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NEUTRONIC CHARACTERISTICS OF A 1200 MWe FUELLED WITH (ThO_2 - 233 U)O_2

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- *INTRODUCTION* -

Recently, in particular within the INFCE discussions, the attention has been called upon the use of the Thorium cycle as a possible fuel for fast breeders.

Among the specific advantages of this cycle, one may quote :

- *the relatively important amount of Thorium available throughout the world ;*

- *the neutronic properties of 233 U which is issued by capture from 232 Th ;*

- *the fact that the higher isotopes produced by a (Th-233U) fueled reactor : 234U, 235U, 236U, 237Np, are less toxic than those issued from a (238 U - 239Pu) fu led core ;*

- *the non-proliferation possibilities of this cycle.*

Moreover for fast breeders, two points can be underlined :

- *from the safety point of view, it must be noted that a (Th-233U) fueled core has a negative Sodium void coefficient instead of a positive one for a (238U-239Pu) fueled one ;*

- *the mixed oxyde (232Th-233U)0_2, which can be used to fuel a fast breeder, presents better thermal and mechanical characteristics than the (238U-239Pu)0_2 presently used.*

In this context, this paper presents the main characteristics of 1200 MWe fast breeder fueled with $(Th\text{-}233U)O_2$ and compares this characteristics to those of an equivalent reactor using the $(U\text{-}Pu)O_2$ fuel.

In Section I, one defines a reference core fueled with $(Th\text{-}233U)O_2$ on the basis of the criteria used for a SUPER-PHENIX type reactor and compares the characteristics of $(Th\text{-}233U)O_2$ and $(Pu\text{-}U)O_2$ fueled cores.

Section II is devoted to the optimization of this reference core by modifying various parameters (e.g. cycle length, maximum linear power, pin diameter).

I - DEFINITION OF A 1200 MWe CORE USING THE $(Th\text{-}233U)O_2$ FUEL -

I-1/ Basic data used :

a) In the CARNAVAL IV system, the basic nuclear data concerning the Thorium cycle isotopes are rather old (1973 or before), and have not been adjusted on integral experiments.

Therefore, for these isotopes (232Th - 233Pa - 233U - 234U - 236U), ones uses in the present calculations the ENDF/B.IV microscopic data processed with the MC2.2 code /1/, into 25 group cross-sections according to the CARNAVAL scheme.

Such a choice has been justified by a preliminary analysis of some integral experiments devoted to 232Th-233U (JEZEBEL - AETR 8) performed successively with CARNAVAL IV and ENDF/B.IV, /2/.

b) To study the burn-up problems, a specific pseudo fission product has been calculated for 233U according the same procedudre as the one used for 235U and 239Pu at CEA /3/. One uses for this definition the specific yields of the Thorium cycle isotopes.

The following table shows that the capture due to fission products in the 233U is significantly lower than the fission product capture in 239Pu for fast breeders :

Isotope	Pseudo fission products capture
233 U	0.212 b/fission
235 U	0.296 b/fission
239 Pu	0.419 b/fission

This leads to a contribution of the fission products to the reactivity loss per cycle which is much lower for $(Th\text{-}233U)O_2$ than for $(U\text{-}Pu)O_2$ in a 1200 MWe core :

10^{-5} $\Delta K/K$	Total reactivity loss	Fission product contribution
U - Pu	1640	1230
Th-233U	2430	510

II - DEFINITION OF THE 1200 MWe REFERENCE CORE -

The reference core of a fast breeder fuêled with $(Th\text{-}233U)O_2$ is defined by using the criteria and contraints which are applied to a SUPER-PHENIX type reactor : this permits a first comparison between the two types of fuel.

. *Electric power : 1200 MWe.*

. *Reactor dimensions : see figure 1.*

. *Pin diameter : 7.14 mm.*

. *Volumic percentages :*

- *fuel : 38.45 % v/o ;*
- *Na : 33.45 % v/o ;*
- *Steel: 24.6 % v/o.*

. *Maximum linear power : 450 W/cm.*

. *Cycle length : 320 days.*

. *The isotopic composition used for the (Th-233U)O_2 fuel is :*

- *233U : 79 %*
- *234U : 16 %*
- *235U : 3 %*
- *236U : 2 %*

. *The critical enrichments are determined with the following conditions : at end of cycle*

- *Keff = 1.00300*
- $q_1max = q_2max$ *($q_i max$ being the maximum power in region i).*

The following table presents the comparison between the enrichments and the reactivity loss per cycle obtained for both fuels (2D (R,Z) calculations) :

	E_1	E_2	10^{-5} $\Delta K/K$ Equilibrium cycle
U-Pu	13.99	17.78	1608
Th-233U	14.20	17.70	2458

One observes that the enrichment values are quite close for both fuels, but that the reactivity loss per cycle is much higher for $(Th\text{-}233U)O_2$. This is essentially due to the core heavy atom balance as shown in the next table where are given the breeding gain values :

		Beginning of cycle	Middle of cycle	End of cycle
I.B.G.	U-Pu	- 0.134	- 0.127	- 0.122
	Th-233U	- 0.255	- 0.233	- 0.222
E.B.G.	U-Pu	0.386	0.373	0.362
	Th-233U	0.329	0.326	0.322
G.B.G.	U-Pu	0.252	0.246	0.240
	Th-233U	0.074	0.090	0.10

The global breeding gain corresponding to $(Th\text{-}233U)O_2$ is significantly lower than the one obtained for $(U\text{-}Pu)O_2$. This is mainly due to the fact that the internal breeding gain of a $(Th\text{-}233U)O_2$ fueled core is much lower than the one of a core using the U-Pu mixed oxide.

As a consequence, the doubling time of a breeder using the Thorium cycle will be quite higher than the doubling type of a SUPER-PHENIX type reactor :

	$(Th-233U)O_2$	$(Pu-U)O_2$
Critical mass Kg	4745	4916
G.B.G.	0.09	0.246
Cycle length (days)	320	320
DPA	103	118
$1 + T_r/T_s$*	1.485	1.485
Fissile Production/Year	129	228
Td (1% reprocessing loss)	42	25

a) The 233U production (129 Kg) takes into account the 233Pa contribution.

b) $1 + T_r/T_d$* is calculated the following hypothesis :

- T_r (reprocessing) = 1 year
- load factor : 0.85

c) With the assumption made for this comparison, one notes that the DPA are lower for the $(Th-233U)O_2$ fuel than for the $(U-Pu)O_2$ one. This would allow to increase the cycle length for the Thorium cycle (see Section II).

. Safety parameters :

The following table summarizes the main safety parameters for both cores :

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	$(U\text{-}Pu)O_2$	$(Th\text{-}^{233}U)O_2$
Doppler coefficient (reactor) $10^{-5}\ \frac{\Delta K}{K}/\ K$	- 1.31	- 1.12
Sodium void effect (total core) $10^{-5}\ \frac{\Delta K}{K}$	+ 1000	- 2300
Rod antireactivity $10^{-5}\ \frac{\Delta K}{K}$	13100	14370
$\beta eff\ 10^{-5}\ \frac{\Delta K}{K}$	369	327

Ones observes that the $(Th\text{-}233U)O_2$ is an interesting fuel from the safety point of view :

- *the Doppler coefficient is close to the value obtained for the $(U\text{-}Pu)O_2$ fuel ;*

- *the Sodium void effect is strongly negative, whereas it is positive for the (U-Pu) mixed oxide ;*

- *the rod efficiency (1D calculation) is slightly higher for the Thorium cycle, and the delayed neutron fraction for the $(Th\text{-}233U)O_2$ is significantly lower than the value corresponding to the $(U\text{-}Pu)O_2$ fuel.*

As a preliminary conclusion, one notes that the use of the $(Th\text{-}233U)O_2$ leads to :

- *interesting safety characteristics ;*

. reactivity loss per cycle higher that the one corresponding to a SUPER-PHENIX type reactor ;

. low breeding gain which could be improved by increasing the fuel enrichment or the fuel volumic fraction ;

. lower displacement per atome number due to the fact that the flux level is lower by ≈ 20% than the flux level in a SUPER-PHENIX type core.

Nevertheless it must be kept in mind that these observations correspond to operation conditions (maximum power, fuel volumic fraction) which has been choosenclose to the ones adopted for a 1200 MWe $(U\text{-}Pu)O_2$ fueled reactor.

II - $(Th\text{-}233U)O_2$ CORE OPIMIZATION -

In order to improve the doubling time of the 1200 MWe reactor using the Thorium cycle, one looks to the influence of the following parameters :

1) residence time of the fuel ;

2) maximum linear power ;

3) addition of the BeO moderator ;

4) fuel volumic percentage ;

5) pin diameter.

. The following table presents the results obtained :

a) when one increases the residence time up to 120 DPA ;

b) when the maximum linear power is lifted up to 600 W/cm to take into account the thermal advantages of the Thorium oxide ;

c) when BeO is added in the core.

	Reference core	a) Cycle length increased	b) Maximum linear power : 600 W/cm	c) BeO added (7.55% v/o)
E_v %	14.2/17.7	14.41/17.97	14.8/18.5	13.8/17.3
GRG	4745	4816	3985	4590
Cycle length (days)	320	360	320	320
DPA	103	120	128	92
T_d	42	49	42	38

One observes that none of the three modifications suggested leadsto an improvement of the doubling time :

a) in order to increase the cycle length up to 360 days (corresponding to 120 DPA) one has to increase the core enrichment by 1.5% and this reduces the global breeding gain by 0.012 ;

b) to lift the maximum linear power up to ≃ 600 W/cm leads to increase the enrichment by 4% and this reduces the G.B.G by 0.015.On the other hand the critical mass is reduced by 931 Kg. Therefore, the doubling time does not change with respect to therefore core ;

c) to add some BeO reduces the internal breeding gain from -0.24 to -0.19 but also the external breeding gain from 0.33 to 0.29 (mid-cycle values). Therefore the global breeding gain is not significantly increased (+0.02). The core enrichment is reduced by ≈3% and the doubling time slightly improved.

. Modification of the fuel volumic fraction :

The following table gives the results obtained :

a) when the subassembly characteristics and the core size are kept fixed (for all the pin diameters) ;

b) when the core size is modified in order to keep the pressure-drop constant ;

	Reference	Subassembly characteristics and core size fixed		Constant pressure drop	
% v/o (fuel)	38.45	42.	46.	41	43.7
Pin diameter (mm)	7.14	7.46	7.81	8.0	9.0
Core volume	10910	10910	10910	12880	15315
E_v %	14.2/17.7	13.4/16.6	12.6/15.8	13.56/16.95	12.90/16.10
M_c (Kg)	4745	4860	5055	5719	6912
Cycle length	320	320	320	450	580
GBG (MoC)	+ 0.09	0.12	0.145	0.105	0.124
TDL	42	33	30	35	31
DPA	103	99	96	120	120

The results obtain show that the GBG and Doubling time may be significantly improved by increasing the pin diameter :

- *if the core size is not modified with respect to the reference core, the core thermohydraulics have to be studied in order to check the pressure-drop ;*

- *if the core and subassembly characteristics are modified, one has to take into account the fuel inventory which increaseswith the pin diameter.*

- CONCLUSION.-

With the assumption that the mixed oxide $(Th\text{-}233U)O_2$ *would be available, the corresponding fast breeder power plants would have the following characteristics with respect to SUPER-PHENIX type cores using the* $(U\text{-}Pu)O_2$ *fuel :*

- *for a given pin diameter (here ≃ 7 mm), the critical masses obtained with both fuels are quite close ;*

- *the reactivity loss per cycle is much higher (for the Thorium cycle (7.68 pcm/day), than for the (U-Pu) cycle. This is essentially due to heavy isotope balance of the Thorium cycle, the fission product capture being less important for that cycle than for the (U-Pu) cycle ;*

- *the global breeding gain associated to the* $(Th\text{-}233U)O_2$ *fuel (0.09) is significantly lower than the one related to* $(U\text{-}Pu)O_2$ *fuel (0.246). This leads to doubling times which are in any case much higher for the Thorium cycle than for the (U-Pu) one* $(\frac{T_D(Th\text{-}233U)}{T_D(U\text{-}Pu)} \simeq 2)$ *;*

. *between the start up and the equilibrium cycle, one has to take into account the 233 Pa build-up ($\simeq$ 1500 10^{-5} $\Delta K/K$) which will influe directly on the control rod insertion ;*

. *on the other hand, when the reactor is stopped, the control rod system must compensate the positive reactivity due to the 233U issued from 233 Pa ($\simeq$ 25 10^{-5} $\frac{K}{K}$/day) ;*

. *the flux level is lower by $\simeq$ 20% for the (Th-233U)O_2 fuel than for the (U-Pu)O_2 one : this reduces the DPA rate and would allow to increase the residence time ;*

. *from the safety point of view, the (Th-233U)O_2 fuel presents the advantage of a negative Sodium void coefficient (-2300 10^{-5} $\Delta K/K$ for a total core voiding), whereas this coefficient is positive for a (U-Pu)O_2 fueled core (+ 1000 10^{-5} $\Delta K/K$ for a total core voiding).*

The preliminary optimization performed show that there is no real significant interest in :

. *increasing the residence time ;*

. *using a moderator (BeO).*

The use of ThO_2 should permit to have a higher value of the maximum linear power (600 W/cm) than for the limit used here for the (U-Pu)O_2 : 450 W/cm. But, this adavantage does not modify the doubling time of the reactor.

The main optimization effect is observed when one changes the pin diameter : the preliminary study presented here indicates that a optimum -which must be assessed- could be ≃ 8 mm. With such a diameter, and with using 600 W/cm as a linear for the maximum linear power, the global breeding gain in increased by ± 0.02 and the doubling time in reduced by ≃10 years

All these indications should be completed by more refined neutronic claculations (e.g. optimization of the control rod location, influence of the rods on the operation conditions), and the conclusion suggested would have to be analyzed from the mechanics and thermohydraulics points of view.

Nevertheless, on the basis of the present results, if one considers that the major aim of the breeder reactor is to provide fuel for future plants, the U-Pu cycle remains presently the only relative solution to achieve this goal.

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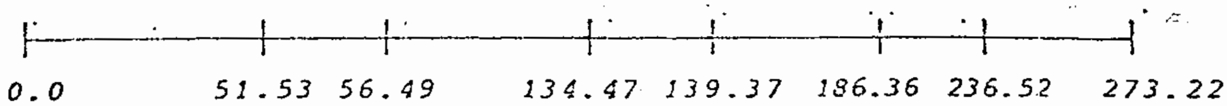
Figure 1

1 - Dimension du SP-Thorium pour le calcul 1D



2 - Dimension du SP-Thorium pour le calcul 2D