A NOVEL FUEL/REACTOR CYCLE TO IMPLEMENT THE 300 YEARS NUCLEAR WASTE POLICY APPROACH - 12377

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ABSTRACT

A thorium-based fuel cycle system can effectively burn the currently accumulated commercial used nuclear fuel and move to a sustainable equilibrium where the actinide levels in the high level waste are low enough to yield a radiotoxicity after 300 years lower than that of the equivalent uranium ore.

INTRODUCTION

In the WM 2011 conference, Westinghouse unveiled [1] a new approach to address the waste "problem" through an appropriate used nuclear fuel (UNF) management.

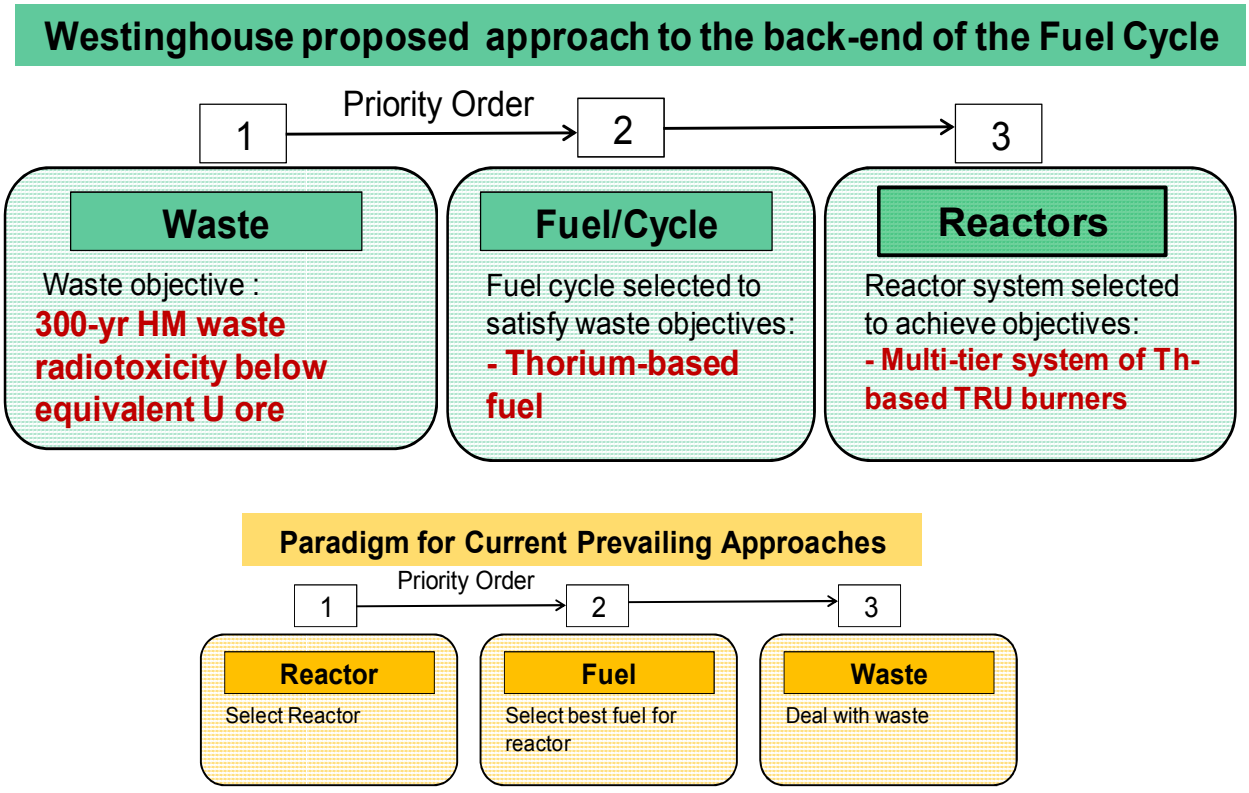

Fig 1. A new approach to the back-end of the fuel cycle

As shown in the bottom part of Figure 1, the traditional approach to-date has been to select a specific reactor type that best addresses the application requirements, then choose the fuel form best fitting the chosen reactor, and finally search for an acceptable waste management solution. Unfortunately, fulfilling the last part has so far been proven to be very elusive. In what has become known as the "back to front" approach [2], Westinghouse proposed the sequence shown in the top part of Figure 1. Reference 1 elaborated the choice of the waste objective: a 300 years heavy metal waste radiotoxicity not exceeding that of the natural U ore required to fuel the typical open cycle LWR. The prerequisite to enable a 300-year waste is to burn the transuranic isotopes (TRU) presently cumulated in the LWR UNF, which are primarily responsible for their long-term radiotoxicity.

The choice of the "best" fuel cycle to comply with the waste objective and deal with the large legacy TRU can be reasoned based on first principles: there are only three "main" fissile isotopes, one natural (U-235 in mixture with U-238) and two manmade (Pu-239, produced from U-238, and U-233, produced from Th-232). The TRU isotopes are the key culprits of the waste's protracted radiotoxicity, thus the lower the atomic number of the starting fissile and fertile materials the fewer TRU isotopes are generated through irradiation. So, fissile U-233 accompanied with fertile Th-232 remains as the logical choice to achieve a self-sufficient cycle with minimal TRU content in the long run. In the meantime, Th-232 admixed with Pu or TRU from reprocessed LWR UNF appears the best compromise to reduce the current waste and minimize further TRU production. This reduction can be started now in the current fleet and continued later in evolutionary reactor designs. Thus, the fuel cycle of choice to achieve the waste objectives is the Th fuel cycle.

The third and final step is to determine the reactor(s) together with the associated facilities and technologies which can best implement the objective of yielding the most "benign" nuclear waste in terms of radiotoxic content and its behavior over time. This, of course, is also the most difficult and complex step and only a very preliminary investigation has been performed so far, as presented in parallel papers [3-4].

For a transition to a more benign radioactive waste, we need to deal with:

1. The presently accumulated TRU waste which was supposed to go to a permanent high level waste repository, such as Yucca Mountain. We call this the "legacy" waste.
2. The TRU waste which keeps being generated during electricity production, the one which was supposed to go to future Yucca Mountains. We call this the "future" waste.

The thorium cycle can deal very efficiently with both types of waste, burning the first and minimizing/burning the second, and can be used in both thermal and fast reactors, thus cumulating benefits. Preliminary calculations with "typical" fast and thermal reactors confirm the high TRU burning rate potential of thorium [4].

THE THORIUM FUEL CYCLE

Thorium has on and off been considered as fuel for power reactors, but it has never generated much traction because of no significant advantages over the well established uranium fuel in terms of power generation economics. However, the situation is quite different once the waste management aspect enters into the equation.

In fact, thorium then has many advantages, such as:

- is a very efficient carrier to burn the legacy waste
- generates a much lower amount of TRU than the U-based cycle, thus positively addressing the future waste
- has a lower 300-year radiotoxicity than U-based fuel assuming comparable separation efficiency
- is a sustainable option: wide availability, breeding potential in both thermal and fast reactors, lower radiotoxicity and decay heat waste for several thousand years after disposal.

The interaction/transmutation chain including both Th-232 and U-238, as well as transuranics, is shown in Figure 2. Due to its "lower" position, Th-232 requires multiple neutron captures to "progress" to long lived TRU, which greatly reduces their concentration with respect to typical U-based options [4].

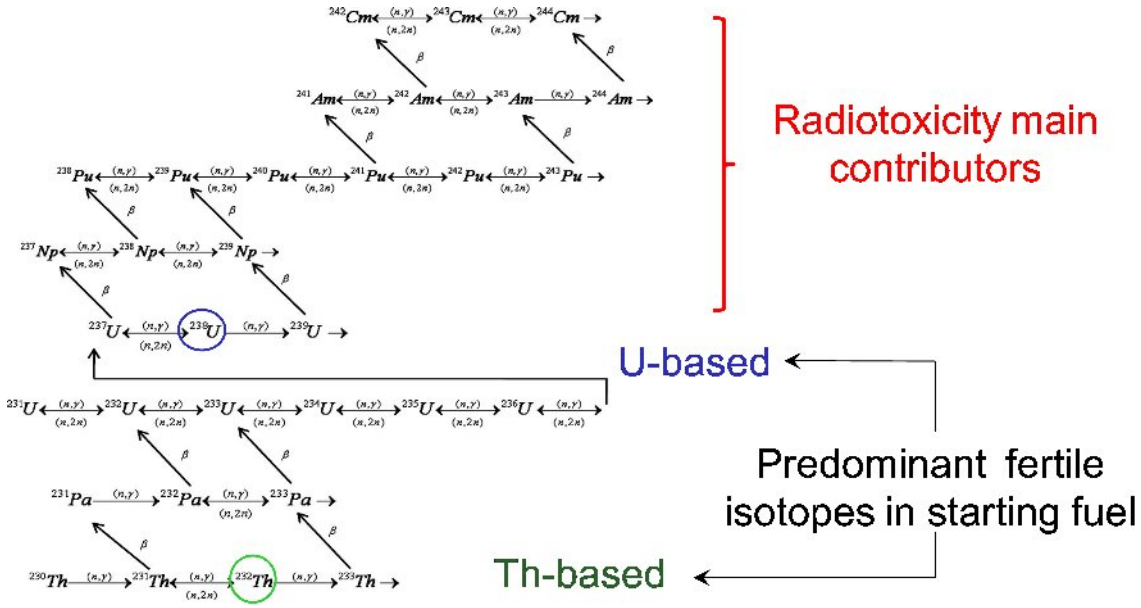

Fig 2. Transmutation chain from Th to Cm (adapted from Ref. 5)

As already outlined in past studies [6-8], thorium is an efficient carrier for TRU transmutation in both thermal and fast spectrums. Since the number of subsequent burning cycles in a thermal reactor is typically limited [9], TRU burning can be initiated in Th-PuOX LWRs but will likely have to be completed in Th-TRU fast reactors.

However, as one would expect, there are technological challenges. The major issue is the generation of high energy gammas from U-232 and Th-228 decay products in the recycled fuel [4], which is a significant issue for conventional fuel manufacturing routes, but it reduces the appeal of the cycle to potential proliferators. Different approaches and their economics must be investigated. One rather straightforward possibility is to keep the in-bred U within the recycled fuel and allow multiple burning cycles only in the FR loop. The resulting fuel cycle scheme is illustrated in Fig 3: This solution will greatly simplify the fuel management and material flows while confining the hot fuel manufacturing route to the FR transmutation fuel (see "fuel

manufacturing" red boxes in Fig 3). As a result of keeping the U within the recycled fuel, the reactivity coefficients and control requirements of the FR are expected to improve, plus the proliferation resistance of the cycle will be enhanced, at the expense of a decrease in the TRU burning rate potential as discussed in Ref. 3.

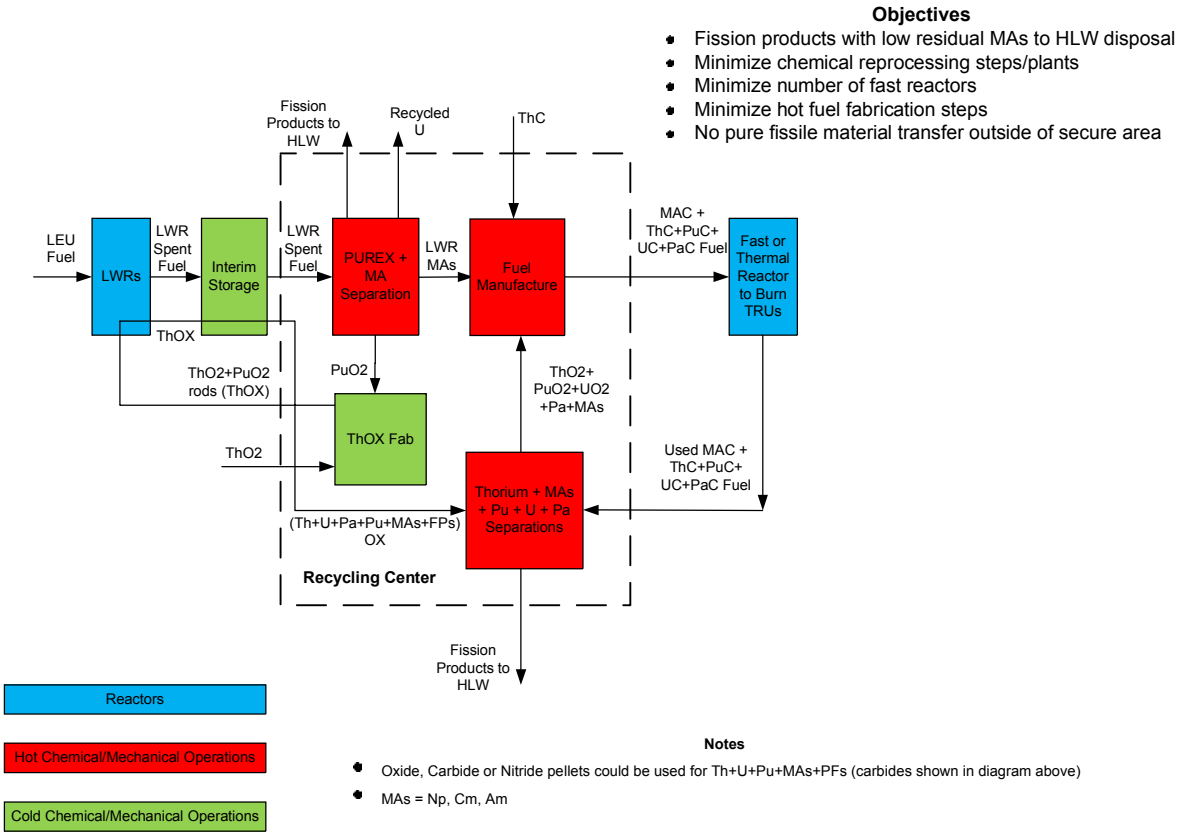

Fig 3. Flowsheet proposed for the thorium fuel cycle implementation

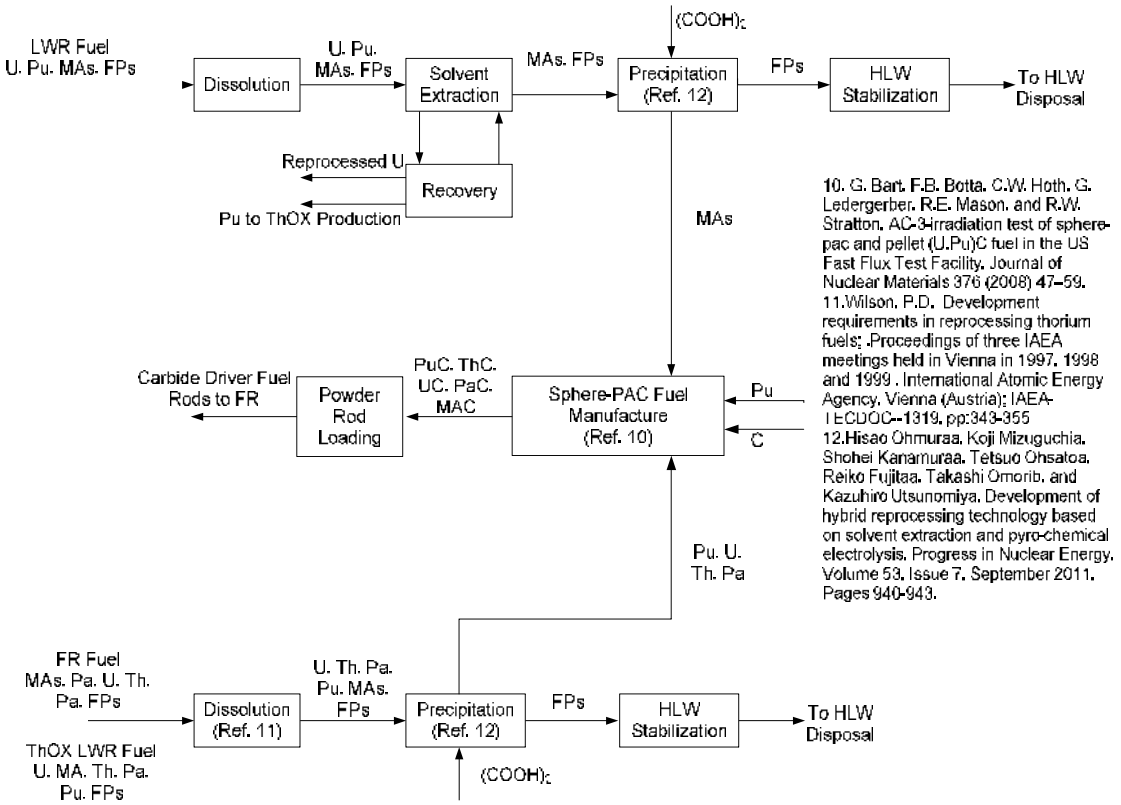

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Fig 4. Reprocessing and manufacturing route for thorium fuel implementation

Fig 4 shows a preliminary layout of a viable industrial process for the reprocessing and manufacturing route and dealing with the high activity characterizing the transmuting fuel, including that from U-232's decay products. This process is based on data from References 10, 11 and 12. Scoping scenario calculations and economics analysis are also being performed for the various options depicted in Fig 5. As expected, direct geological disposal is undoubtedly the lowest cost option but has contributed to the current political and societal stalemate. In lieu of direct disposal, the thorium-based options appear more promising than the alternatives explored, thus supporting the need for a more detailed exploration of Th-based fuel cycles.

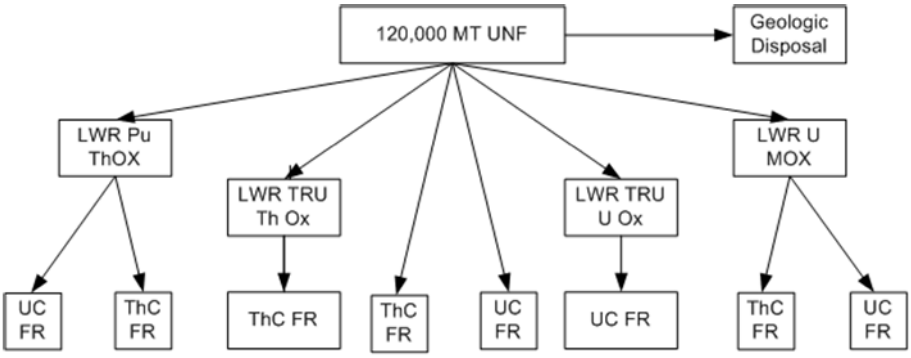

Fig 5. Reprocessing and manufacturing route for thorium fuel implementation

IMPLEMENTATION AND REACTOR SYSTEM

Previous sections indicate that the thorium fuel cycle can indeed satisfy the 300 year waste specification of our new approach. Next, a reactor system(s) which can best implement it must be identified. There are, of course, many alternatives, with the one presented here being a possible route which satisfies the following top-level objectives:

- Address both the legacy and future wastes
- Present a viable pathway for industrial implementation
- Engage the current LWR fleet to initiate the TRU transmutation
- Keep the number of fast reactors and associated cost at a minimum
- Have the potential for long-term sustainability

To illustrate the beneficial impact of TRU transmutation and burning, some representative results from Reference 3 are reviewed here. In particular, the core inventory of a Th-fueled FR transmuter during various phases of the TRU transmutation is analyzed. For the first 60 EFPY, the reactor operates using the legacy TRU external supply as the primary fissile feed and thorium as the fertile make-up (“Phase I”). Unlike what is proposed in Fig 5, the in-bred U was not kept with the recycled fuel during this initial phase, and the fuel employed was ThN instead of ThC, but the general principles are still valid. At 60 EFPY, a second phase starts (“Phase II”) where the TRU external supply is assumed to be exhausted and the in-bred U provides the required fissile material to continue operating the reactor effectively enabling it to burn the TRU accumulated in the core inventory during Phase I. After sufficient operation under the new fuel management scheme, an isotopic equilibrium state typical of the thorium-closed fuel cycle is reached (“Phase III”). The resulting core inventories of TRU and U characterizing the various phases are shown in Fig 6, together with the TRU feed (Phase I) and in-bred U feed from the blanket to the driver fuel region of the FR.

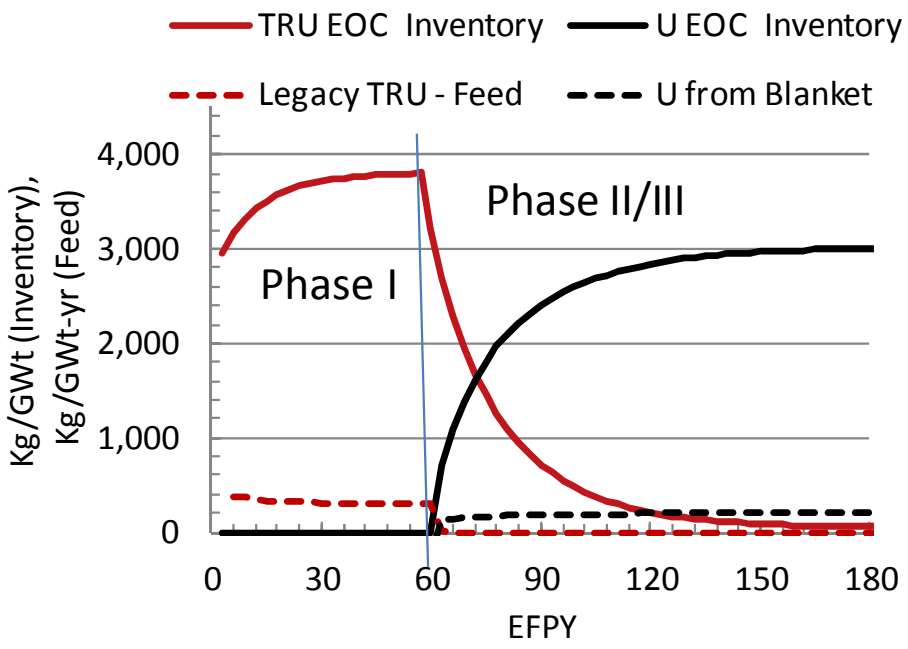

Fig 6. TRU and U core inventory and feed requirements from TRU burning to closed Th-cycle

As Fig 6 shows, as a result of the TRU supply being interrupted and the U-233 being recycled within the reactor, the TRU core inventory starts decreasing and in-bred U starts accumulating. The TRU core inventory will be reduced to 10% of the value at the end of Phase I after ~45 EFPY of operation in Phase II. It will then take an additional ~120 EFPY for the TRU content to be reduced to 1% of the initial value, after which it reaches virtual equilibrium.

The long-term beneficial effect of burning the TRU out of the core inventory is shown in Figure 6, giving the ingested radiotoxicity index of 0.1% actinide waste (assumed losses from reprocessing of the transmutation fuel) at representative times during the various phases.

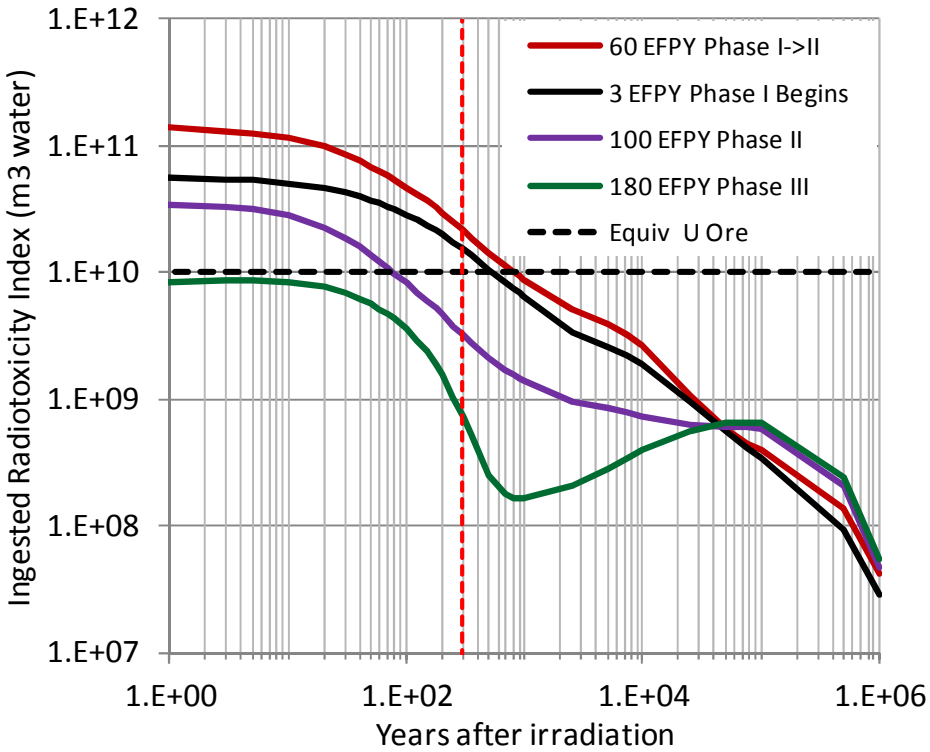

Fig 7. Ingested radiotoxicity of 0.1% actinide waste from reprocessing of the FR discharged fuel

Fig 7 shows that while the legacy TRU is being burned (Phase I), the radiotoxicity increases as a result of the increasing TRU content in the core inventory, and accordingly in the actinide process losses. The radiotoxicity peaks at about 60 EFPY at the beginning of the transmutation. Due to the high radiotoxicity of the fuel during Phase I, it is important to minimize its radiotoxic impact, which corroborates using thorium to expedite the legacy TRU consumption. As Fig 7 reveals, satisfying the 300-year waste criterion during the transmutation phase and the subsequent ~20 years will demand HLW with actinide waste below 0.1% of the core inventory, i.e. less than 10 Kg of actinides for a reprocessed core, which may prove unrealistic. The high radiotoxic content of the core inventory in the transmutation phase is the price to pay for the reduction in the overall TRU of the system obtained by reducing the legacy waste to a fraction of its original amount.

The radiotoxicity of the transmuter starts decreasing only after the TRU external supply is interrupted (exhausted) and the TRUs are being burned from the core inventory and the recycled fuel, using the in-bred U as the primary fissile material instead of the TRU external feed. Eventually, as the core inventory evolves towards that typical of a Th-closed cycle, the 300-year radiotoxicity approaches the characteristically low level of a Th-closed cycle. It should be noted that it takes several decades before the transmuting fuel and resulting HLW will achieve the low radiotoxicity typical of the Th cycle. Therefore, a strong, long-term commitment to transmutation, technological needs and associated expenses should be ensured before embarking on such undertakings.

CONCLUSIONS

The second step of the Westinghouse approach to solving the waste "problem" has been completed. The thorium fuel cycle has indeed the potential of burning the legacy TRU and achieve the waste objective proposed. Initial evaluations have been started for the third step, development and selection of appropriate reactors. Indications are that the probability of showstoppers is rather remote.

It is, therefore, believed that development of the thorium cycle and associated technologies will provide a permanent solution to the waste management. Westinghouse is open to the widest collaboration to make this a reality.

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Each year in the United States, nuclear power reactors produce about 2,000 tons of spent nuclear fuel rods. This highly radioactive waste, which will remain dangerous for hundreds of thousands of years, is currently stored at the reactor sites where it is generated.Â The figure and table show the volume of different waste streams generated by three different reactor fuel cycles. In the "once-through" cycle, which reflects the current U.S. strategy, the spent fuel is stored and ultimately disposed of in a geologic repository. In the second fuel cycle, all spent fuel would be reprocessed and the plutonium extracted from reprocessing would be used as new fuel in advanced, yet-to-be-developed "fast burner" reactors. The text of the report of the independent Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle, commissioned by the Director General, is reproduced in this document for the information of Member States. INFCIRC/640 - 22 February 2005. INFCIRC/640 - 22 February 2005. Multilateral approaches to the nuclear fuel cycle. Expert Group Report submitted to the Director General of the International Atomic Energy Agency. 22 February 2005. And this waste is only two to three per cent of the total fuel we put into the reactor. Entire spent fuel is not waste; plutonium and uranium are recycled which contribute to about 97-98 per cent of the spent fuel.Â Now the problem with nuclear power waste is that it will remain radioactive for a few hundreds of years and even more. Now again you see, this waste can be divided into two parts â€” one where within 300 years, 99 per cent of the waste becomes non-radioactive and the rest is going to remain radioactive for a longer time.Â Properly designed buildings and structures can stand for 300 years. The waste is first vitrified in the vitrification plant operational in India. It will be put in steel canisters, which in turn will be put in steel over-packs.