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DCPM 16 - CEA 1

A COMPARISON BETWEEN THORIUM - URANIUM AND LOW ENRICHMENT URANIUM CYCLES IN THE HIGH TEMPERATURE REACTORS

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In a previous report, it was shown that the Uranium cycle could be used as well with multi-hole block (GGA type) as with tubular elements. Now, in a F.S.V. geometry, a comparison is made between Thorium cycle and Uranium cycle. This comparison will be concerned with the physical properties of the materials, the needs of natural Uranium, the fissile material inventory and, at last, an attempt of economical considerations.

In this report the cycle will be characterizd by the fertile material. So, we write "Thorium cycle" for Highly Enriched Uranium - Thorium cycle and "Uranium cycle" for low Enrichment Uranium cycle.

I - PHYSICAL PROPERTIES

A first stage in the comparison and in the understanding of the results is a quick survey of the properties of the fissile and fertile materials loaded in the reactor.

In the two cases, the fissile feed material is the same, U_{235} or, perhaps, Plutonium. But with the bred fissiles materials, U_{233} and U_{235} with Thorium, Pu_{239} and Pu_{241} with Uranium cycle, very clear differences appear in their neutronic properties, in the spectrum of an HTR reactor :

$$\eta = \nu \frac{\sigma_f}{\sigma_a} \quad \text{and} \quad \alpha = \frac{\sigma_c}{\sigma_f}$$

We give, as an exemple, the η and α values calculated over the spectrum of a Thorium loaded core (U_{233}) or of an Uranium core (U_{235}, Pu_{239}, Pu_{241}).

	U_{233}	U_{235}	Pu_{239}	Pu_{241}
η	2.27	1.91 2.05, 2.05, 2.05(*)	1.78 1.922, 1.835, 1.83	2.12 2.08, 2.08, 2.08
α	0.11	0.26 0.184, 0.184, 0.184	0.62 0.583 0.574, 0.585	0.43 0.427, 0.426, 0.426

(*) Values from D-HHT ref. design: 3 fuel ages, $N_C/N_U \approx 333$, BU = 86 MWd/kg

The η value, averaged over the fissile materials will be better in the Thorium cycle. From that, it appears that more neutrons will be available for fertile captures, giving a greater conversion ratio and a lower requirement of fissile material.

An other aspect is the radioactivity of the bred fuel : U_{233}, because of the presence of U_{232}, and Pu. It is always a difficulty. <u>But the penalty will be greater in the Thorium cycle, because of the larger amount of radioactive material (twice the quantity of Pu) and of the more important shielding</u>. The Pu fuel elements technology is better known and Pu can be used in FBR where it will have a greater value.

II - CONDITIONS CHOOSEN FOR THE COMPARISON

2.1. - Two previous parametric studies have been completed

- one for Uranium cycle that was reported on in a previous DCPM
- the other for Thorium cycle

From these studies it is possible to choose more than one case, for each cycle , giving an optimized cost. For a question of homogeneity in the comparison, two optimized cycles have been chosen with the following and a little arbitrary options :

- the same life time (4 years) and also the same power density (8 MW/m^3) are imposed. Thus we will have the same fast dose.

- final Burn-up is a free parameter, allowing thus the possibility of the same fuel element geometry (FSV element). It is clear that the influence of the geometry is not directly comparable for the two cycles. But, as it has been shown that, even for Uranium cycle, the geometry was not an important parameter if the burn-up was free, we think that the comparison is well representative in these conditions. The only stress will be the necessity of an intermediate enrichment Uranium cycle rather than a low enrichment one.

- the basic cycle will be annual refueling. Semi annual and continuous on-load refueling will be examined as a possible improvement

To summarize the most important data :

Geometry	: FORT SAINT VRAIN element
Reactor power	: 3000 MWTh
Power density	: 8 MW/cm^3
Fuel lifetime	: 4 years
Load-factor	: 0.75
<u>Particules</u>	
Uranium cycle	: 800 μ kernel diameter
Thorium cycle	: fissile : 200 μ kernel diameter
	fertile : 450 μ kernel diameter

2.2. - A few options have been examined

For the thorium cycle, the long term normal situation is a closed cycle, where the U_{233} is recycled in the reactor, the make-up fissile material being U_{235}. But we have to consider a starting period where a refabrication plant will have not been built, at least in Europe, and where U_{233} will have to be sold or stored. As reprocessing is concerned an European plant would have to be built in the first years of the HTR's, for example from an existing and not more used, Uranium reprocessing plant. We don't examine the possibility of the storage of the blocks for a future reprocessing.

So, two situations are considered :

- a closed cycle with recycling of U_{233}
- an open cycle with sale of U_{233}

Even without considering the HTR's starting period, three periods must be considered along the life of a power plant :

- the first core : Thorium and U_{235}
- a period without recycling of U_{233}, during which the U_{233} is not yet available from the reactor : the first two or three reloads.
- a period with recycling

For the Uranium cycle, the Bred Plutonium is always sold and the discharged Uranium is either sold or recycled once.

RESULTS OF CALCULATIONS OF THE CORE - FISSILE MATERIALS REQUIREMENTS

The table III below gives the characteristics of the fuel and of the core.

TABLE III

	THORIUM with sale of U_{233}	With recycling of U_{233}	Uranium
Burn-up	90000 MWD/T_{HM}	90000 MWD/T	120000 MWD/T
C/(U+Th) or C/U	250	250	342
Heavy metal density in the core	0.0975 g/cm^3 ≈ 0.5	0.0975 g/cm^3	0.073 g/cm^3 ≈ 0.33-.35
Enrichment or $U_{235}/Th + U_{235})$	6.74%	3.92%	11.50%
FIFA	1.39	1.50	1.10
Conversion Ratio	0.629	0.687	0.553
Age Factor	1.40	1.40	1.20
Part of the fissions due to U_{233} or fissile Plutonium	45%	68%	40% [illegible]
Part of the bred U_{233} or fissile Plutonium burnt "in situ"	68%	68%	84 %

In the table IV are given the quantities of charged and discharged fissile and fertile materials and the needs of natural Uranium. All these indications concern a reload (Yearly refueling).

TABLE IV

	Thorium without recycling of U_{233}	Thorium with recycling of U_{233}	Uranium
Feed Thorium or U	8500 kg	8500 kg	6050 kg
Feed U_{235}	616 kg	345 kg	786 kg
Needs of Natural Uranium	150 T	84 T	187 T
U_{233} discharged or recycled	199 kg	202 kg	
U_{235} discharged or recycled with U_{233}	10 kg	25 kg	
U_{235} discharged	20 kg	20 kg	146 kg
Fissile Pu discharged			100 kg

Load factor 0.75 , therm.-eff. 0.445 → 1000 MW(e)/full power year
" — " 0.42 → 945 " — "

The same results can be given in a different way looking at :

- the yearly requirements of natural Uranium in the different cores
- the requirements of U.S.W.
- the apparent quantity of fissile material which is burnt,

in an open cycle :

fissile depletion = Feed U_{235} - Discharged U_{235} - Sold (U_{233} or fissile Pu). In a closed cycle :

fissile depletion = Feed U_{235} - Discharged U_{235}

The table V summarizes these results :

TABLE V

	Thorium open cycle	Thorium with recycling	Uranium
Feed U_{235} kg	616	345	786
Discharged U_{235} Kg	30	20	146
Discharged U_{233} or fissile Pu kg	199		100
Apparent fissile Depletion kg	387	325	540
Natural Uranium T	150	84	187
U.S.W	150000	80000	160000

Thorium cycle requires 10 - 20 times more uranium than thorium (8.5 t/y
For the first core an equivalent of roughly 400t Unat is needed.

2.3. - Discussion of the results

It appears clearly that the great advantage of Thorium cycle is its higher conversion ratio. But this advantage can be completely valorized only with recycling of U_{233}. Indead :

- 200 kg of U_{233} are discharged each year and only 68% of the bred U_{233} is burnt "in situ" in the core (compared to 84% of the bred Plutonium). This U_{233} has to be recycled to be completely valorized.

Because of properties of U_{233}, conversion ratio is improved with recycling and the need of fissile material (see table V) is reduced (feed material and fissile depletion). The needs of natural Uranium become 84 T, compared to 150 T with a Thorium open cycle and 187 with an Uranium cycle, and the requirements of U.S.W. is also reduced from 160000 for Uranium to 80000.

Thus with Thorium cycle the resources of natural Uranium are better used and the investment in enrichment plants can be reduced. But, and it is an important point, U_{233} has to be recycled in good economic conditions in a refabrication plant built in a not too far future.

2.4. - Future improvements - semi annual and continuous on-load Refueling

The study has been made for annual refueling, but it is not clearly an optimum, rather a solution studied by sellers and accepted by customers. Two other options are examined :

- a reload period of six months
- continuous on-load refueling

The results are given by the table VI :

TABLE VI

Thorium cycle (closed cycle)	Annual refueling	Semi annual refueling	Continuous refueling
Feed U_{235} kg	345	299	248
Recycled U_{233} kg	202	197	192
Uranium cycle with recycling U_{235}			
Feed U_{235} kg	680	631	577
Discharged Plutonium kg	100	93	84

It results from this calculation that the reduction of the amount of fissile feed material is the same in the two cases and that there is no clear advantage for one or for the other.

III - ECONOMIC CONSIDERATIONS

A cycle cost can be given for the two options from which conclusions can be drawn. But it is clear that the comparison will depend in the hypothesis made on the costs of the different components of the cycle cost. So it seems better to compare the answer of the total cost to variations of the most important components. These comparisons are made over the life of the plant, first core included.

- Uranium ore cost : The tendancy of the market will be probably an increasing price of the Uranium ore. From the results above, it is clear that the sensibility of Thorium cycle will be lower. If the cost of ore increases from 6.5 to 12 $ lb, the advantage of Thorium is increased of 0.2 mill/kwh.

- Cost of U.S.W. : In the same manner, an increase of cost of separation work gives an additionnal advantage to Thorium.

- Plutonium : Here, an increase of fissile Pu value from 10 to 15 $ lb is an advantage of 0.07 mill/kwh for uranium.

- Fabrication-Refabrication : It is an important and difficult point. If we consider a power plant, over its life, as indicated above for the first core and the first two or three reloads, there is no U_{233} available from the plant it self. In the following reloads, approximatively 40% of the blocks contain U_{233} and 60% are free of U_{233}. In these conditions the weight of the refabrication cost in reduced. But, as the number of blocks and the weight of particules to be re-fabricated are reduced, the unit price will be high. Or, it will be necessary to have an important installed power to reduce this cost.

From our calculation and for a given fabrication cost, the refabrication price which gives the same cost for the cycles is near three times and a half the fabrication cost.

III - CONCLUSION

Nuclear fuel requirements

The uranium ore requirement of a Thorium HTR, in an equilibrium cycle, is only 50% of that of an Uranium HTR. The use of Thorium will reduce the future demand of nuclear materials. It is a clear advantage for the ten or twenty following years..

Economic point of view

In a large market, with a refabrication plant, there is probably an economic advantage for Thorium, perhaps 10 to 15%. But this point is not so clear in the starting period and in the European market Nevertheless we can hope that the HTR's development will be sufficiant to offer the possibility of the economical use of a refabrication, and also reprocessing, plant.