Synergy between Fast Reactors and Thermal Breeders for Safe, Clean, and Sustainable Nuclear Power

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Abstract: *This paper proposes a new approach to nuclear power to achieve a sustainable nuclear future in which the transuranic elements or TRUs (neptunium, plutonium and americium) from today's nuclear waste are burned in safe fast reactors such as lead-cooled fast systems. These breed, at the same time,* ^{233}*U for use in thermal breeder reactors that are based on the thorium-uranium cycle. Since thermal breeders require a much smaller fissile mass than fast reactors, one fast reactor can generate during its lifetime a considerable number of critical masses needed to start up new thermal breeders. With regard to the use of* ^{233}*U/thorium, this approach is similar to the one pursued by India, the difference being that existing and continuously generated nuclear TRU waste is burned as well.*

1. Introduction

The availability of conventional uranium resources is limited to 14.8 million tonnes, according to the recently released OECD/IAEA study [1]. This is enough to sustain nuclear energy for more than 250 years at current electricity generation levels. However, the demand for fissile material is projected to increase, given the forecast growth in nuclear power capacity by a factor of four by 2050 [2]. To sustain this increase, a large number of fast breeders would be needed in 30-40 years. However, bearing in mind the burning of minor actinide (MA) waste (americium, neptunium) and breeding plutonium to feed future fast reactors, the doubling times for breeding enough fuel to start these additional fast reactors are too long (15-30 years). Furthermore, in many OECD countries the use of plutonium is not well thought of, whereas the ^{233}U/thorium cycle may be more acceptable. What is more, thorium is about 3 to 4 times more abundant in the Earth's crust than uranium.

The initial ^{233}U could be produced, and at the same time no minor actinides would be generated, if thermal, water-cooled reactors used ^{235}U/thorium fuel. However, the timing for starting these light-water reactors (LWRs) with thorium matrix fuels will depend on the amount of plutonium available in spent LWR fuel (“nuclear waste”) and needed to fuel fast reactors for burning the minor actinide waste and to breed ^{233}U. Note that just a few sub-assemblies with ThO_2 could also be placed in LWR cores to generate the initial ^{233}U [3]. The main problem with the near-term use of thorium in reactors, however, is the lack of industrial-scale thorium fuel reprocessing. The basic THOREX process is well known, and India (Bhabha Atomic Research Centre) is working on a larger-scale facility.

In this study, we show that transuranic elements (TRUs) can be burned and ^{233}U bred in a 600 MW_e lead-cooled fast reactor (LFR). This LFR design is one of the variants in the European Lead-Cooled System (ELSY) Strategic Targeted Research Project (STREP), an ongoing project within the 6th Framework Programme of the European Commission. In this paper, a 2m tall core of some 4m diameter for the $(Th,TRU)O_2$-fuelled core and 6m for the larger $(Th,Pu)O_2$-fuelled core are considered. The Monte Carlo burn-up code MCB [4] was used for performing the calculations.

2. Results

In Table 1, the first case relating to (Th,TRU)O_2-fuelled LFR shows one of the most significant aspects dealt with in this paper: a sizeable quantity of minor actinides are consumed – equal to the amount generated in 1.5 European Pressurised Reactors (EPRs) per year. Also, the amount of ^{233}U generated is sizeable – in 2.7 years enough is bred to start a new thermal 300 MW_e Advanced Heavy Water Reactor (AHWR) [5] (see also Section 3). The AHWR itself is designed to be a self-breeder, i.e. it breeds enough fissile material (^{233}U) to sustain its own consumption. According to Bergelson et al. [6] heavy-water cooled CANDUs using ^{233}U/thorium fuel can also be self-breeders.

Table 1: Amount of annually transmuted transuranics and generated ^{233}U in LFR burners/breeders. The figures correspond to a 4-yr average of the start-up cycle. In the spent fuel, all ^{242}Cm was assumed to decay to ^{238}Pu.

System	**Actinide mass (tonnes)**	**Average TRU enrichment (at%)**	**^{233}U generated (kg/y)**	**Pu consumed (kg/y)**	**MA consumed/ generated (kg/y)**
Burner / Breeder (Th,TRU)O_2	35.48	29.5	+225	–320	–80
Burner / Breeder (Th,Pu)O_2	39.91	22.0	+303	–407	+32
Burner / Breeder (Th,Pu)O_2	103.4	20.0	+382	–472	+55

In the two other cases given in Table 1, we tried to show that even more ^{233}U could be generated, albeit at the cost of generating additional minor actinides. But if a temporary need arose for a large amount of ^{233}U, these options might be useful. However, in this case, it seems to be better to generate ^{233}U by using ^{235}U/Th-fuelled thermal reactors. Also, if lead-cooled reactors do not become available soon enough, or if their development comes up against technological problems, there are already sodium-cooled fast reactors available, and new ones may become still safer and more economic.

The burn-up reactivity swing of a (Th,TRU)O_2-fuelled LFR breeder/burner is set out in Fig. 1.

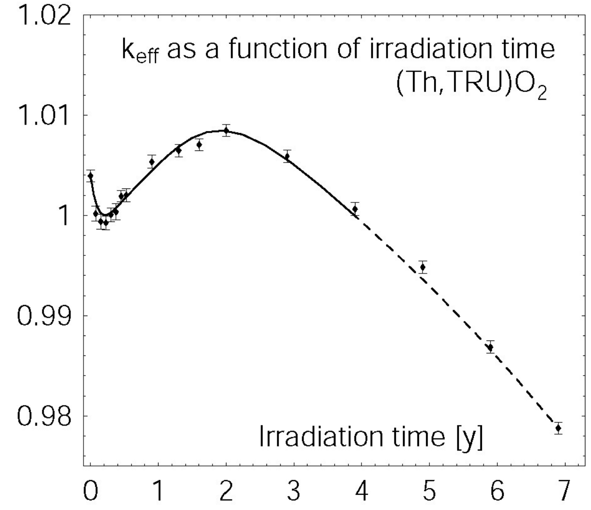

Fig. 1: Burn-up behaviour of a (Th,TRU)O_2-fuelled 600 MW_e LFR showing a reactivity swing allowing a 4-year fuel residence time. Larger and lower enriched cores will show an even lower reactivity swing, but at the cost of reprocessing a larger amount of fuel.

The burn-up behaviour of the larger $(Th,Pu)O_2$-fuelled LFR core is shown in Fig. 2. It confirms that a larger and lower enriched core has a better burn-up swing.

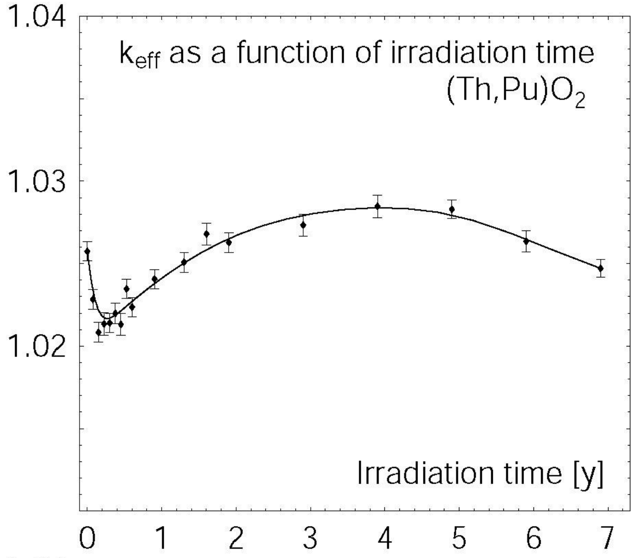

Fig. 2: The excellent reactivity swing in the large $(Th,Pu)O_2$-fuelled 600 MW_e LFR core with lower ^{233}U enrichment (20 at%). Actinide mass at beginning-of-life is 103.4 tonnes.

It should also be mentioned here that the calculations shown in this paper require moderating pins that keep the spectrum softer so that the negative Doppler reactivity feedback for a fuel heat-up of 100 K is higher than the positive coolant temperature reactivity coefficient per 100 K of coolant heat-up [7]. This is particularly important in cores with a sizeable amount of minor actinides such as the $(Th,TRU)O_2$-fuelled LFR core with 5% MAs in the actinide vector (Th+Pu+MAs) of start-up fuel. Therefore, this case requires 16 CaH_2 pins per sub-assembly, whereas the $(Th,Pu)O_2$-fuelled core needs only 9 such moderating pins. More details about these waste-burning calculations are given in [8]. Details of the calculations with thorium matrix fuels are available in the published ICAPP'07 paper by the same authors [9].

3. Advanced Heavy Water Reactor

The construction of the Advanced Heavy Water Reactor has already started (Fig. 3). The AHWR is like a vertical CANDU including also on-power refuelling. Like the new CANDU design (Advanced CANDU Reactor, ACR) it uses light water in the fuel channels, but the water is boiling and driven only by gravity. The main difference, however, is the use of thorium-based fuel. Apparently, due to the current lack of ^{233}U, both ^{233}U/Th and Pu/Th pins are to be used in the initial cycles.

The key aspect lies in the following statement by the Bhabha Atomic Research Centre (BARC): "The AHWR fuel cycle will be self-sufficient in ^{233}U after initial loading. The spent fuel streams will be reprocessed and thorium and ^{233}U will then be recycled and reused. There are also plans to recycle the actinides back into the reactor". This means that this is a 300 MW_e self-breeder that has a critical mass of only about 600 kg of ^{233}U [5,10,11,12].

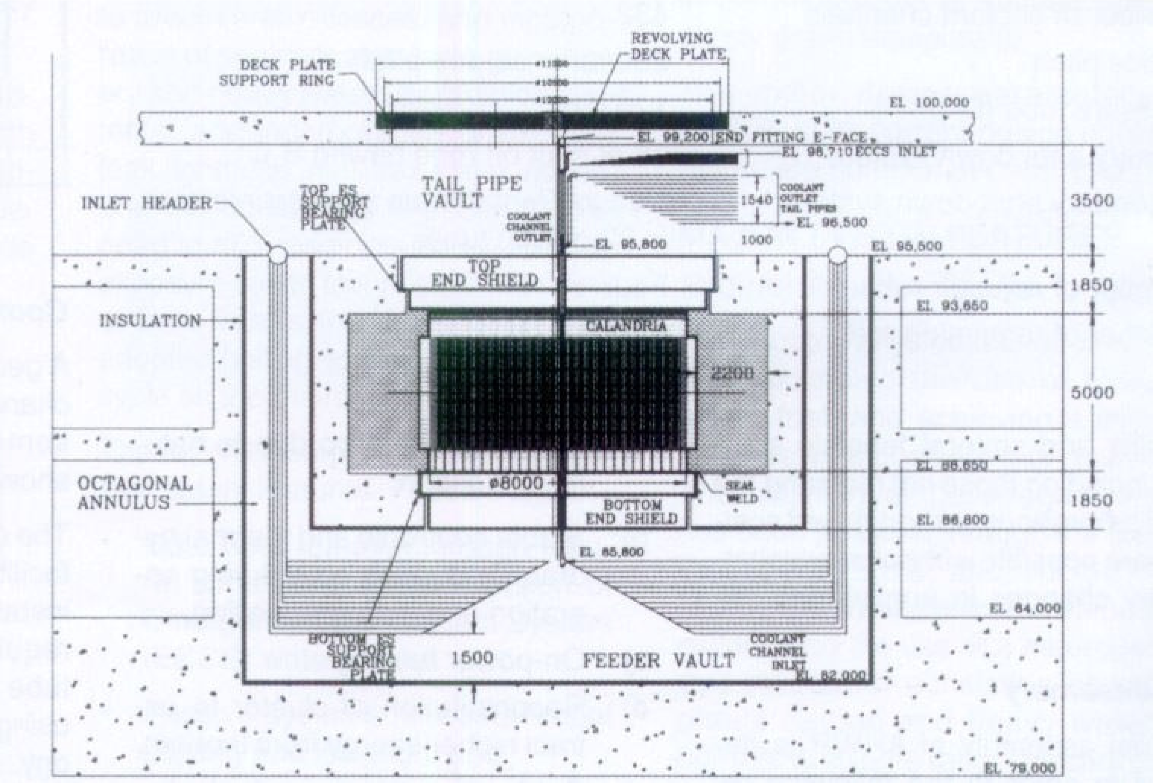

Fig. 3: A view of the Advanced Heavy Water Reactor (AHWR) core, vessel and its internals including the shielding and the array of feedwater-pipes for each fuel channel [11].

4. Conclusions

As indicated above, a 600 MW_e LFR could in 27 years generate critical masses necessary for starting up ten new 300 MW_e AHWRs. This means in 54 years 20 critical masses, leading to a corresponding total AHWR capacity of 6000 MW_e. On the other hand, if the LFR had during that time (54 years) bred an additional 2-3 critical plutonium masses, the result would be no more than 1800-2400 MW_e of installed LFR capacity. Therefore, thermal breeders such as the AHWR, a heavy water-cooled CANDU and even a thermal molten salt breeder reactor would considerably boost long-term nuclear sustainability and would also get us into the cleaner thorium-uranium cycle. The other advantage would also be the potentially larger reserves of thorium, which are also reasonably well distributed in the world. Australia, India, Norway, USA, Canada, South Africa and Brazil have about 90% of known thorium reserves. With the proposed new approach, we would additionally burn existing nuclear waste (plutonium and minor actinides from spent nuclear fuel) and convert it to energy.

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