International Conference
Nuclear Energy for New Europe 2007
Portorož /Slovenia /September 10-13

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PORT2007, Nuclear Society of Slovenia, Jamova 39, SI-1000 Ljubljana, Slovenia

Potential for the Near-Term Use of the Thorium Cycle in a Sustainable Way

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ABSTRACT

Nuclear sustainability is generally believed to be only reachable through the building of many fast breeder reactors. This paper shows that there is another possibility by using existing reactors that are either thermal breeders or have at least a high conversion ratio and considerably smaller critical masses than fast systems. Earlier it was believed that thermal molten salt breeders could eventually use the thorium / 233U cycle, which doesn't generate minor actinides and is therefore a cleaner fuel cycle. In the meantime, it has become rather clear that CANDU reactors that use heavy water cooling can also be self-breeders. The CANDU reactors could generate themselves 233U in thorium targets and could become self-sustaining after 12 years. However, additional 233U could also be generated in LWRs and fast reactors. It is shown that this generation of 233U will allow a faster large-term nuclear expansion than fast reactors alone. There could actually be a synergy between thermal and fast breeders if the latter are run with Pu/Minor Actinides/Th fuel, which burns the minor actinides and generates sizeable amounts of 233U. The main problem is still the necessary reprocessing on which India is working and intends to have in 10 years a large scale reprocessing facility available. However, there is at least an existing method for removing the 233U by the fluoride volatility method and to further use it in CANDUs. For the preparation of the use of 233U, we should attempt to run thorium subassemblies in CANDUs, LWRs, and fast reactors. Besides breeding 233U or at least having a high conversion ratio, CANDUs have the further advantage that they don't need a pressure vessel and therefore could be built in large numbers faster than LWRs.

1 INTRODUCTION

In times of increasing uranium prices and concerns about minor actinides in the nuclear waste, the thorium / ^{233}U fuel cycle would be quite attractive. Moreover, it could be important for a large nuclear build-up. But how could it be used in a sustainable way before we have Molten Salt Breeder reactors running? The first indication that this is possible was actually presented at one of the previous conferences "Nuclear Energy for New Europe" in 2005. The paper was called "Thorium Self-Sufficient Fuel Cycle of CANDU Power Reactor" (Ref. 1).

These calculations showed that a heavy water-cooled CANDU reactor could be a self-breeder. In the meantime, Canadian colleagues from the AECL have confirmed that CANDUs employing heavy water cooling and the ^{233}U/Th cycle can breed. The Indian Advanced Heavy Water Reactor will generate much of its energy from ^{233}U and will also be self-sustaining regarding this uranium isotope. But, it will also need some plutonium fuel due to the use of light water cooling that absorbs a reasonable amount of neutrons. In Ref. 1, it is suggested that the ^{233}U can be self-generated in a CANDU reactor by operating the reactor using enriched uranium or LWR plutonium as fuel and also containing thorium rods for the generation of ^{233}U. To produce whole core load of self-breeding CANDU will take about 12 years since the average ^{233}U content in ThO_2 rods has to be about 1.3% (which is the lower limit for self-breeding in CANDUs).

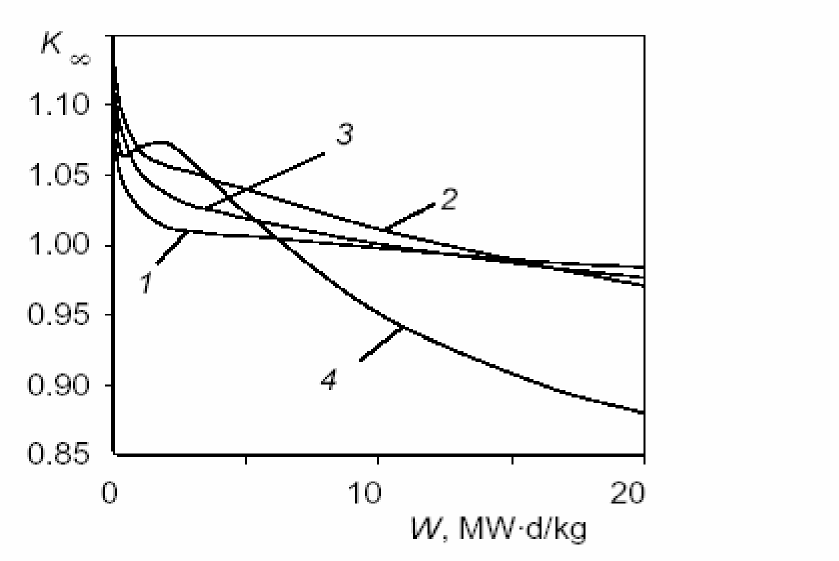

Fig. 1: Burn-up histories for different CANDU loadings: 1-3 depict different arrangements of ^{233}U in a CANDU channel. Nr. 4 is the normal CANDU loading with natural uranium. Since a CANDU has many channels, the k_∞ of a cell calculation is rather close to k_{eff} – probably the ^{233}U enrichments will have to be increased somewhat relative to the Ref. 1 calculations.

But one can also accelerate the generation of ^{233}U by producing it in light water reactors and later in fast reactors. This generation of ^{233}U in LWRs or fast reactors will be discussed in some detail in this paper. It will also be discussed in some detail how fast breeders could become important generators of ^{233}U in a large nuclear expansion if they used a thorium matrix based fuel.

One approach to generate ^{233}U in LWRs is the use of a Pu/Th fuel, which is described in Ref. 2. This reference shows that about 300 kg of ^{233}U can be generated per year in a 900 MWe PWR. Although this Pu/Th fuel has been tested in single pin experiments, it is not a standard fuel and one also degrades the quality of the plutonium vector, which is afterwards not well suited for the subsequent use in fast breeders. But, one could start one CANDU-900 self-breeder with 880 MWe in 5 years. In 30 years, one could start 6 CANDU-900 self-breeders. 300 LWRs with Th/Pu fuel could start in 30 years 1800 CANDU self-breeders with a total of ~1580 GWe – however, we would run out of plutonium after running about half about of them.

2 METHOD AND RESULTS

In this study, we have investigated another strategy, which would not degrade the plutonium quality and would also need a less complex fuel. We replaced in an LWR 32.1% of the pins *or* 29.9% of the entire subassemblies with pure ThO_2 rods and calculated with our Monte Carlo burn-up calculation MCB (Ref. 3) that about 300 - 350 kgs of ^{233}U can be generated in 5 years (see Table 1 below) or even better 240 kgs after 2 years. So in 12.5 years, we could start 1 CANDU-900 and in 30 years 2.4 CANDU-900. With 350 LWRs we could start 840 CANDU-900 or ~740 MWe in 30 years. Of course the more LWRs came on line the more CANDUs we could start. A certain disadvantage would be that the LWR fuel would have to be enriched to 4.5% instead of the regular 3.5-3.7 %. If we also used a sizeable amount of the existing 5000 tons of plutonium by 2030, we could probably generate 1500 GWe or nearly 4 times the existing amount of nuclear power.

Table 1: Generating ^{233}U in LWR either in different pins or different subassemblies.

DESIGN	ThO_2	UO_2	ThO_2/ (ThO_2+UO_2)	1 year burn-up			5 year burn-up		
				U-232 [g]	U-233 [g]	U-232/U-233 [ppm]	U-232 [g]	U-233 [g]	U-232/U-233 [ppm]
900 MWe PWR, different pins	85 pins	180 pins	32.1%	1.59E+02	1.42E+05	1120	2.14E+03	3.54E+05	6050
900 MWe PWR different SAs	47 SAs	110 SAs	29.9%	8.96E+01	1.36E+05	660	1.47E+03	2.94E+05	5010

The ratio of ^{232}U / ^{233}U is important for non-proliferation aspects – it should be between 1000 and 2000 ppm. Therefore, the thorium pins and assemblies should be in the core for about 2 years.

Table 2: Generating ^{233}U in LWRs either in different pins or subassemblies but with a higher fraction of thorium in the LFR cores

DESIGN	ThO_2	UO_2	ThO_2/ (ThO_2+UO_2)	1 year burn-up			4 year burn-up		
				U-232 [g]	U-233 [g]	U-232/U-233 [ppm]	U-232 [g]	U-233 [g]	U-232/U-233 [ppm]
900 MWe PWR, different pins	117 pins	148 pins	44.2 %	2.89E+02	2.23E+05	1297	2.39E+03	4.58E+05	5231
900 MWe PWR different SAs	63 SAs	94 SAs	40.0 %	9.60E+01	1.70E+05	565	1.41E+03	3.73E+05	3768

To further increase ^{233}U production in LWRs, the number of thorium pins or sub-assemblies with only thorium was increased (Table 2). In the case of the thorium assemblies we would have to run for 2 years to get 300 kgs of ^{233}U and a ^{233}U / ^{233}U of 1200 ppm. Or in 10 years one could get one CANDU-900 going. The disadvantage of this approach is that several driver assemblies have to be replaced by fresh ones in order to keep the LWRs running.

Another important future approach is the use of fast reactors such as the Lead-Cooled Fast Reactors (LFRs) for generating ^{233}U and also for burning minor actinides (Table 3).

Table 3: Generating ^{233}U in fast reactors with (Th,TRU) oxide fuel.

DESIGN	1 year burn-up			5 year burn-up		
	U-232 [g]	U-233 [g]	U-232/U-233 [ppm]	U-232 [g]	U-233 [g]	U-232/U-233 [ppm]
600 MWe LFR, $(Th,TRU)O_2$ fuel, 29.5% TRU/(Th+TRU)	6.59E+02	2.56E+05	271	1.04E+03	1.06E+06	978

The results indicate that we could start every 7.5 years an 880 MWe self-breeder with its critical mass of 1.5 t. In 30 years, we can start 4 times 880 MWe ~ 3500 MWe of CANDU-900 self-breeders. Since the doubling time of an LFR is at least 20 years, we would only get 1200 MWe from two 600 MWe LFRs. This shows clearly that we could increase nuclear power nearly 3 times faster if we use fast reactors to breed ^{233}U and use it in thermal breeders (Ref. 4). This is of course due to the fact that thermal breeders have a considerably lower critical mass due to the higher fission cross sections in the thermal region. This approach would be similar to the Indian plans of a combination of fast reactors and thermal breeders. However, our present approach also burns minor actinides (MAs) – in the case shown above it is 85 kgs of MAs per year. Since an EPR generates around 55 kgs per year we could burn the MAs from more than 1.5 EPRs in addition to breeding ^{233}U.

The burn-up reactivity swing of a 600 MWe $(Th,TRU)O_2$ fuelled LFR breeder/burner reactor is displayed in Fig. 2.

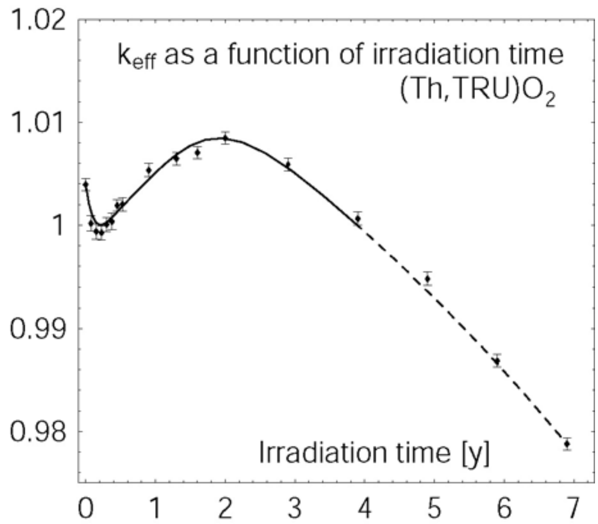

Fig. 2: Burn-up behavior of a 600 MWe $(Th,TRU)O_2$ fuelled LFR that shows a reactivity swing that allows about a 4-year fuel residence time. Larger and lower enriched cores will show an even lower reactivity swing, but at the cost of reprocessing a larger amount of fuel.

A sodium-cooled fast reactor could have a lower doubling time of about 15 years but it can also burn MAs somewhat better than an LFR (Ref. 5). Moreover, there is more experience with SFRs but there are still improvements in the economy and safety aspects needed. But even if it led to 3 times 600 MWe SFRs in 30 years, it would still be less than the ~3500 GWe we could get via thermal breeders.

Regarding CANDUs one could consider the short burn-up of a self-breeder of about 15 GWd/t as a disadvantage. But since CANDUs are designed for fast on-line refueling, this is not a major problem. AECL staff believes that they could get to 30 GWd/t. The more serious problem is the reprocessing of ^{233}U/Th fuel. India is working on the industrial scale reprocessing and we learnt recently from Mr. Sinha (BARC, India) that their large-scale reprocessing efforts should be ready in 10 years. A partial reprocessing of the ^{233}U is possible through the fluoride volatility method that leads to a preferential evaporation of UF_6, which could then be reused together with fresh thorium. The Nuclear Research Institute in Rez in the Czech Republic and Hitachi in Japan have expertise in this type of reprocessing.

A good thermal converter ought to be the Indian Advanced Heavy Reactor (AHWR), which is currently under construction. Different from a heavy-water cooled CANDU reactor the AHWR is cooled by boiling light water. Since it is like a vertical CANDU reactor it works with natural circulation. But it needs always some plutonium to keep the system critical.

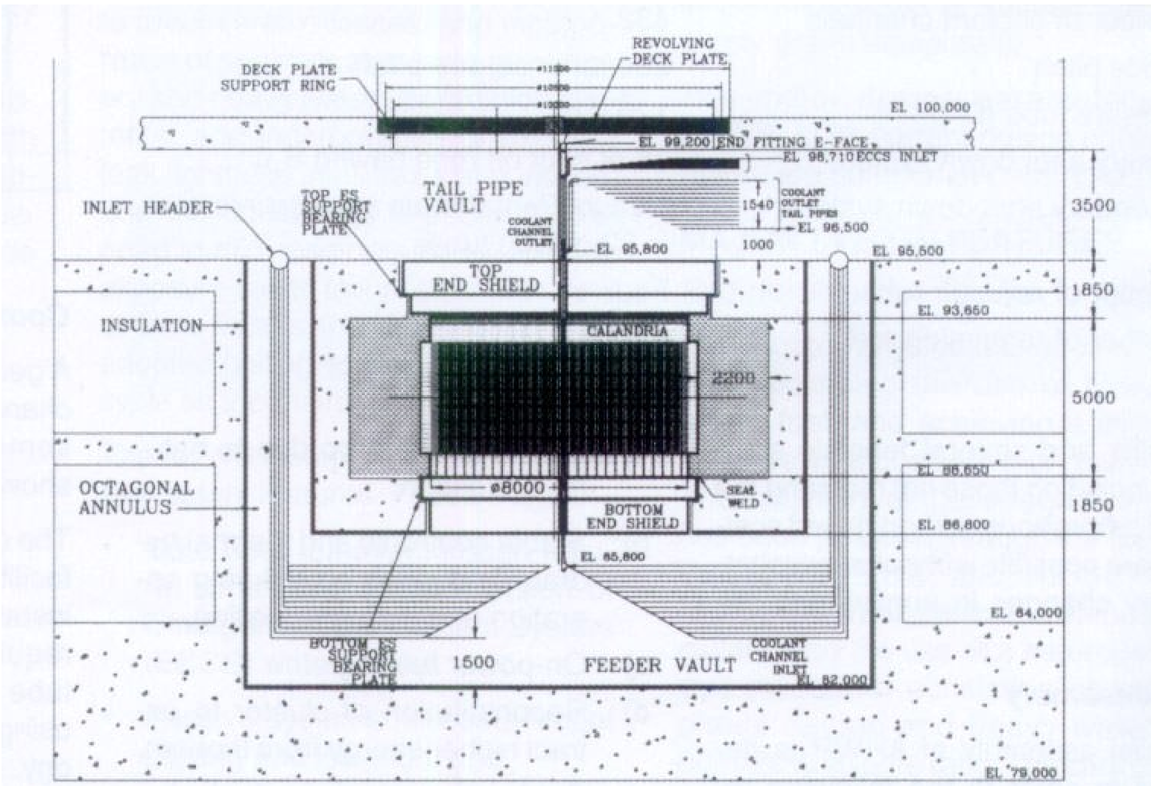

Fig. 3: A view of the Advanced Heavy Water Reactor (AHWR) core, vessel and its internals including the shielding and the array of feed water pipes for each fuel channel.

The AHWR is intended to use ^{233}U/thorium and Pu/Th fuel. The BARC research centre claims: "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 good 300 MW_e converter that has a critical mass of about 600 kg of ^{233}U (Refs. 6,7,8,9). It will be interesting to find out how high the conversion ratio is since regular (although boiling) light water is used for cooling the fuel channels. For the advanced CANDU reactors with light water cooling it has also not been claimed that they can be self-breeders.

3 CONCLUSIONS

Since it appears possible that nuclear power may increase by a factor of 4 by 2050 and also since uranium prices go up and there are concerns about the long-lasting waste problem of minor actinides, the ^{233}U/thorium cycle is getting more prominent. In particular, this could be due to the recognition that heavy water-cooled CANDU reactors are probably self-breeders and the Indian Advanced Heavy Water Reactor should be a good converter. Ref. 1 indicates that the heavy water-cooled CANDU can itself breed enough ^{233}U in about 12 years. It might also be possible to use the irradiated thorium rods directly (without removing the fission products) to get into some extended burn-up. On the other hand, it would be a useful preparation to irradiate thorium assemblies in light water reactors and to measure the amount of fission products generated to see whether a reprocessing would be needed before using it in a CANDU reactor. Of course detailed calculations and experiments are also needed to validate the cross section data in an area where not much effort has been spent. Also fast reactor pins containing thorium should be tested to confirm that a rather large amount of ^{233}U could be generated in a fast system. Of course a major obstacle is the lack of large-scale reprocessing of irradiated ^{233}U/Th fuel. Fortunately, India is working hard on a large-scale reprocessing, other countries should probably also do research in this field and the fluoride volatilization method should lead to an earlier possibility to remove the fissile ^{233}U and re-use it. This paper indicates that there is a large potential regarding the use of thorium fuels. In particular, we will not need so many fast reactors if we used them mostly for breeding ^{233}U and burning minor actinides. The most important aspect of this paper may, however, may be the recognition that we have already thermal reactors (CANDUs with heavy water cooling) that could do some breeding and in the not to far future the Advanced Heavy Water Reactor that should be a very good converter of ^{233}U.

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