0.795	1.736
	74.85	2.59	0.05	3.50	0.766	1.922
	92.21	3.54	0.06	3.75	0.742	2.041
225	56.84	1.88	0.06	3.12	0.775	1.853
	74.82	2.76	0.05	3.31	0.747	2.071
	92.19	3.73	0.04	3.51	0.725	2.222
250	56.79	2.02	0.06	3.02	0.757	1.953
	74.75	2.92	0.05	3.17	0.731	2.199
	92.11	3.91	0.04	3.35	0.710	2.378

Table 16

Main physics results of plutonium - thorium cycles
with recycling of bred fuel in feed particles
(for all Pu dilution degrees)

C/Th	BU [GWd/tHM]	Init. enr. [Pu fiss]	Final enrichment [U233]	Age factor
200	57.0	2.88	2.59	1.85
	75.0	3.74	2.94	2.17
	92.5	4.80	3.22	2.38

5.4. Fuel cycle cost

The above physics results have been used as a basis for a broad parametric survey of the economics of the different fuel cycles.

A reference fuel cycle cost with standard cost data (cfr. Table 3) has been calculated for all cross variations of :

4 moderation ratios
3 burn-ups
3 plutonium dilution factors
2 types of cycle.

All these calculations have been repeated with slightly different cost data so as to measure the sensitivity of the fuel cycle cost to these cost data : a higher U233 credit, lower Pu price and global fabrication cost have been used.

A last serie of calculations have been performed for a set of new fabrication costs whereby a much higher weight has been given to the plutonium fabrication penalty and to its variation with the plutonium dilution in the kernels. The main results of all these calculations are given in Tables 17 and 18 and in figs 5 to 10.

These results show a wide variation in fuel cycle cost for different moderation ratios, burn-ups and plutonium dilutions in the kernels. However if we consider the age factor of the reference uranium - thorium cycle as an upper limit, we see for the once through cycle that this limit defines a fairly invariable fuel cycle cost. With the standard cost data (Table 3) this cost is approximatively 1.8 mills/kWh (fig 5). It is slightly lower for the higher dilution degrees (C/Pu = 10,20) than for the lower (C/Pu = 5). It also decreases slightly with increasing burn-up. The limit moderation ratio is a function of the burn-up and the dilution degree.

Changing the U233 or the plutonium value does not change fundamentally these results. It is mainly the level of fuel cycle cost that is influenced (fig 6, 7).

Adopting a much higher fabrication cost for the higher plutonium dilution kernels than for the lower, will change the relative cost between these types of fabrication, making the cycles corresponding to C/Pu = 20 more expensive than those with C/Pu = 5 (fig 8). But for a same type of particles, the fuel cycle cost is again rather stable, decreasing only slightly with increasing burn-up.

Table 17

PLUTONIUM THORIUM CYCLE : FUEL CYCLE COST

Once through cycles [mills/kWh]

U_{233} value [$/gr]			14	14	14	14	16	14
Pu fiss. value [$/gr]			10	10	8	8	10	10
Fabrication cost			"Standard"	"Low"	"Standard"	"Low"	"Standard"	"High"
C/Pu	MC/Mth	BU						
20	150	49.03	3.540	3.390	2.902	2.763	3.474	3.974
		65.87	3.048	2.930	2.490	2.381	2.996	3.381
		82.74	2.750	2.652	2.246	2.154	2.710	3.026
	200	50.14	2.891	2.748	2.387	2.253	2.825	3.254
		70.06	2.027	1.926	1.669	1.573	1.972	2.234
		88.10	1.785	1.702	1.468	1.388	1.741	1.951
	225	54.05	1.984	1.862	1.657	1.541	1.918	2.184
		72.45	1.662	1.568	1.378	1.288	1.608	1.811
		89.55	1.596	1.515	1.317	1.240	1.552	1.735
	250	55.37	1.734	1.619	1.460	1.348	1.670	1.883
		73.09	1.569	1.476	1.307	1.217	1.516	1.701
		90.10	1.521	1.441	1.260	1.182	1.478	1.649
10	150	99.01	3.540	3.390	2.902	2.763	3.474	3.784
		65.85	3.048	2.930	2.490	2.381	2.996	3.235
		82.73	2.750	2.652	2.246	2.154	2.710	2.903
	200	50.16	2.891	2.748	2.387	2.253	2.825	3.086
		70.11	2.027	1.926	1.669	1.573	1.972	2.132
		88.10	1.785	1.702	1.468	1.388	1.741	1.877
	225	54.17	1.984	1.862	1.657	1.541	1.918	2.070
		72.45	1.662	1.568	1.378	1.288	1.608	1.743
		89.55	1.596	1.515	1.317	1.240	1.552	1.673
	250	55.38	1.734	1.619	1.460	1.348	1.670	1.816
		73.09	1.569	1.476	1.307	1.217	1.516	1.642
		90.10	1.521	1.441	1.260	1.182	1.478	1.592

U_{233} value [$/gr]			14	14	14	14	16	14
Pu fiss. value [$/gr]			10	10	8	8	10	10
Fabrication cost			"Standard"	"Low"	"Standard"	"Low"	"Standard"	"High"
C/Pu	NC/Nth	BU						
5	150	49.48	3.390	3.248	2.778	2.645	3.324	3.489
		66.50	2.907	2.796	2.375	2.269	2.855	2.983
		83.45	2.634	2.540	2.151	2.063	2.594	2.697
	200	53.04	2.229	2.107	1.847	1.730	2.162	2.287
		71.26	1.854	1.760	1.529	1.438	1.800	1.897
		88.36	1.756	1.675	1.443	1.365	1.712.	1.795
	225	54.98	1.815	1.701	1.519	1.408	1.749	1.855
		72.98	1.646	1.555	1.365	1.276	1.593	1.681
		89.55	1.594	1.515	1.315	1.239	1.550	1.627
	250	55.50	1.717	1.603	1.445	1.335	1.653	1.752
		73.05	1.574	1.482	1.311	1.221	1.522	1.606
		90.01	1.527	1.448	1.264	1.187	1.484	1.558

Table 18

PLUTONIUM THORIUM CYCLE : FUEL CYCLE COST

Bred fuel recycling [mills/kWh]

	U_{233} value		14	14	14	14	16	14
	Pu fiss. value		10	10	8	8	10	10
	Fabrication cost		"Standard"	"Low"	"Standard"	"Low"	"Standard"	"High"
C/Pu	MG/Mth	BU						
20	150	56.74	1.803	1.701	1.714	1.615	1.887	1.927
		74.64	1.755	1.670	1.649	1.566	1.842	1.878
		91.86	1.803	1.727	1.676	1.603	1.895	1.930
	200	56.85	1.685	1.580	1.589	1.487	1.744	1.797
		74.83	1.587	1.501	1.477	1.393	1.647	1.697
		92.18	1.581	1.506	1.455	1.382	1.643	1.693
	225	56.84	1.675	1.567	1.574	1.469	1.727	1.785
		74.81	1.562	1.475	1.448	1.363	1.614	1.669
		92.17	1.539	1.463	1.410	1.336	1.592	1.648
	250	56.78	1.679	1.570	1.574	1.467	1.727	1.790
		74.73	1.554	1.465	1.435	1.349	1.600	1.660
		92.09	1.516	1.439	1.384	1.309	1.563	1.623
10	150	56.74	1.803	1.701	1.714	1.615	1.887	1.872
		74.64	1.755	1.670	1.649	1.566	1.842	1.823
		91.86	1.803	1.727	1.676	1.603	1.895	1.873
	200	56.85	1.685	1.580	1.589	1.487	1.744	1.747
		74.83	1.587	1.501	1.477	1.393	1.647	1.648
		92.18	1.581	1.506	1.455	1.382	1.643	1.643
	225	56.84	1.675	1.567	1.574	1.469	1.727	1.736
		74.81	1.562	1.475	1.448	1.363	1.614	1.621
		92.17	1.539	1.463	1.410	1.336	1.592	1.598
	250	56.78	1.679	1.570	1.574	1.467	1.727	1.741
		74.73	1.554	1.465	1.435	1.349	1.600	1.612
		92.09	1.516	1.439	1.384	1.309	1.563	1.575

Table 18 (continued)

U233 value			14	14	14	14	16	14
Pu fiss. value			10	10	8	8	10	10
Fabrication cost			"Standard"	"Low"	"Standard"	"Low"	"Standard"	"High"
C/Pu	NC/Nth	BU						
5	150	56.74	1.803	1.701	1.714	1.615	1.887	1.833
		74.64	1.755	1.670	1.649	1.566	1.842	1.786
		91.86	1.803	1.727	1.676	1.603	1.895	1.832
	200	56.85	1.685	1.580	1.589	1.487	1.744	1.715
		74.83	1.587	1.501	1.477	1.393	1.647	1.614
		92.18	1.581	1.506	1.455	1.382	1.643	1.606
	225	56.84	1.675	1.567	1.574	1.469	1.727	1.705
		74.81	1.562	1.475	1.448	1.363	1.614	1.589
		92.17	1.539	1.463	1.410	1.336	1.592	1.564
	250	56.78	1.679	1.570	1.574	1.467	1.727	1.711
		74.73	1.554	1.465	1.435	1.349	1.600	1.581
		92.09	1.516	1.439	1.384	1.309	1.563	1.541

The cycles with recycling of the bred fuel all have too big an age factor, according to the uranium thorium reference cycle. Lower age factors would only be reached with lower moderation ratios, but fig 9 and 10 show that these cycles would then reach a fuel cycle cost of about 1.9 or 2.0 mills/kWh and hence become more expensive than the once through cycles. Consequently if the age factor criterion is valid it does not seem very attractive to recycle the bred fuel in a plutonium thorium cycle.

5. CONCLUSIONS

The calculations have shown that it is possible to design integral block fuel cycles in which plutonium is the feed fuel. If the reference age factor of the uranium - thorium cycle is a feasibility criterion, only once through cycles will economically be acceptable (with a U_{233} credit of 14 $/gr).

By parametrically changing the value of the fissile plutonium and imposing the fuel cycle costs to be equal to the cost of the reference uranium - thorium cycle, an equivalent plutonium fissile value can be deduced fig 11 and 12.

This plutonium value was found to be in the range between 8.4 and 9.5 $/gr fiss. Pu depending on the values adopted for the fabrication cost corresponding to the different degrees of plutonium dilution in the kernels. These values are almost independent of the cycle burn-up and of the U_{233} credit value.

REFERENCES

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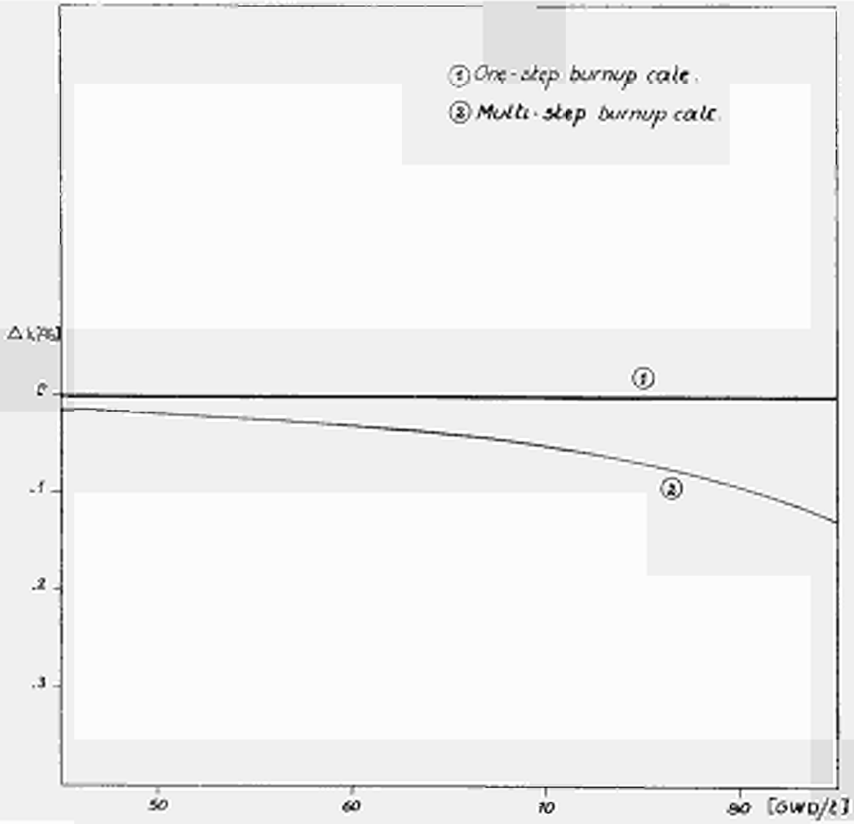
[2] Joanou et al : GAM - GATHER combined. GA 4265 and 4132 ; 1963

[3] Zanantoni C. et al :

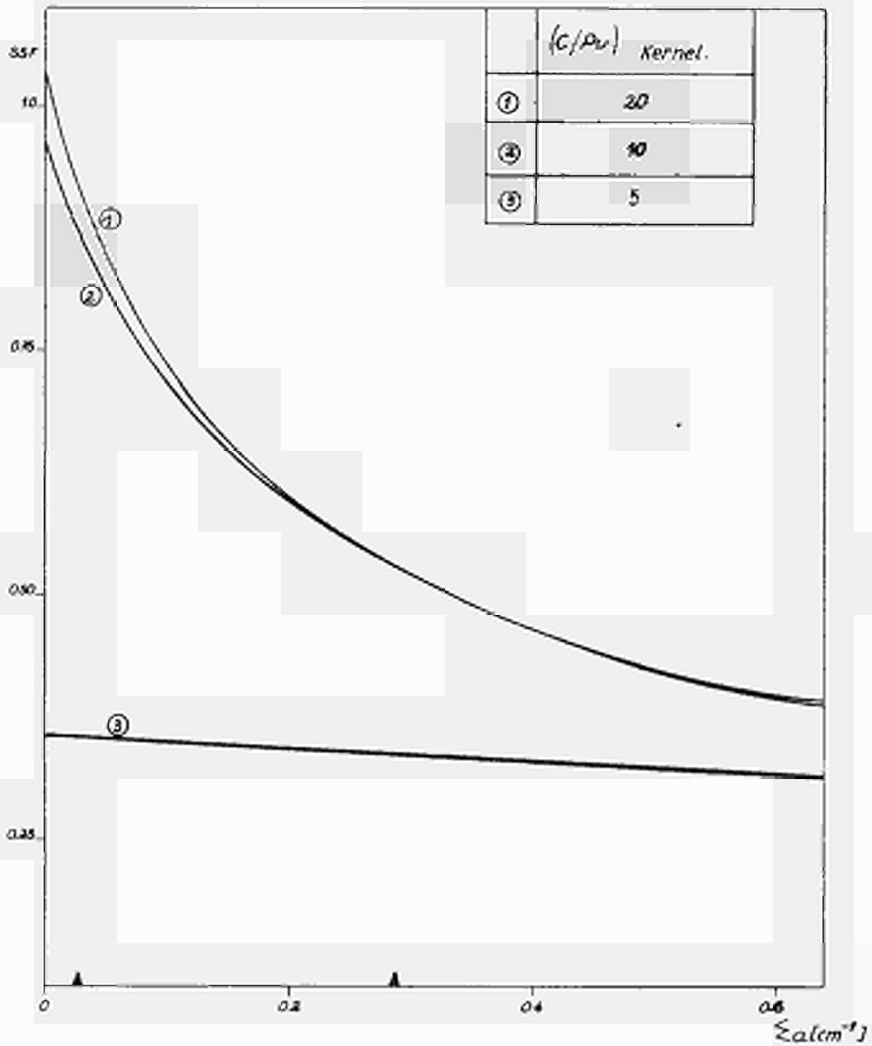
[4] Zanantoni C. et Paruccini M. : COFFEE, a code for the assessment of fuel cycle costs. DPR 584, TCR 100.81.

[5] Fischer P.U., Joye S. et Stewart H.B. : Alternate fuel cycles for the HTGR ; Gulf General Atomic ; SM - 111/70.



Average core reactivity variation between a multi-step and a one-step burnup calculation

FIG. 1.



Self schielding factor for Pu^{240} in energy group 1090 to 1025 eV.

FIG. 2.

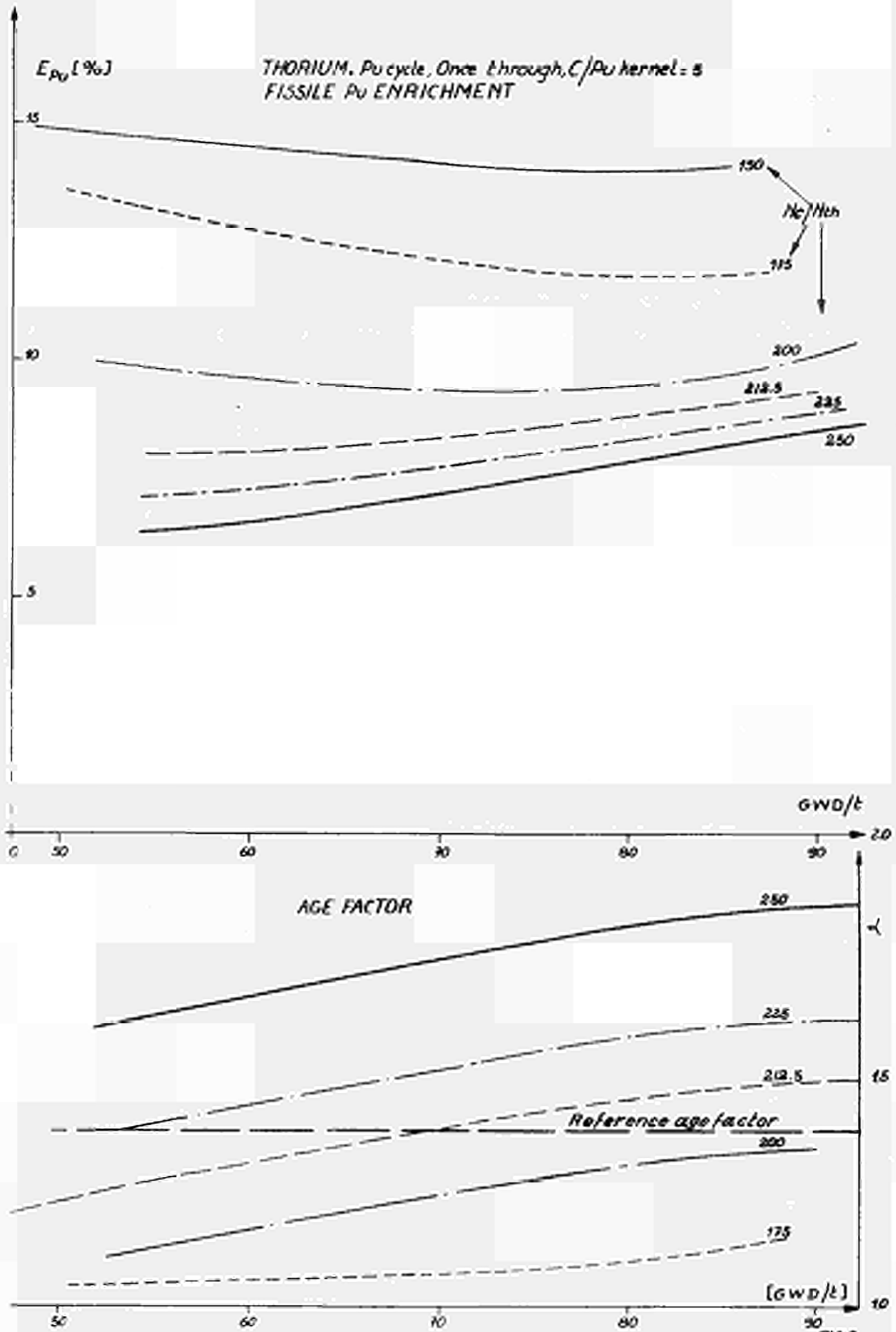

THORIUM. Pu cycle, Once through, C/Pu kernel = 5
FISSILE Pu ENRICHMENT
E_{Pu} [%]
Nc/Nth
150
175
200
212.5
225
250
GWD/t
AGE FACTOR
Reference age factor
[GWD/t]

FIG. 3.

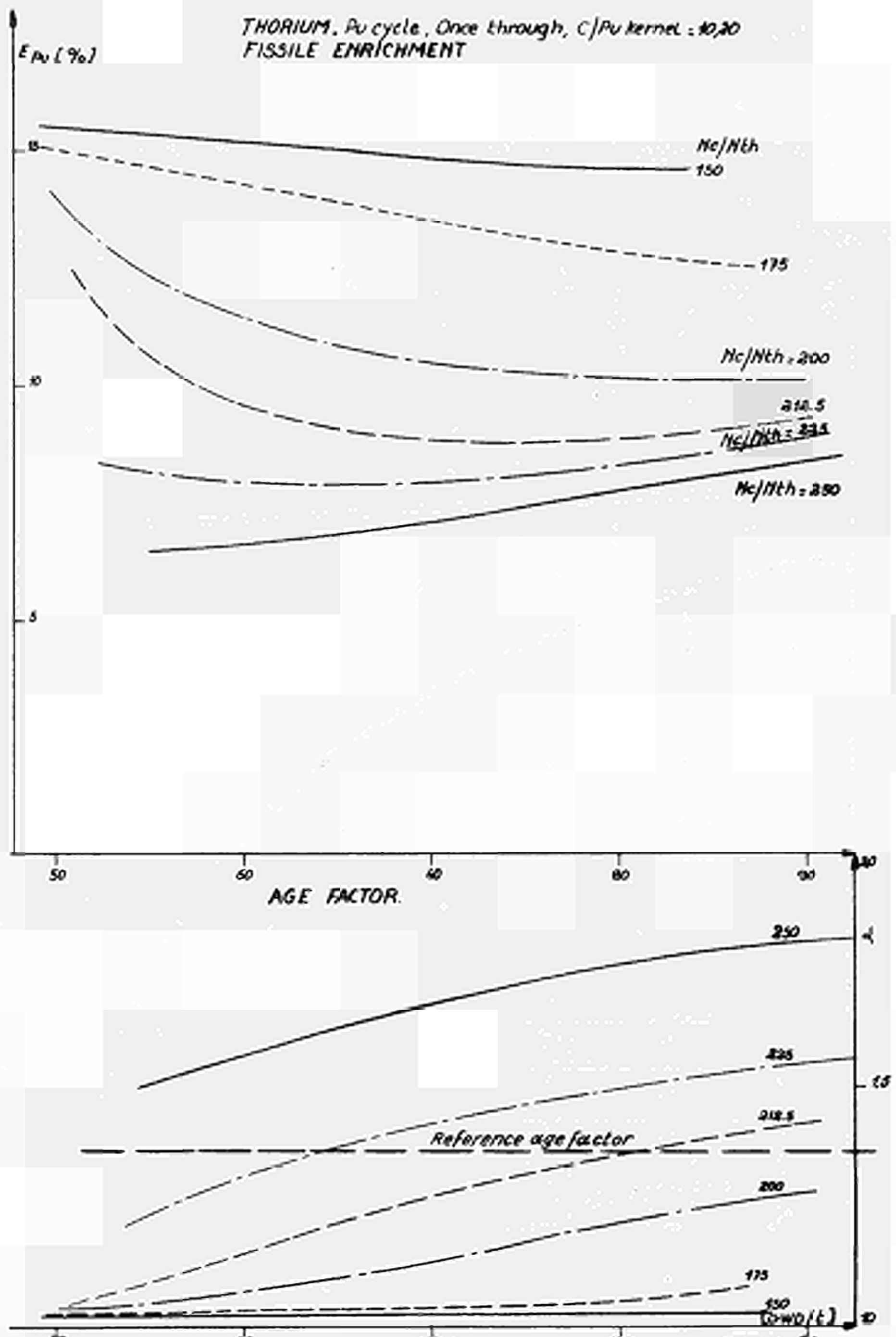

THORIUM. Pu cycle, Once through, C/Pu kernel = 10,20
FISSILE ENRICHMENT
E_{Pu} [%]
Nc/Nth
150
175
Nc/Nth = 200
212.5
Nc/Nth = 225
Nc/Nth = 250
AGE FACTOR
Reference age factor
[GWD/t]

FIG. 4.

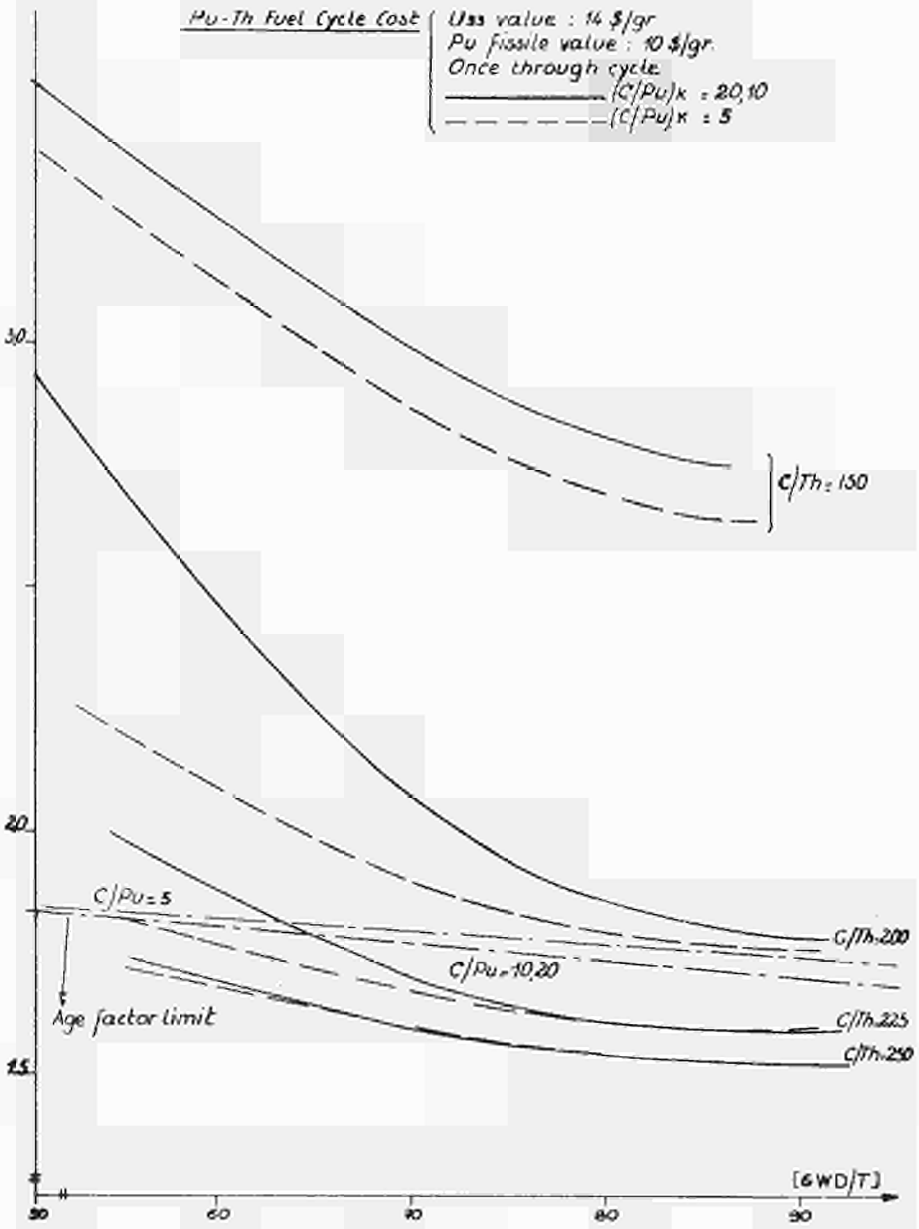

Pu-Th Fuel Cycle Cost
U33 value : 14 $/gr
Pu fissile value : 10 $/gr.
Once through cycle
(C/Pu)K = 20,10
(C/Pu)K = 5
C/Th = 150
C/Th = 200
C/Th = 225
C/Th = 250
C/Pu = 5
C/Pu = 10,20
Age factor limit
3.0
2.0
1.5
[GWD/T]
50
60
70
80
90

FIG. 5.

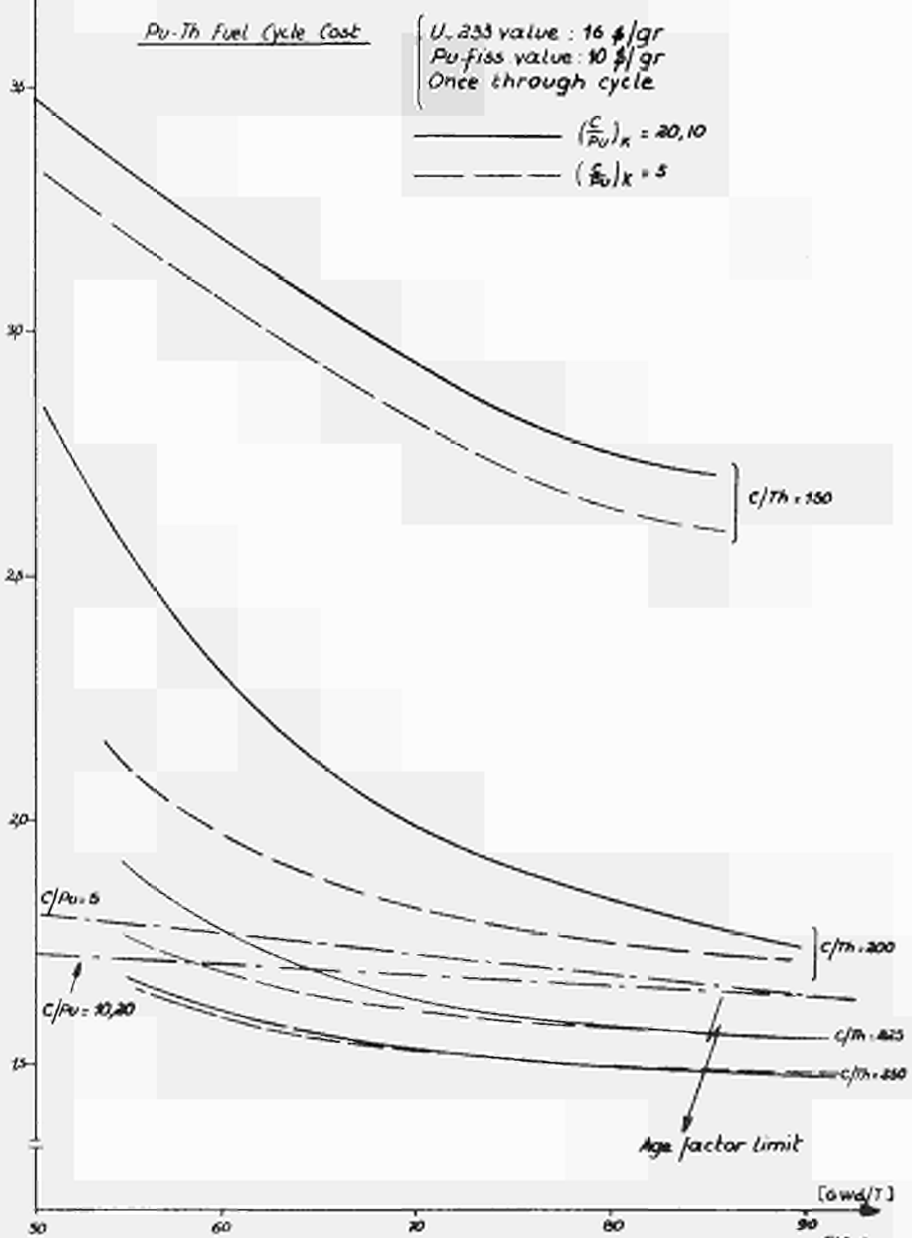

Pu-Th Fuel Cycle Cost
U 233 value : 16 $/gr
Pu fiss value : 10 $/gr
Once through cycle
(C/Pu)K = 20,10
(C/Pu)K = 5
C/Th = 150
C/Th = 200
C/Th = 225
C/Th = 250
C/Pu = 5
C/Pu = 10,20
Age factor limit
3.0
2.5
2.0
1.5
[GWd/T]
50
60
70
80
90

FIG. 6

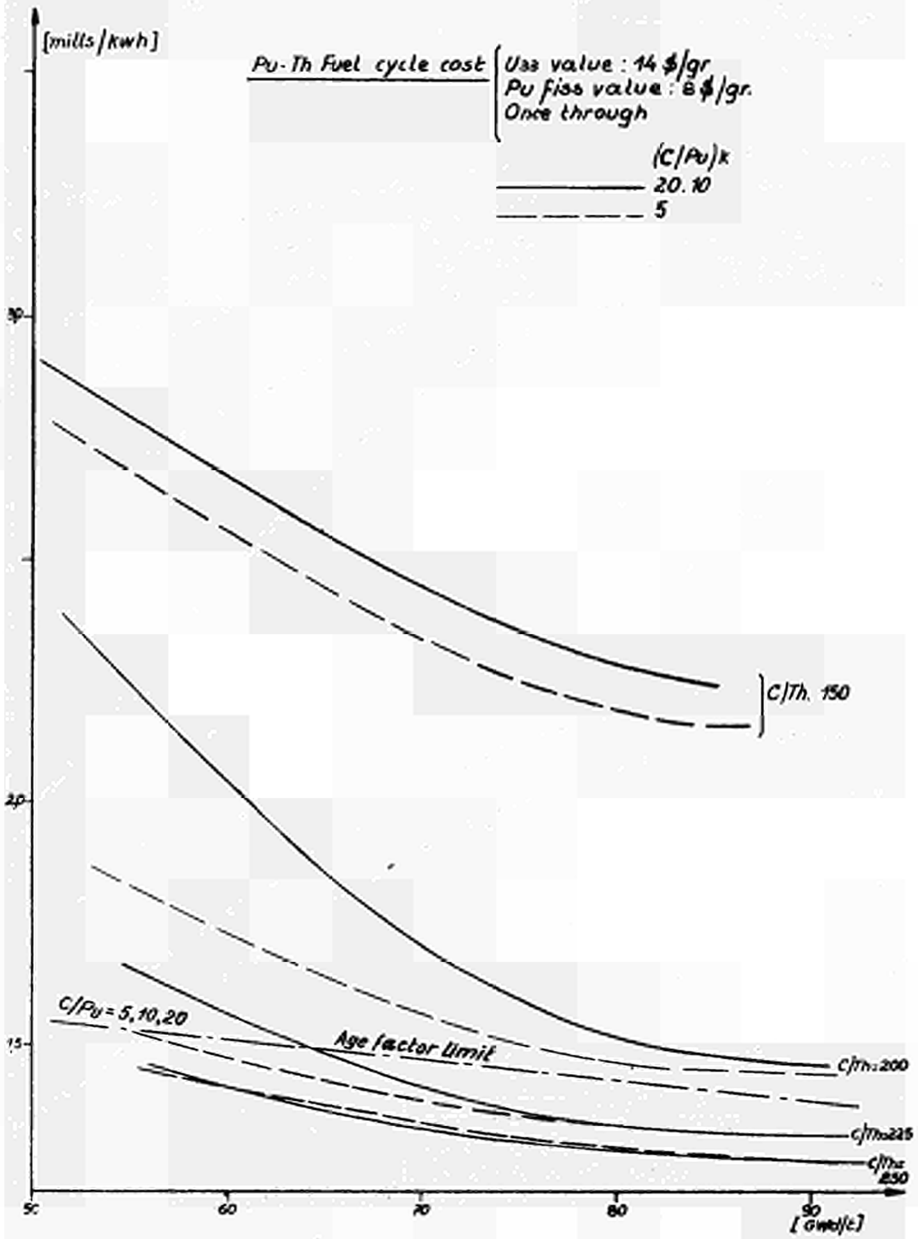

[mills/kwh]
Pu-Th Fuel cycle cost
Uss value : 14 $/gr
Pu fiss value : 8 $/gr.
Once through
(C/Pu)K
20. 10
5
C/Th. 150
C/Pu = 5,10,20
Age factor limit
C/Th:200
C/Th:225
C/Th: 250
50
60
70
80
90
[GWd/t]

FIG. 7.

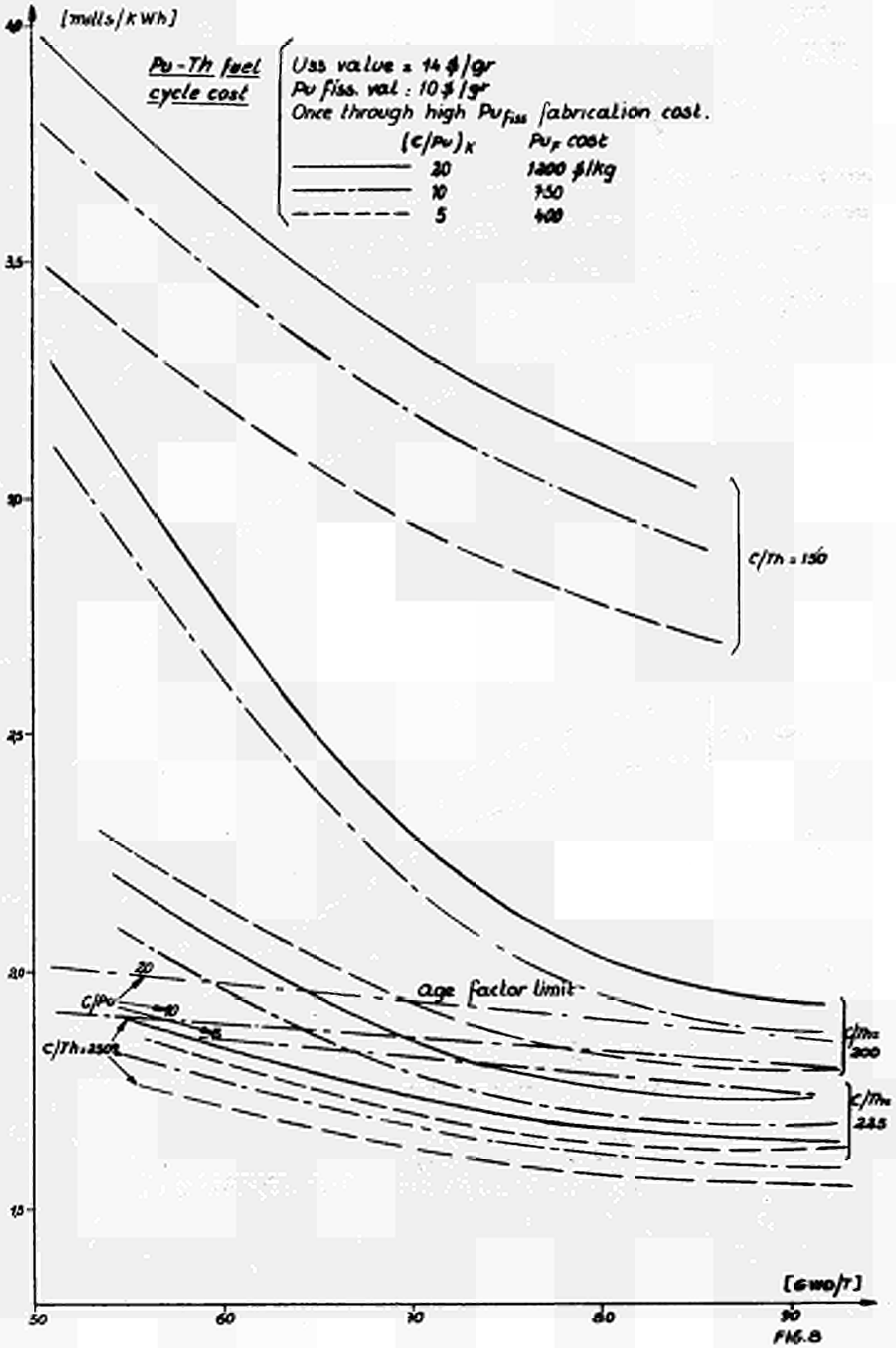

[mills/kWh]
Pu-Th fuel cycle cost
Uss value = 14 $/gr
Pu fiss. val : 10 $/gr
Once through high Pu fiss fabrication cost.
(C/Pu)K
Pu F cost
20
1200 $/kg
10
750
5
400
C/Th = 150
age factor limit
C/Th 200
C/Th 225
C/Th:250
C/Pu
20
10
5
4.0
3.5
3.0
2.5
2.0
1.5
50
60
70
80
90
[GWd/T]

FIG. 8

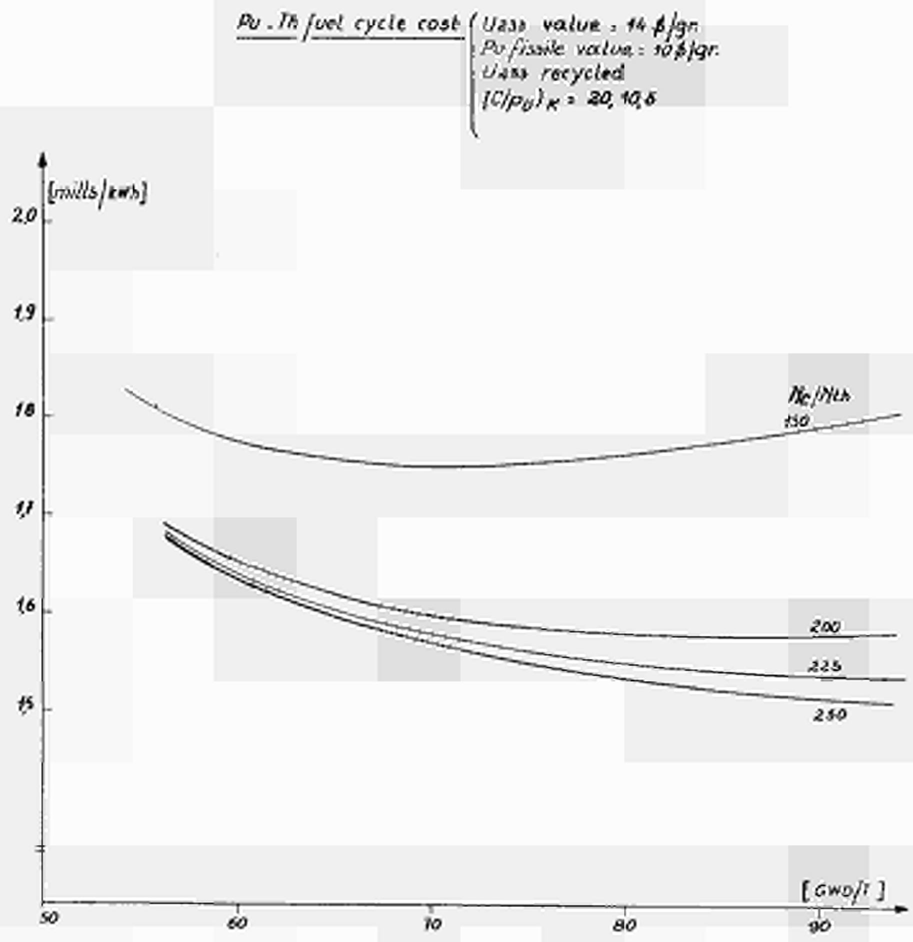

Pu . Th fuel cycle cost
U233 value : 14 $/gr.
Pu fissile value : 10 $/gr.
U233 recycled
(C/Pu)K = 20, 10, 5
[mills/kWh]
2,0
1,9
1,8
1,7
1,6
1,5
Mc/Mth
150
200
225
250
[GWD/T]
50
60
70
80
90

FIG. 9.

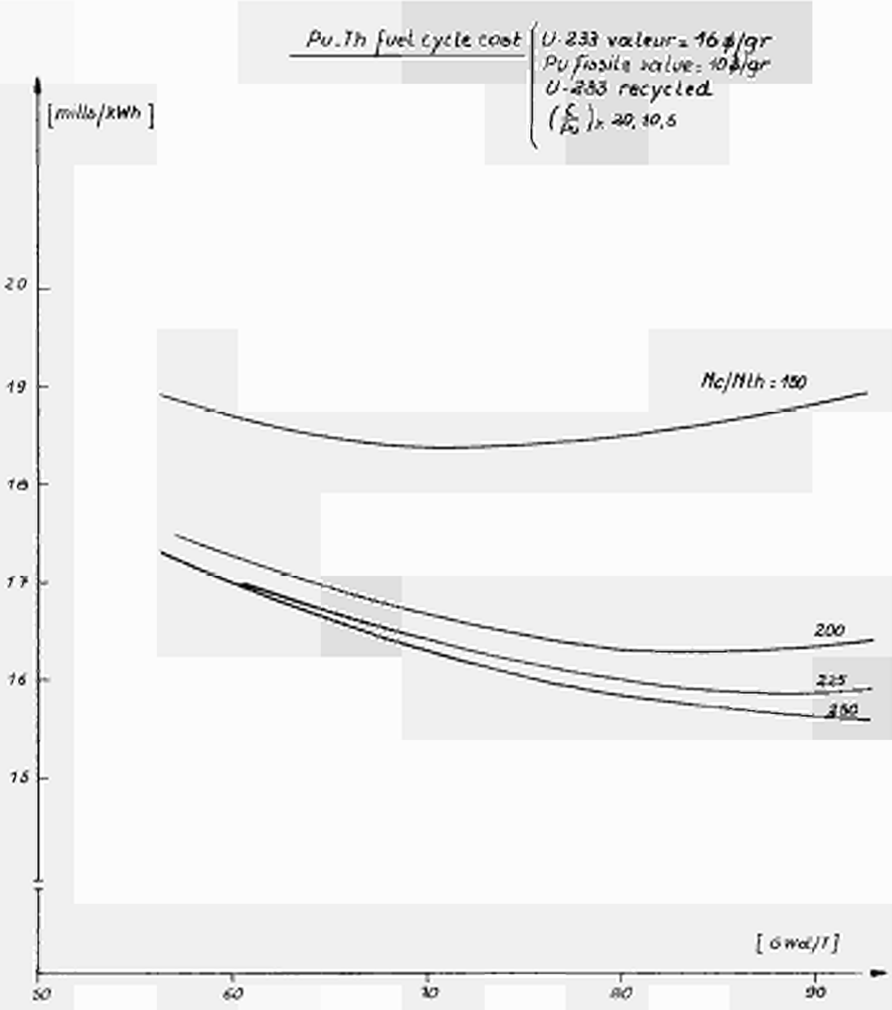

Pu . Th fuel cycle cost
U-233 valeur = 16 $/gr
Pu fissile value : 10 $/gr
U-233 recycled
(C/Pu)K = 20, 10, 5
[mills/kWh]
2.0
19
18
17
16
15
Mc/Mth : 150
200
225
250
[GWd/T]
50
60
70
80
90

FIG. 10

Pu . VALUE.

(bu. of the reference cycle (U5/Th) 68 Mwd/Kg)

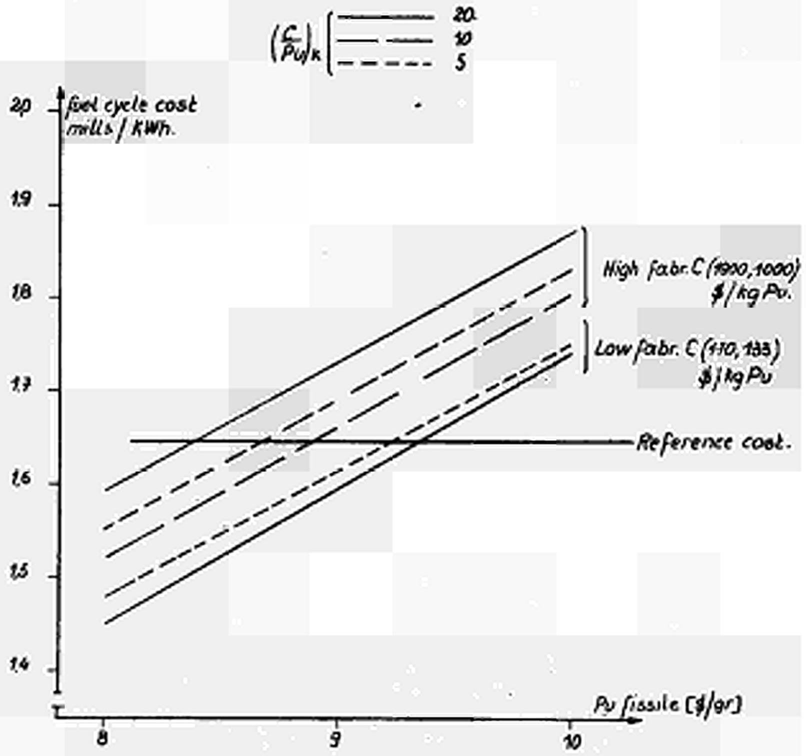


FIG. 11

Pu. value

(bu of the reference cycle (U5/Th) 80 Mwd/Kg)

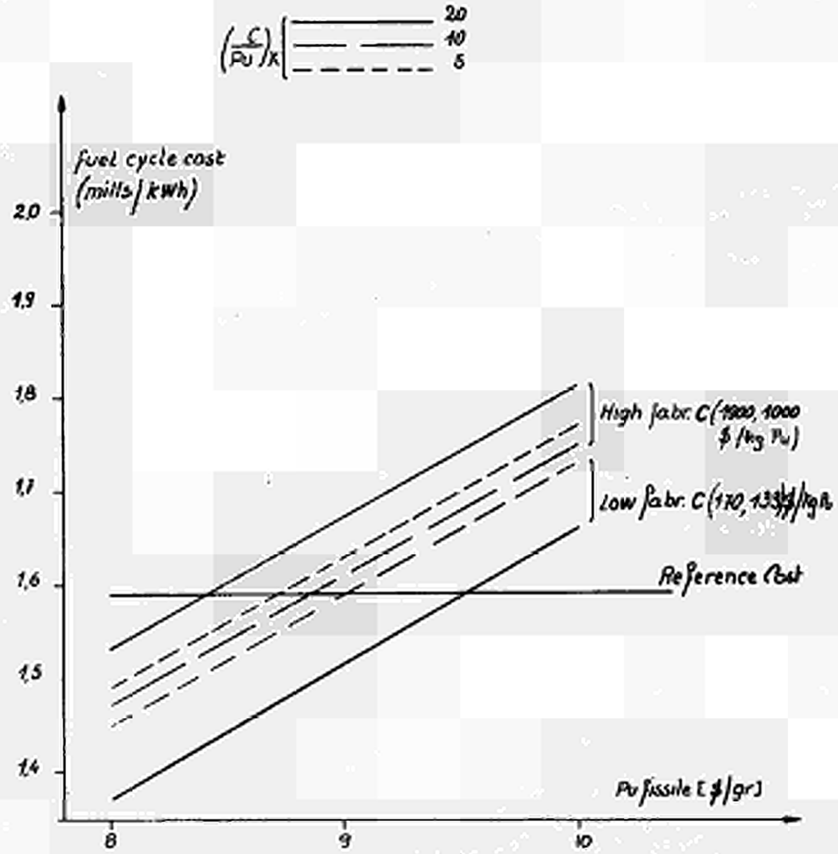


FIG. 12

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Alfred Nobel

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