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Document Title

Studies on LWR-HTR Symbiotic Fuel Cycle

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1. Introduction

Work Packages 3 of the <<HTR-N>> and <<HTR-N1>> contracts[17,18] are concerned with the assessment of the performance of fuel types in different reactor systems to be investigated with respect to Pu-incineration capabilities, economics and safety, with emphasis on Pu-incineration. This work represents UNIPI contribution to the task N1/3.3 (Strategic study on LWR/HTR symbiosis).
Gas Cooled Reactors were the first ones to be used at the beginning of the nuclear era[1].
The basis of the modern fuel element of this kind of reactors is the coated particle (TRISO CP) which allows a long technological burnup. Therefore it is possible to use self breeding fuel as U-Th, obtaining a reduction of the fuel cost. However, it is important to highlight that HTRs, actually candidate to be a solution to worldwide energetic problem, have, among the others (e.g. high efficiency, safety, hydrogen production, etc.), the positive capability to be particularly able to burn Pu[16]. Their very long (*ultra high*) burnup seems to allow the minimisation and an easier management and disposal of radioactive waste.
These are key issues for the present and future use of nuclear energy. Actual reprocessing of LWR spent fuel and a first recycling as mixed oxide (MOX) fuel in LWR already contribute to a reduction of waste volumes and radiotoxicity. But symbiotic fuel cycles of LWR and HTR can reach much better these performances. It happens because of the specific features of HTRs cores among which it should be highlight the ability to accommodate a wide variety of mixtures of fissile and fertile materials without any significant modification of the core design[19]. Finally, due to the much lower parasitic capture rate in the moderator, the neutron economy of HTRs is better than that of LWRs. The much larger thermalisation length leads also to an epi-thermal neutron spectrum with considerable fast flux contributions. All these capabilities (among which the ultra high burnup is the most important) allow the almost complete burning of Pu minimizing the waste radiotoxicity.
The demonstration of the capability to reach this goal is the subject of this document.

2. Model

Depending on the core structure, present HTRs can be divided into two main classes:

- Block-type
- Pebble-bed

Since the pebble-bed allows on-line refuelling (without the necessity of using control rods and burnable poisons), this kind of reactor was chosen. For this reason it was necessary to model a pebble-bed. In order to have preliminary indications, in this stage a single pebble in an infinite lattice (white boundary conditions) was considered. The used geometry is represented in fig 1.

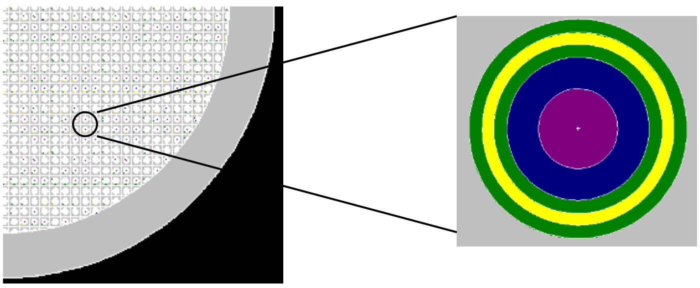

Figure 1 – Cross section of a sector of pebble and of a CP

3. MONTEBURNS and CARL codes

To perform these calculations, we used an original chain of codes, i. e. MONTEBURNS[2] and CARL2 (CAlculation of Radiotoxicities Lifetime version 2)[3].
MONTEBURNS couples MCNP[4] and ORIGEN[5] codes through MONTEB utility and a PERL[6] procedure. By means of this code, we are able to evaluate the values of criticality factor vs. burnup and the final isotopic composition of spent fuel[7]. We had benchmarked this code, with good results, in an international exercise (in the frame of HTR-N1 EC project) on a pebble-bed HTR using Pu-based fuel[8].
The "radiotoxicity" of a radionuclide is the potential capability to induce harmful effects to living tissues as a result of inhalation or ingestion. Its value varies with the nuclide, depending on the nature and energy of emitted radiations, the physical and biological half-life and the radiosensitivity of the organ interested (or of the whole body).
In order to evaluate radiotoxicity time evolution of a mixture of nuclides, we developed the original code CARL. The former version of the code[9] was developed in *MathCAD®* environment, but recently we improved this code obtaining an enhanced version, CARL2, in *Matlab®* environment. By solving a set of Bateman's equations, CARL2 evaluates the isotopic decay and it determines the activity, the radiotoxicity (taking the dose factors from the ICRP database[9]), various radionuclides contributions, decay power, integrated dose, and gamma rays spectrum (for spent fuel disposal applications) vs. time. The masses (in grams) of the different nuclides (uranium, plutonium, thorium, neptunium, americium, curium, and some fission products), obtained from a neutronic code, are required as input data. As output, the code calculates the radiotoxic inventories (in sieverts) vs. time, and plots them in different graphs. The nuclides taken into account for our calculations are those considered more dangerous because of their (and of their daughters) very long half-lives and radiotoxicities.

4. Calculations

In order to demonstrate the capability of HTRs to contribute in reducing nuclear waste (actinides in particular), it was decided to analyse Pu-based fuel[20]. It was assumed to discharge the fuel when k_∞ is still greater than unit (~1.05).
Particularly, 1st generation Pu[8] (i.e. Pu deriving from reprocessing typical LWR spent fuel) and 2nd generation Pu[8] (i.e. Pu deriving from the reprocessing of typical MOX spent fuel) were considered[7]. Finally, Pu-Th mixed fuel was also studied, in order to improve fuel exploitation[10]. Therefore the following cases were considered[11]:

- HTR loaded with 1g/pebble 1st generation Pu (Fg-Pu)
- HTR loaded with 1.5g/pebble 2nd generation Pu (Sg-Pu)
- HTR loaded with 50% (1.5g/pebble) Fg-Pu plus 50% Th
- HTR loaded with 33% (1g/pebble) Fg-Pu plus 67% Th
- HTR loaded with 25% (0.75g/pebble) Fg-Pu Pu plus 75% Th

To check the advantages in using different fuel cycles, we mainly took into account the radiotoxicity evolution of the spent fuel vs. time. As reference for radiotoxicity, we defined[9] the *LOMBT (Level Of Mine Balancing Time)* as the time (years) necessary for the radiotoxicity of the exhausted fuel to return to the same value of the amount of the mineral extracted from the mine (natural U) that generates the used fuel, i. e. the *LOM (Level Of Mine)*. This value is linked to the type of fuel cycle and not fixed (due to its oscillation range). However, in this paper , we adopt the LOM as a conceptual reference level.

5. Results

In table 1 the obtained results are summarized. In column 7 the ratio between inlet and outlet transuranic elements (Pu+MA) and in column 8 the ratio between inlet and outlet actinides (Th+U+Pu+MA) are shown.
In the case of LWRs spent fuel, the LOMBT is about 250000 years[12]. From table 1 we can see that this figure of merit (the most important in terms of safety) is significantly reduced (an order of magnitude) using HTR (to make a comparison, Yucca Mountain waste repository is designed for a minimum of 10000 years).

Case 1	Fuel 2	Pu_{in} [g] 3	LOMBT [y] 4	Energy $\left[\frac{GJ}{g_{Pu}}\right]$ 5	$\frac{Pu_{out}}{Pu_{in}}$ 6	$\frac{TRU_{out}}{Pu_{in}}$ 7	$\frac{Act_{out}}{Act_{in}}$ 8
a	Fg-Pu	1	37547	51.84	32.9%	37.6%	37.6%
b	Sg-Pu	1.5	49510	37.15	46.4%	54.9%	54.9%
c	Fg-Pu/Th (1/1)	1.5	37982	60.16	24.1%	31.8%	63.9%
d	Fg-Pu/Th (1/2)	1	37547	59.40	27.8%	33.9%	76.3%
e	Fg-Pu/Th (1/3)	0.75	37117	58.89	29.1%	34.4%	81.9%

Table 1 – Summary of the obtained results

6. Conclusions

This work represents a contribution to the studies on waste reduction problem.
In fact from the results we can see that HTRs reduce waste radiotoxicity of an order of magnitude burning Pu and supplying energy. Adopting Th-Pu based cycle, it appears that, in the case c (Th/Pu 1/1), the total amount of produced energy is larger than in the other cases. Also in terms of TRU destruction, the behaviour of case c seems to be the best. The LOMBTs in the cases a, c, d, e are substantially the same while it is quite higher in the case b.
As a first improvement, calculations on a whole core (using the real k_{eff} for 3D geometrical shape) should have to be made. In fact, at the moment, only k_{∞} calculations were performed for HTR (even if the whole pebble was realistically represented). At the same time, it is necessary to highlight that a correct definition of the *LOM* is very important in order to state realistic constraints for the waste repository. Of course the total amount of waste has to be taken into account, too. However, at the end of the work it was demonstrated that the use of HTRs can reduce the actinides in exhaust fuel.
As already theoretically indicated[13,14,15], it was also confirmed that a high neutron flux and fluence are necessary, in order to reduce some MA (e.g. ^{244}Cm). Therefore the use of GCFRs with high neutron flux for an adequately long period of time could be an interesting solution to be investigated.

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