FUEL CYCLE RELATED PARAMETRIC STUDY CONSIDERING LONG LIVED ACTINIDE PRODUCTION, DECAY HEAT AND FUEL CYCLE PERFORMANCES

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Abstract

One of the very attractive HTGR reactor characteristics is its highly versatile and flexible core that can fulfil a wide range of diverse fuel cycles. Based on a GTMHR-600 MWth reactor, analyses of several fuel cycles were carried out without taking into account common fuel particle performance limits (burnup, fast fluence, temperature). These values are, however, indicated in each case. Fuel derived from uranium, thorium and a wide variety of plutonium grades has been considered. Long-lived actinide production and total residual decay heat were evaluated for the various types of fuel. The results presented in this papers provide a comparison of the potential and limits of each fuel cycle and allow to define specific cycles offering lowest actinide production and residual heat associated with a long life cycle.

1. INTRODUCTION

Among the well-known identified HTGR characteristics often mentioned, one can remind essentially the inherently safe behaviour of the concept vis-à-vis of the Lost Of Forced Circulation (LOFC) major accident, the highly flexible reactor core allowing many different fuel applications with generally a low long-lived radiotoxic waste production whatever the fuel type concerned. In collaboration with Framatome, a study has been initiated in CEA, to compare the potential of a wide range of diverse fuel cycles from the neutronic point of view (life cycle and generated amount of long-lived actinides) without taking into account the common limits of the fuel particles performances usually respected.

Indeed, being optimistic enough concerning the future fuel performances and technology, it is interesting to perform investigations on long-life fuel cycles without, in a first step, limiting them by the fuel technological recommendations (fluence, %FIMA and burnup). That does not exclude, however, to notice the values achieved in each case. Due to the neutron moderation and reactor cooling functions which are totally independent, HTGR cores allow to accommodate different neutronic parameters, i.e. the fuel/graphite ratio, neutron spectrum, power density, etc... Important parameters such as fissile/fertile particle fraction, particle volume fraction in the graphite matrix, type of fuel (enrichment, plutonium quality and content...), burnable poison,... can be adjusted in order to tentatively approach the optimum cycle life that can be achieved for several types of fuel. For each one and based on the GTMHR-600 MWth concept, equilibrium cycle lengths are given and generated amounts of long-lived actinides are estimated by varying these parameters.

Moreover, it is useful to consider the impact of each possible fuel cycle on the inherent safe behaviour of the concept. The presence in fuel of plutonium, thorium or minor actinides (in case of incineration) does not always induce lower or similar residual decay heat level than in the case of low enriched uranium. Therefore, for each promising fuel cycles, the residual decay heat has been evaluated. Only calculations related to the evolution of the decay heat after a reactor shutdown are performed in this study. The results are compared to the existing ones (benchmark calculation or detailed conceptual studies).

This study is not a complete and exhaustive study of the HTGR fuel cycles, more detailed core neutronics analyses on the capacity of operating with the same high level of safety would be necessary. Preliminary results of the present paper could allow to address in the near future a much more complete reactor core study including the reactivity control aspects, the temperature coefficient, neutronic core stability...

2. CATEGORIES OF FUEL EXAMINED

In the present study, UCO/U_{nat} and UCO/Th have been considered as a first step to validate the calculation process employed. Indeed, UCO/U_{nat} with a uranium enrichment of 20 %, is the basic cycle of the commercial version of the GTMHR-600 MWth power plant proposed by General Atomics. On the other hand, UCO/Th which has been considered for a long time as the most promising fuel of the MHTGR-350 MWth, provides also a possible comparison for establishing a calculation method.

For both fuel types, cycle length in the range of 420 and 462 Equivalent Full Power Days (EFPD) for respectively the UCO/U_{nat} and UCO/Th are commonly announced. In this case, the equilibrium burnups taken into account by General Atomics were 110 and 92 GWd/t.

Moreover, previous studies have shown that due to the high burnups achievable with the coated particles, the fissile isotope composition of the spent HTGR fuel is degraded much beyond the spent fuel standard. Calculations have been then performed with different categories of plutonium exclusively in oxide form inside the particle kernel.

First, plutonium coming from the spent light water reactor fuel (LWR) has been envisaged. Partially burnt in France in the same reactor (LWR) as MOX fuel, it generates a second generation of plutonium that has also been taken into account in the present study. Plutonium containing typically 36 % to 54 % of ^{239}Pu (50 to 66 % in fissile Pu) has allowed to cover the various isotopic vector changes of the plutonium that could be found today or in a near future (planned increases fuel burnups in LWR will lead to lower fissile plutonium content in the spent LWR fuel).

Second, plutonium coming from the dismantling of nuclear warheads has also been studied. Since the end of December 1995, GA, MINATOM, Framatome, and Fuji Electric have been working together on the design of a plutonium-consuming GTMHR with the final goal of replacing the existing weapons-grade plutonium

production reactors at Tomsk-7, or other regions of the Russian Federation [1]. In this framework, CEA in collaboration with Framatome is investigating the possibilities of burning highly enriched plutonium in an HTGR. Finally, all the plutonium gathered in the Table I below are classified by their spent fuel origin (enrichment, burnups and fuel management).

Table I. Plutonium isotopic compositions

Cycle name	*Plutonium origin*	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}	Pu_f/Pu_t
PU1	PWR 3,7 % (U5/U) 42 GWj/t - 1/4	2,7	54,5	22,9	11,7	7	1,0	66,2 %
PU2	EPR 5,0 % (U5/U) 60 GWj/t	4,49	50,31	23,56	12,39	8	1,25	62,7 %
PU3	PWR 4,5 % (U5/U) 55 GWj/t - 1/6	4	50,4	23	12,3	9,1	1,20	62,7 %
PU4	First generation MOX-PWR 45 GWj/t - 1/4	3,5	47,4	27,1	11,1	9,8	1,10	58,5 %
MOX1	Second generation MOX-PWR 33 GWj/t - 1/3	3,3	41,70	28,70	14,50	10,7	1,10	56,2 %
MOX2	Second generation MOX-EPR 60 GWj/t	5,62	36,75	28,76	13,40	14,13	1,35	50,15 %
PUW	Weapons	0,01	94,0	5,4	0,6	0,01	0,01	94,6 %

3. COMPUTER CODES AND METHODOLOGY

3.1 - Core neutronic calculations

For the following calculations, the French reactor physics code system SAPHYR is used. Usually applied to industrial PWR calculations and research & development purposes, SAPHYR gathered several CEA codes like APOLLO2 (transport) based on data base given by THEMIS/NJOY, CRONOS2 (diffusion-transport), FLICA4 (3D thermal hydraulics)..., which are interconnected. The first calculations presently performed on the GTMHR indicate that SAPHYR is adapted for the assessment of the HTGR performances and characteristics.

The core neutronics analysis is essentially based on a specific calculation process employing the APOLLO2 transport code [2], which is a portable/modular code for multigroup transport calculations. The formalism used to solve the Boltzmann transport equation is either the Integral-Equation (collision probability 1D and 2D) or Integral-Differential-Equation (discrete ordinates and nodal methods in 2D). The main functions of the code are: the self shielding computation, the leakage calculations, the direct and adjoin multigroup flux solver (source and eigenvalue problem, criticality search), the fuel depletion calculation and homogenization by an equivalence procedure.

Containing over 400 isotopes issued mainly from JEF 2.2, the standard 99-groups (47 thermal) APOLIB library has been used in the present study. The calculations have been performed in fundamental mode (critical buckling), considering a linear anisotropic collision hypothesis for the calculation of graphite diffusion coefficient.

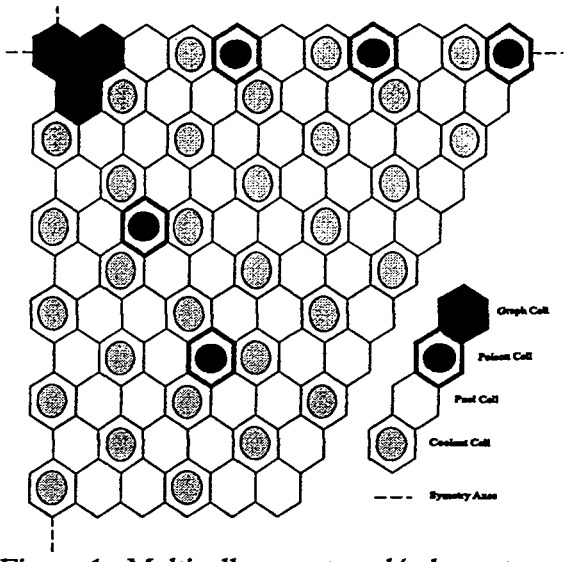

Figure 1 : Multicell geometry - ¼ element

The geometry representative of the standard fuel element is a hexahedral multicell geometry (Fig. 1). 216 channels are available in the element for compact columns of fuel and burnable poison. Some calculations have been performed without fixed burnable poison, such as, for example, in the case of low fissile isotope contained in the plutonium or in the case of high fuel loaded in the core. The poison compacts are therefore substituted with fuel compact, taking care that the plutonium mass loaded in the element is still the same.

Likewise, the double heterogeneity of the geometry characterised by the spherical fuel particles on the one hand and the hexagonal multicell on the other hand are taken into account by a two step internal flux resolution in the code.

The standard depletion chain consists of 20 heavy nuclei and 77 fission products. Nine of the principal heavy nuclides are self shielded during the fuel evolution. The depletion calculations are made independently for each of the media and the isotopic concentrations evolution can be given for fertile, poison and fissile material. Erbium and bore depletion are also taken into account by simplified chains :

$$^{162}_{68}Er \quad ^{164}_{68}Er \quad ^{166}_{68}Er \xrightarrow{n,\gamma} ^{167}_{68}Er \xrightarrow{n,\gamma} ^{168}_{68}Er \qquad\qquad ^{10}_{5}B \xrightarrow{n,\alpha} ^{7}_{3}Li$$

In order to estimate the multiplication coefficient (k_{eff}) of the reactor core, the relation below has been used to determine the k_{eff} from the infinite multiplication coefficient of the fuel element in evolution:

$$k_{eff}^{3D}(J) = \frac{k_{\infty}(J)}{1 + M^2(J)B_g^2} \qquad (1)$$

where :

- M^2 is the migration area in cm^2,
- B_g^2 is the geometric buckling,
- k_{∞} is the ratio Production/Absorption in fundamental mode (fuel element calculations),
- J the burnup.

The equivalent geometric buckling mentioned above is assumed to be constant in the estimation of the evolution of the neutron volumetric leakage. Much more representative of the characteristic core geometry than the global neutron leakage, it takes into account the reflector efficiency function of the neutron spectrum. This parameter is determined for each type of fuel, at the core's beginning of cycle, by using the following formulation and an homogeneous annular core calculation:

$$B^2_g = \frac{1}{M^2(BOC)}\left(\frac{k_\infty(BOC)}{k^{3D}_{eff}(BOC)} - 1\right) \qquad (2)$$

For each type of fuel cycle, two calculations have been made so as to estimate the radial and axial leakage. The geometry used for the radial calculation is a cylindrical one. The core structure consists of four layers, including internal reflector (graphite), active zone (homogenised fuel element), outer reflector (graphite) and core barrel (steel). The axial leakage is estimated using a 1D plane geometry with a similar description for internal structure.

The formalism used to solve the Boltzmann equation in this configuration is the Integral-Differential Equation, using the discrete ordinates methods (P_1-S_8). The calculation performed on the fuel element in fundamental mode allows to generate a 99-group macroscopic cross section library for each burnup step. These macroscopic cross sections are used for the 99-groups transport calculation described previously (Fig. 2). Finally, the multiplication coefficient of the 3D-annular core can be estimated using the formulation:

$$k^{3D}_{eff}(BOC) = \frac{k^{2D}_{eff}(BOC)}{1 + F_z} \qquad (3)$$

where F_z are the axial leakage and $k^{2D}_{eff}(BOC)$ the effective multiplication coefficient calculated on the annular geometry.

The average burnup of the core is estimated at the beginning of the cycle and depends of course on the type of the fuel management. However, the annular core geometry, with a low active core thickness, leads to an important gap between the spectrum in fundamental mode and the average spectrum in the annular core. Considering a core fuelled uniformly with the *PU1* plutonium at a burnup of 250 GWd/t, Figure 2 displays an example of the differences obtained between the average spectrum in the fuel element and in the annular core region.

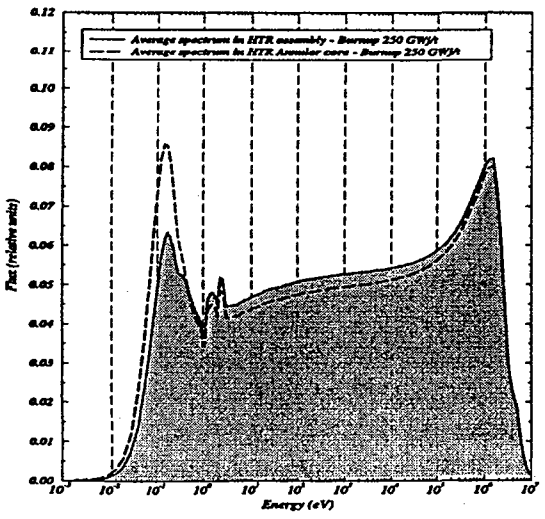

Figure 2 : Neutron spectrum comparison between the fuel element and the core

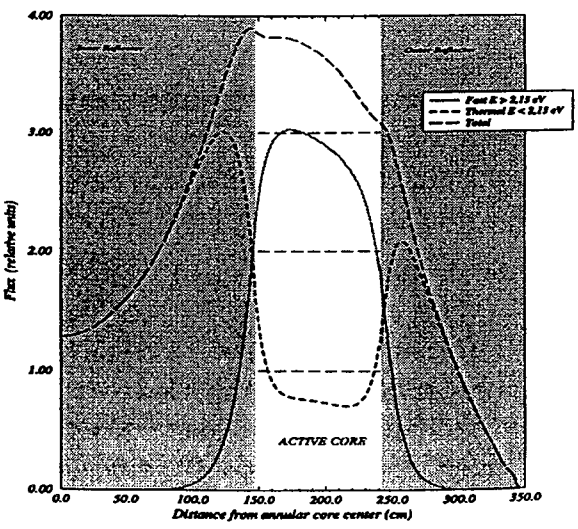

Figure 3 : Core radial fluxes in a 2D annular geometry

Figure 3 exhibits the radial variation of fast and thermal flux in the annular core region. These effects, which are important in the regions close to the reflector, lead to an increase of 3D leakage during evolution. Taking into account the error induced by the calculation, we can estimate a global uncertainty on the fuel cycle length to 20 EFPD.

3.2 - Decay heat calculations

The annular core geometry of the GT-MHR was selected to maximise the power density and still permit passive core heat removal while maintaining reasonable fuel temperatures during accident conditions. Only calculations related to the decay heat removal after the reactor shutdown allow to say if the amount of energy that can be extracted passively during a LOFC accident will not lead to excessive fuel particles temperatures. Moreover, recent benchmark calculations [5] or well defined existing design like the GT-MHR of General Atomic in its commercial version offer a possible comparison of the residual heat evolution curves.

In the code system SAPHYR, the DARWIN/PEPIN2 code [3] calculates, by an analytical method, the radioactive decay equations of 762 fission products and 88 heavy nuclides using a specific CEA library based on JEF2. It allows to assess the concentrations and activities of each nuclide so as to calculate the decay heat and the activity of a reactor, depending of its operating time. The historical irradiation is reconstructed from the multigroup self-shielded cross sections and fluxes (σ_g, ϕ_g) directly issued from the evolution transport calculation for the nuclides present in APOLLO2. The cross sections of the others isotopes are evaluated from the library by using the ϕ_g fluxes.

Only the β and γ decay heat of the fission products on the one hand and α, β and γ of the heavy nuclei on the other hand have been considered. No fission power decreasing kinetic has been considered here. Depending on the temperature coefficient, then of the type of fuel, the major contribution to the fission power decrease is the total reactivity inserted in the core during the reactor shutdown. This fission power evolution correspond to a very low fraction of energy deposited into the core during a LOFC accident (0.1 % of the total energy accumulated during 240 h). It may be omitted in a first approximation.

4. RESULTS AND DISCUSSIONS

4.1 - Fuel element analyses

4.1.1 - Reactivity and neutron spectrum change in evolution

Some of the characteristics of the fundamental mode calculations are presented hereafter. Figure 4 shows the evolution of the multiplication coefficient for three types of plutonium: one weapons grade plutonium (*PUW*) and two reactor grade plutonium with the lower and the higher fissile isotopic weight (*PU1* and *MOX2*). The strong slope observed for the *PUW* at the beginning of life is due to the ^{239}Pu consumption and ^{240}Pu build-up. On the opposite, the erbium's consumption (^{167}Er

isotope), combined with the ^{241}Pu production induces a low and steady decrease between 250 and 450 GWj/t. These phenomena do not exist for other plutonium because of the very low mass of erbium charged in the fuel element (there is a ratio of 8 between the erbium charged with *PUW* or *PU1*).

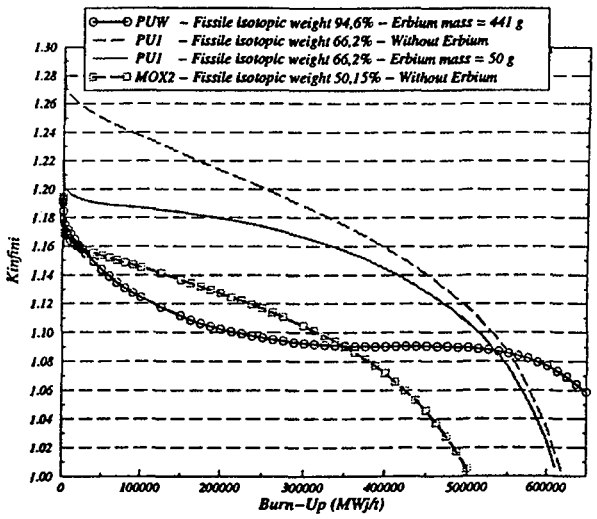

Figure 4 : Infinite multiplication coefficient in evolution for divers plutonium

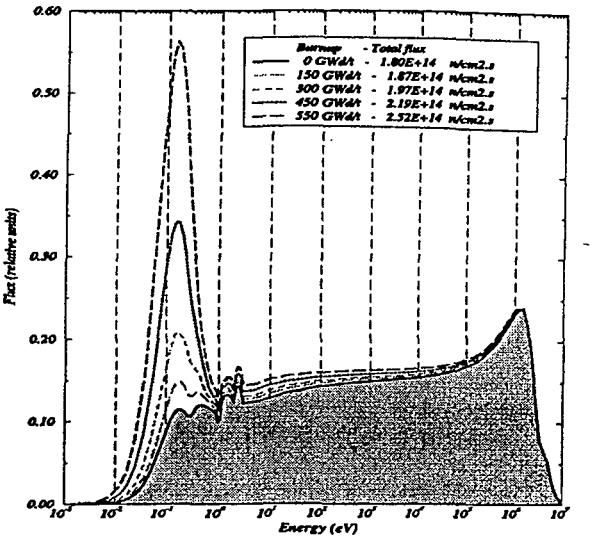

Figure 5 : Evolution of the neutron spectrum in the fuel element - Plutonium *PU1* -

The evolution of the average neutron spectrum in the fuel element is described in Figure 5. The loss of both erbium and ^{240}Pu during the fuel depletion induces an increase of the thermal flux (there is a factor greater than 3 on the thermal flux between the beginning and the end of life).

4.1.2 - The burnable poison impact

It should be stressed that compared to a similar fuel evolution without erbium (*Pu1* in Fig. 4), the fuel with poison presents an initial negative reactivity of around 9000 pcm which strongly decreases towards 600 GWd/t, corresponding to the loss of 90 % of ^{167}Er. The cycle lengths are however comparable. This important feature of the burnable poison equivalent to that observed with ^{10}B allows to adjust the initial reactivity of the different fuel cycle without changing the cycle lengths.

The optimum load of fixed burnable poison has not been estimated in the present study and therefore the different fuel cycles analysed do not exhibit the same initial reactivity. Nevertheless, we should not forget that the presence of the erbium in fuel element may play an important part in the core behaviour with regard to the negative reactivity feedback. Unlike the Doppler coefficient which is always negative, the graphite temperature reactivity coefficient can be positive in presence of plutonium, especially at the end of life.

4.1.3 - Power distribution in the fuel element

Figures 6 and 7 present the power distributions (in percent) for the standard fuel element at the beginning and at the end of life for two types of fuel loaded in the core (respectively 701 and 1200 kg). The average compact power is done taking into account both fuel and burnable poison compact.

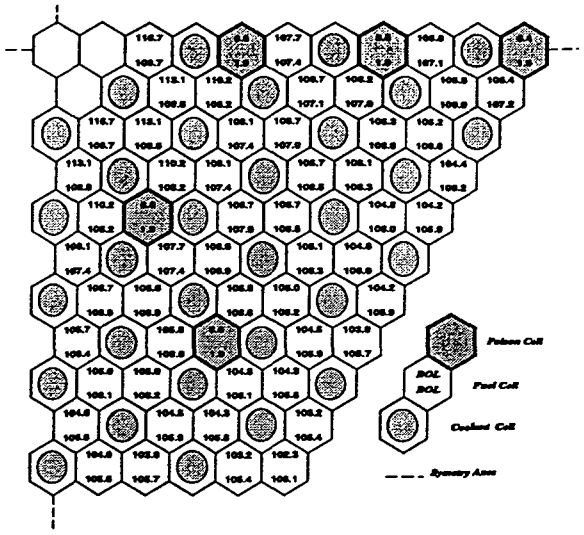

Figure 6 : Fuel element power distribution - Core with 701 kg plutonium *PUI* (with Er)

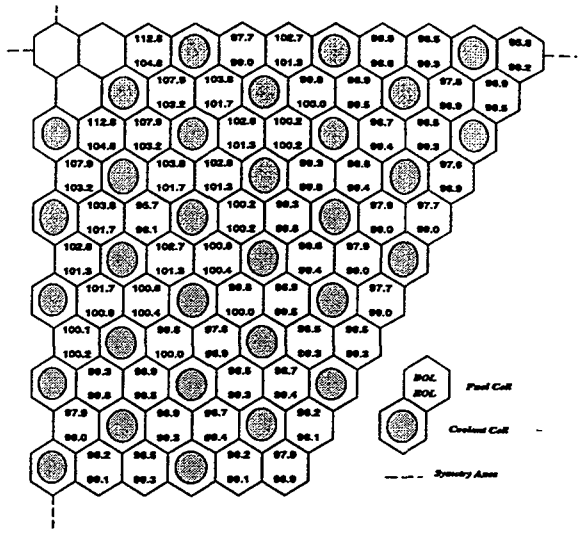

Figure 7 : Fuel element power distribution - Core with 1200 kg plutonium *PUI* (without Er)

One should note that an important power is emitted by the fuel compact located at the centre of the element. Similar to the one observed at the interface core-reflector, this phenomenon is amplified by the presence of the plutonium (a peak power of only 6 to 7 % is obtained with the uranium fuel).

4.2 - Fuel cycles study

Table II below gathers the various parameters characterising the uranium and weapon grade fuel cycles. All the isotopic balances are given for a cooling time of 5 years after the fuel discharge. Uranium cycles employ low enriched uranium (20 %) in fissile particles and natural uranium or thorium as fertile fuel while in the others cycles only one type of particles containing plutonium in oxide form is used.

For the different fuel types feeding the reactor, the discharged burnup was determined in order to achieve a reactivity margin of 2000 pcm at the end of cycle (k_{eff}=1.02) embracing the possible uncertainties. The values of k_{eff} at the beginning of life are not indicated in the tables. They depend essentially of the presence of the ^{240}Pu for the plutonium cycles and must be adjusted by addition of burnable poison without really shortening the cycle length.

The cycle length results obtained with the uranium fuels (U/U_{nat} and U/Th) are in good agreement with those generally encountered in this type of reactor. For both fuels, the production of plutonium and minor actinides is two times smaller than the one achieved in a standard uranium fuel cycle of a pressurised water reactor (PWR). However, as far as the U/Th cycle is concerned, the minor actinides build-up is comparable to the one estimated for a PWR loaded with a similar fuel [4].

In general, the generation of transuranium nuclides is lower in presence of thorium due on the one hand to its position in the heavy nuclei chain and on the other hand to the small capture to fission ratio of ^{233}U produce from the thorium. This tendency is highlighted in Table II between both uranium cycles. That is the reason why,

associated with the large epithermal neutron spectrum of HTGR, $^{233}U/Th$ was for a long time considered as the reference cycle of the concept.

The *PUW* cycle presents a cycle length in agreement with the previous studies [1] and a very high fuel burn-up compare to the uranium cycles. Its strong initial reactivity imposes nevertheless the use of burnable poison and demands a multi-batch fuel management scheme. The small ^{240}Pu content in the *PUW* leads to a relatively low build-up of minor actinides. Likewise, a very good utilisation of the heavy metal load in the reactor is observed with some Fission rates greater than 70 % per Initial Fissile Atom (FIFA) and then around 70 % per Initial Metallic Atom (FIMA).

Table II. Uranium and weapon-grade plutonium fuel cycles characteristics

Fuel cycle		UCO/Unat	UCO/Th	PUW
Fuel core loading (kg)		3496/1028	3400/2380	701
Fuel element loading (g)		3543/1042	3450/2416	727,51
compact fuel volume fraction (%)		*20.8/2.8*	*20.8/7.3*	*14.0*
Type of burnable poison		natural B_4C	natural B_4C	natural Er_2O_3
Burnable poison loading		3 g / std elem	3 g / std elem	441 g / std elem
compact poison volume fraction (%)		*0.87*	*0.87*	*22.56*
Fuel power density (W/g)		132.6	99.6	855.9
Total neutron flux (BOC/EOC in n/cm^2/s)		1,86 / 2,20 10^{14}	1,83 / 2,04 10^{14}	2,023 / 2,163 10^{14}
Std element peak power (BOC/EOC)		1,075 / 1,0161	1,071 / 1,0161	1,146 / 1,131
Equilibrium cycle length EFPD		**490**	**460**	**260**
Fraction of core refueled per cycle		1/2	1/2	1/3
Average discharged fuel burnup (GWd/t)		130	97.5	668
% FIFA		*87.5*	*81.9*	*73.0*
% FIMA		*13.7*	*9.6*	*69.1*
Particles average fluence (E_n > 0.18 MeV)		1.8 n/kb	1.45 n/kb	3.2 n/kb
Uranium balance per cycle :		**- 368 kg (-16.3%)** **- 109 kg/TWhe**	**- 268 kg (-15.7%)** **- 85 kg/TWhe**	**+37 g** **+ 21 g/TWhe**
Plutonium balance per cycle :		**+ 51.5 kg** **+ 15.3 kg/TWhe**	**+ 38.6 kg** **+ 12.2 kg/TWhe**	**- 169.3 kg(-72.5%)** **- 95.5 kg/TWhe**
Minor actinides balance per cycle :	Np	**+ 4.3 kg** **+ 1.2 kg/TWhe**	**+ 3.4 kg** **+ 1.1 kg/TWhe**	**+ 3 g** **+ 1.7 g/TWhe**
	Am	**+ 3.5 kg** **+ 1.1 kg/TWhe**	**+ 2.4 kg** **+ 0.8 kg/TWhe**	**+ 7.3 kg** **+ 4.1 kg/TWhe**
	Cm	**+ 0.3 kg** **+ 89 g/TWhe**	**+ 150 g** **+ 47 g/TWhe**	**+ 0.5 kg** **+ 0.3 kg/TWhe**
	Th		**- 50.4 kg** **- 17.2 kg/TWhe**	
	Pa231		**+ 9.2 g** **+ 3 g/TWhe**	
	Total : Np+Am+Cm	**+ 8.1 kg** **+ 2.3 kg/TWhe**	**+ 6.1 kg** **+ 1.9 kg/TWhe**	**+ 7.8 kg** **+ 4.4 kg/TWhe**
Np+Am+Cm in % of the consume matter		*2.2 %*	*2.3 %*	*4.6 %*

Table III gathers the results obtained for the plutonium fuels. What should be established at the very outset is that ^{240}Pu appears especially as a fertile material. The higher conversion process existing inside this type of core implies that a great part of the initial plutonium loaded in the reactor core is burnt (between 55 and 72 %). The conversion level of each fuel is underscored by the comparison between the %FIFA and the residual plutonium enrichment. Up to 98 % FIFA can be reached and the fraction of the heavy metal used ranges from 44 to 70 % FIMA.

Table III. Plutonium fuel cycles characteristics (core power density of 6.6 MW/m^3)

Fuel cycles	PuW	Pu1	Pu1#	Pu2	Pu3	Pu4	Mox1	Mox2
Fuel core loading (kg)	701	701	1200	1200	1200	1200	1200	1200
Fuel element loading (g)	727,51	727.51	1245.38	1245.38	1245.38	1245.38	1245.38	1245.38
compact fuel volume fraction (%)	*14.0*	*14.0*	*22.5*	*22.5*	*22.5*	*22.5*	*22.5*	*22.5*
Type of burnable poison	natural Er_2O_3	natural Er_2O_3	no erbium	no erbium	no erbium	no erbium	no erbium	no erbium
Burnable poison loading (sdt elem)	441 g	50 g						
compact poison volume fraction (%)	*22.56*	*2.56*						
Fuel power density (W/g)	855.9	855.9	500.0	500.0	500.0	500.0	500.0	500.0
Neutron flux (BOC/EOC in 10^{14}n/cm^2/s)	2,023 / 2,163	1,83 / 2,04	1,774 / 1,881	1,793 / 1,908	1,796 / 1,914	1,826 / 1,927	1,827 / 1,923	1,867 / 1,936
Std element peak power (BOC/EOC)	1,146 / 1,131	1,154 / 1,131	1,112 / 1,088	1,110 / 1,086	1,110 / 1,088	1,109 / 1,084	1,107 / 1,085	1,105 / 1,087
Equilibrium cycle length EFPD	260	223	406	384	377	370	356	287
Fraction of core refueled per cycle	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3
Average discharged fuel burnup (GWd/t)	668	572.8	609.0	576.0	566.5	555	535.0	431.5
% FIFA	*73.0*	*89.2*	*95.3*	*95.3*	*93.6*	*98.2*	*98.5*	*89.0*
% FIMA	*69.1*	*59.0*	*63.1*	*59.7*	*58.7*	*57.4*	*55.3*	*44.6*
Particles average fluence# (E_n > 0.18 MeV)	3.2 n/kb	2.72 n/kb	4.94 n/kb	4.67 n/kb	4.60 n/kb	4.51 n/kb	4.34 n/kb	3.51 n/kb
Plutonium balance per cycle :	**- 169.3 kg**	**- 151.7 kg**	**- 283.3 kg**	**- 271.3 kg**	**- 269.1 kg**	**- 266.1 kg**	**- 259.9 kg**	**- 218.9 kg**
	-72.5%	-65.7%	-71.7%	-68.7%	-68.1%	- 67.2 %	-65.7%	-55.5%
(kg/TWhe)	**- 95.5**	**- 99.8**	**- 102.4**	**- 103.7**	**- 104.5**	**- 105.5**	**- 106.9**	**- 111.7**
Residual enrichment (Pu_f/Pu_{tot} at the EOL)	54.7 %	31.2 %	35.9 %	35.7 %	36 %	35.6 %	34.9 %	36.6 %
Minor actinides balance per cycle : Am	+ 7.3 kg	+ 10.6 kg	+ 21.2 kg	+ 22.5 kg	+ 23.8 kg	+ 25.4 kg	+ 27.3 kg	+ 30.4 kg
(kg/TWhe)	+ 4.1	+ 7.1	+ 7.7	+ 8.6	+ 9.2	+ 10.0	+ 11.2	+ 15.5
Cm	+ 0.5 kg	+ 3.1 kg	+ 9.8 kg	+ 9.9 kg	+ 10.4 kg	+ 10.9 kg	+ 11.2 kg	+ 10.0 kg
(kg/TWhe)	+ 0.3	+ 2	+ 3.5	+ 3.8	+ 4.1	+ 4.3	+ 4.6	+ 5.0
Total M.A. : Np+Am+Cm	+ 7.8 kg	+ 13.8 kg	+ 31.0 kg	+ 32.3 kg	+ 34.2 kg	+ 36.3 kg	+ 38.5 kg	+ 40.4 kg
(kg/TWhe)	+ 4.4	+ 9.1	+ 11.2	+ 12.3	+ 13.3	+ 14.4	+ 15.8	+ 20.6
M.A. in % of the initial metal burnt	*4.6 %*	*9.1 %*	*10.9 %*	*11.9 %*	*12.7 %*	*13.6%*	*14.8 %*	*18.4 %*

the maximum fluence can be estimated by taking into account a core peak power in the order of 2.4 multiply by the element peak power mentioned above.

Besides, the reactivity swings presented in Figure 4 are significantly smaller for the reactor grade plutonium than those observed for the weapon grade plutonium. In fact, the greater the fertile isotopes content, the smaller the criticality swing, because of the high conversion process.

Therefore, the reactor grade plutonium might not necessitate additional poison if its initial mass was adjusted. This is illustrated by the *PU1* cycle envisaged with two different masses of fuel fed in the core. A very flat curve of the k_{eff} evolution is observed for the highest load case and permit much more longer cycle lengths. A once through management scheme could even be envisaged if adequate means were used to minimise the radial peak power at the core-reflector interface (fuel managed on a three-batch basis allows to soften annular-radial power distribution by placing irradiated fuel near the reflector).

It is noteworthy that second generation plutonium can also be used as fuel in the GT-MHR but leads, unfortunately, to a higher minor actinide level of production due to the important ^{242}Pu initial concentration. Finally, the HTGR seems to be a good candidate to use all type of plutonium and then could reduce the plutonium stockpiles.

4.3 - Residual decay heat results

Figure 8 and 9 describes for various types of fuel the evolution over 100 days of the residual power of a the GTMHR-600 MWth after a reactor shutdown arisen at the end of cycle.

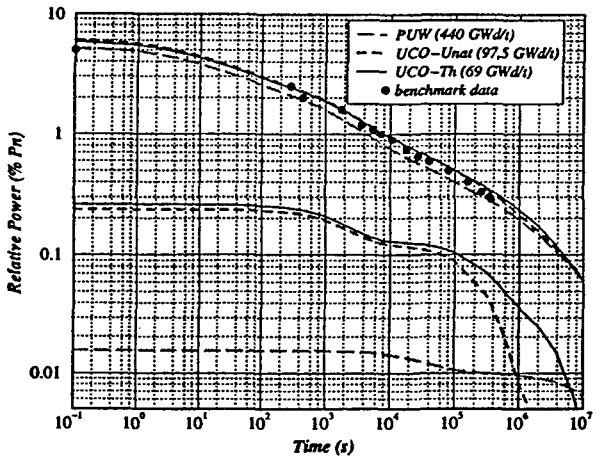

Figure 8 : Decay heat evolution (heavy nuclei and total) for the *PUW* and Uranium fuels.

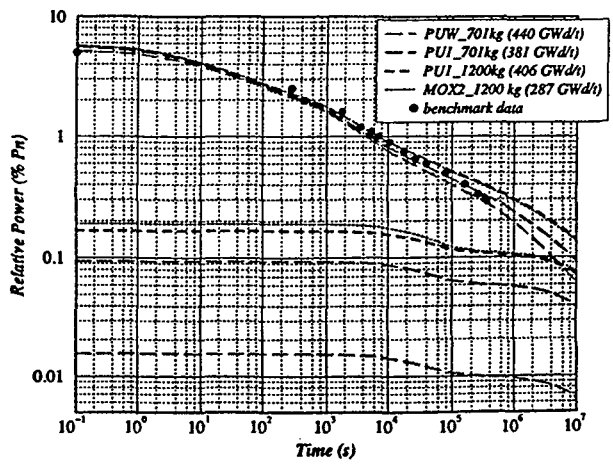

Figure 9 : Decay heat evolution (heavy nuclei and total) for different plutonium fuels.

The residual power obtained in the cases of the uranium fuels are very similar (Fig. 8). For the first 100 hours, the high heavy nuclei heat source resulting essentially from beta emission of ^{239}Np and ^{239}U on the one hand and, on the other hand, the high fission product afterheat (total energy generated during one cycle greater in the case of the uranium fuel) leads to a total residual power greater (10-20%) than for the *PUW* fuel.

On the Figures 8 and 9 are also indicated the power values used for the last calculational benchmark aiming at estimating the fuel and vessel maximum temperatures achieved during a thermal transient following the LOFC major accident [5]. These values appear slightly conservative compared to the *PUW* rundown curves observed on Figure 8 and obtained for identical cycle length and fuel type. One of the essential characteristics of the *PUW* fuel is the low heavy nuclei residual heat due to the small initial amount of ^{240}Pu which therefore did not produce a significant amount of actinides. In spite of the high operating power density of the *PUW* fuel, the total residual power remains lower (10 to 20 %) than the one of the uranium fuel with a cycle length almost two times longer.

When other plutonium isotopic compositions are taken into account (Fig. 9), the higher amount of minor actinides created, generates a higher heat source of radiation decay of the heavy nuclei. In particular, a factor 2 between the *PU1* and the *MOX2* on the quantity of ^{242}Pu (yielding the strong alpha emitter ^{242}Cm) and ^{238}Pu, leads to a greater actinides residual power level for the MOX2.

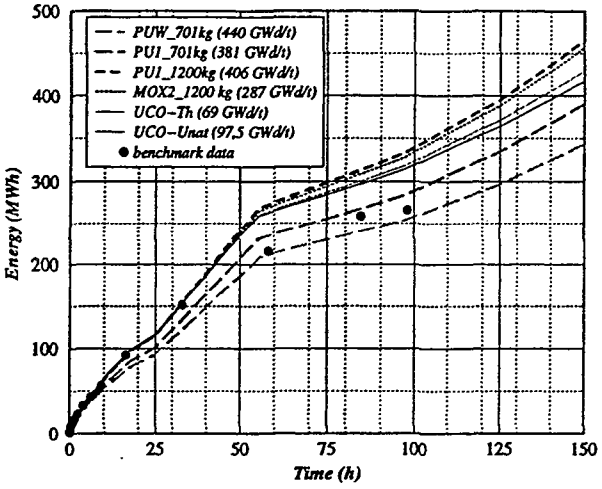

Figure 10 : Energy stored in the core after the reactor shutdown

Figure 10 opposite shows detailed evolution of the stored energy during a typical length of time of the LOFC accident. The maximum difference achieved between all the examined fuels is on the order of 30 % (100 h). This values should of course have a significant impact on the maximum temperature reached by the fuel in the course of the accident. Independently of the fuel performances, only a sensitivity study of the GT-MHR to the residual power, taking into account the radial power profile in the annular core, will permit to define the acceptable limits to recycle highly degraded plutonium fuel. Finally, it should be stressed that an increase of the fuel loading (*PU1* case) induces directly a growth of the energy deposited in the core and limits therefore the possibility to adjust the initial mass of fuel.

5. CONCLUDING REMARKS

This paper is a part of a much more general and exhaustive study which is aimed at assessing the potential application of several fuels in the HTGR providing long cycle lengths. Starting from fuel cycles previously studied, a calculation method dedicated to a parametric analysis, has been set up to evaluate the evolution of the reactor core reactivity during the fuel depletion. The core modelling takes into account particular features of the HTGR such as the double geometric heterogeneity and neutron leakage evolution in the annular core.

The first results obtained with a wide spectrum of plutonium isotopic compositions prove HTGR potentials to use the plutonium as fuel without generating large amounts of minor actinide and respecting the same high level of safety. If the very high burnups reached by fuel particles were confirmed, the GT-MHR would be a good candidate to burn economically all type of plutonium. Providing energy, this option could therefore reduce the plutonium stockpiles.

Long cycles are possible if burnups as high as 700 GWd/t and fluences in the order of 12 n/kb (a factor 2 with the common requirements) sustained by the fuel particles are technologically feasible. Nevertheless, more detailed core neutronic analysis are necessary to assess the reactivity control aspects, the temperature coefficients, neutronic core stability... These additional analyses should also permit to define the appropriate fuel management and to answer the power distributions related issues especially important in the case of the plutonium use. Only such an effort will allow to conclude on the feasibility to have in an HTGR long plutonium cycles greater than three years.

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REFERENCES

[1] A.I. Kiryushin, N.G. Kodochigov, N.G. Kouzavkov, N.N. Ponomarev-Stepnoi E.S. Gloushkov, V.N. Grebennik - Project of the GT-MHR high-temperature helium reactor with gas turbine - Nuclear Engineering and Design 173, 119-129 (1997)

[2] R. Sanchez, J. Mondot, Z. Stankovski, and I. Zmijarevic - APOLLO2: a user-oriented, portable modular code for multigroup assembly calculations - International conference on development of reactor physics and calculation methods - Paris - (April 87)

[3] A. Tsilanizara, B. Nimal, C. Garzenne, P. Marimbeau, V. Allais, C. Monier - The Darwin fuel cycle package - Procedures for material balance calculation and qualification. ENC'98 - Nice, France (1998)

[4] J. Tommasi, A. Puill and Y.K. Lee - Use of thorium based fuels in thermal and fast reactors - International Conference on Future Nuclear System - Global'97 Vol.1 p 308

[5] Benchmark solution for CRP-3 GT-MHR-PU Heatup Accidents IAEA report in preparation

[6] D. Alberstein, W. Simom - The Plutonium Consumption Modular Helium Reactor (PC-MHR) - IAEA Technical Commitee Meeting - (nov. 1994).

[7] C. Hamilton, A. Baxter - The MHTGR- Maximum Plutonium Destruction without Recycle - General Atomics Project 9866 - (July 1993).

[8] J. van GEEL, Hj. Matzke and J. Magill - Bury or Burn ? Plutonium - the next nuclear challenge - Nuclear Energy - (Aug 1997).

[9] C. Lombardi, A. Mazzola and M. Ricotti - Analyis of a Pu-Th fuel cycle for the reduction of the plutonium stockpiles - 5th international Conference on Nuclear Engineering, Nice, France (1997)