Transuranic Waste Burning Potential of Thorium Fuel in a Fast Reactor - 12423

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ABSTRACT

Westinghouse Electric Company (referred to as “Westinghouse” in the rest of this paper) is proposing a "back-to-front" approach to overcome the stalemate on nuclear waste management in the US. In this approach, requirements to further the societal acceptance of nuclear waste are such that the ultimate health hazard resulting from the waste package is “as low as reasonably achievable”. Societal acceptability of nuclear waste can be enhanced by reducing the long-term radiotoxicity of the waste, which is currently driven primarily by the protracted radiotoxicity of the transuranic (TRU) isotopes. Therefore, a transition to a more benign radioactive waste can be accomplished by a fuel cycle capable of consuming the stockpile of TRU “legacy” waste contained in the LWR Used Nuclear Fuel (UNF) while generating waste which is significantly less radiotoxic than that produced by the current open U-based fuel cycle (once through and variations thereof).

Investigation of a fast reactor (FR) operating on a thorium-based fuel cycle, as opposed to the traditional uranium-based is performed. Due to a combination between its neutronic properties and its low position in the actinide chain, thorium not only burns the legacy TRU waste, but it does so with a minimal production of “new” TRUs. The effectiveness of a thorium-based fast reactor to burn legacy TRU and its flexibility to incorporate various fuels and recycle schemes according to the evolving needs of the transmutation scenario have been investigated. Specifically, the potential for a high TRU burning rate, high U-233 generation rate if so desired and low concurrent production of TRU have been used as metrics for the examined cycles.

Core physics simulations of a fast reactor core running on thorium-based fuels and burning an external TRU feed supply have been carried out over multiple cycles of irradiation, separation and reprocessing. The TRU burning capability as well as the core isotopic content have been characterized. Results will be presented showing the potential for thorium to reach a high TRU transmutation rate over a wide variety of fuel types (oxide, metal, nitride and carbide) and transmutation schemes (recycle or partition of in-bred U-233). In addition, a sustainable scheme has been devised to burn the TRU accumulated in the core inventory once the legacy TRU supply has been exhausted, thereby achieving long-term virtually TRU-free.

INTRODUCTION

A comprehensive approach for management of used nuclear fuel (UNF) and high level waste (HLW) has been proposed by Westinghouse [1]. In summary, this approach proposes the development of a nuclear system from the “back to the front” of the fuel cycle, i.e. first setting an appropriate criterion for the waste and subsequently developing a viable system with the best potential to conform to the waste specifications. The waste criterion proposed, ultimately aimed at improving public acceptance of nuclear energy, is a waste package resulting in a health hazard “as low as reasonably achievable”. Acknowledging its limitations to represent the risk of exposure, we use the waste radiotoxic content to illustrate the general principle, reserving a more sophisticated set of metrics for a future comprehensive treatment based on the detailed system design.

The criterion for the waste acceptance is to have a radiotoxicity, after ~300 years of post-irradiation isolation, lower than that of the U ore needed to generate the same amount of electricity when employed in a once-through cycle. The choice of the 300-year time frame has been motivated by the fact that this is the time needed for decay of most of the fission products, which, of course, cannot be avoided or transmuted in bulk. On the other hand it is conceivable to recover, recycle and transmute the more hazardous actinides (and some of the long lived fission products) while having a viable nuclear system.

Given that transuranic (TRU) isotopes are primarily responsible for the protracted radiotoxicity of current UNF, a nuclear system capable of efficient TRU separation and recovery, as well as high TRU transmutation rate is an essential condition to satisfy the 300-year waste criterion. The TRU stock cumulated in the current legacy UNF, ~65,000 MT heavy-metal (HM) with ~1,000 MT TRU, should be recovered through reprocessing and transmuted together with any future TRU generated.

The main pathway to TRU generation in current UOX fuel starts with neutron captures in U-238. The lower position of thorium in the transmutation chain, together with the fact that thorium per se does not contain any fissile isotopes, confers to thorium-bearing fuels two appealing features to achieve a low radiotoxicity waste: a minimal endogenous TRU generation and a high TRU transmutation rate potential.

ANALYSIS METHOD

As outlined in past studies and confirmed by recent analysis, high TRU transmutation rates in both thermal and fast spectra can be achieved using Th as the TRU carrier [2-4]. For instance, ~3 times more Pu can be burned in a PWR fueled by Th-PuOx instead of the typical U-PuOx (MOX). However, it appears arduous to achieve multi-cycle TRU transmutation in current LWRs due to the quick rise in TRU content of the recycled fuel and associated issues. Therefore, a fast spectrum is more practical to extend the TRU transmutation to multiple cycles [5].

Burner Design

The base core design of the Toshiba 1,000 MWth, sodium-cooled, Advanced Recycling Reactor (ARR) [6] has been employed to evaluate the TRU transmutation performance of various Th-based fuels in a fast spectrum. The ARR core main features are summarized in Table I. A radial map of the core is shown in Figure 1. No blankets, radial or axial, have been utilized to increase the TRU burning performance.

Table I. Main features of the ARR burner core

Core thermal power	MW	1000
Coolant type	-	Sodium
Number of inner/outer core assemblies	-	198/126
Number of stainless steel shield assemblies	-	150
Number of B_4C shield assemblies	-	84
Number of control assembly locations	-	37
Refueling interval	yr	1
Number of batches	-	3
Pins per assembly	-	271
Pin OD	mm	6.50
Pin pitch	mm	7.41
Fuel/coolant/structure volume %	%	41/33/26
Fuel height	mm	600
Lower/upper plenum height	mm	450/870

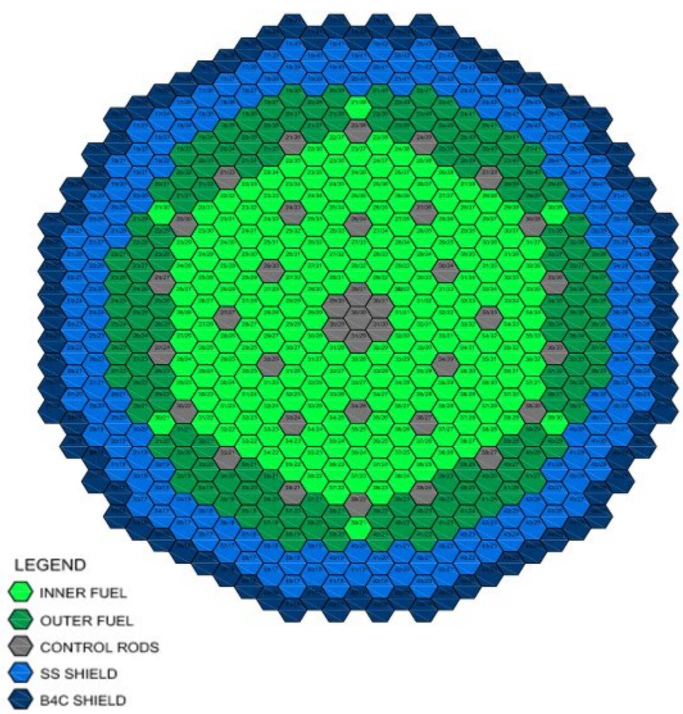

Fig 1. Radial view of the ARR burner design

The TRU supply is provided by standard 4.2 wt % UO_2 PWR fuel, discharged at 50 GWd/tHM, with a 10-year cooling period before reprocessing. The TRU wt % values are given in Table II.

Table II. External TRU wt % vector

Isotope	wt %
Np237	4.7
Pu238	2.2
Pu239	47.4
Pu240	22.8
Pu241	8.4
Pu242	6.8
Am241	5.6
Am243	1.6
Cm244	0.5
Cm245	0.0

Single Tier Cases

Eight combinations of fuel types and reloading schemes, referred to as "single-tier cases", have been studied and their TRU transmutation performance assessed. These single-tier cases are summarized as follows:

1. U-TRU-10%Zr metal fuel with 75% smeared density (All Actinides Recycled)
2. Th-TRU-10%Zr metal fuel with 75% smeared density (All Actinides Recycled)
3. Th-TRU-10%Zr metal fuel with 75% smeared density (All Actinides Recycled except U-233)
4. Th-TRU oxide fuel with 85% smeared density (All Actinides Recycled)
5. Th-TRU-N with natural N and 85% smeared density (All Actinides Recycled)
6. Th-TRU-N with 95% N-15 and 85% smeared density (All Actinides Recycled)
7. Th-TRU carbide fuel with 70% smeared density (All Actinides Recycled)
8. Th-TRU carbide fuel with 70% smeared density (Actinides Recycled except U-233)

It should be pointed out that remote fuel manufacturing will be needed for all transmutation fuels proposed. Remote fuel manufacturing for metal fuel is conceivable but it has never been demonstrated on an industrial scale. The 75% smeared density adopted for metal fuel is driven by the porosity necessary to accommodate high swelling. The 10 weight percent Zr content assumed is tentative and needs further investigation. The oxide and nitride fuel feature a higher smeared density but due to the constraints imposed by remote fuel manufacturing, their manufacturing viability through pellet-based techniques on an industrial scale is questionable. A sphere-pac based manufacturing technique could be employed instead and would be more suitable for remote manufacturing. Such a manufacturing route has been assumed in the neutronic analysis for carbide fuel together with a 70% smeared density to be verified in future studies.

Multi-Tier Cases

Supplementary to the single-tier cases, additional multi-tier cases were studied for carbide fuel as follows:

9. Th-TRU carbide fuel with TRU and U-233 from reprocessed Th-Pu "MOX" LWR (e.g. Th-MOX) and minor actinides (MA, e.g. Np, Am and Cm) from reprocessed UOX LWR-Legacy Material. (All Actinides Recycled in FR)

10. Th-TRU carbide fuel with TRU and U-233 from Th-MOX LWR and MA from UOX LWR-Legacy Material. (All Actinides Recycled in FR except U-233; U-233 extracted from Th-MOX LWR feed and recycled FR fuel)
11. Th-TRU carbide fuel with TRU from U-Pu MOX LWR (i.e. U-MOX) and MA from UOX LWR (All Actinides Recycled in FR, no LWR recycling)
12. U-TRU carbide fuel with TRU from U-MOX LWR and MA from UOX LWR (All Actinides Recycled in FR, no LWR recycling)

The multi-tier cases (9-12) represent the continuation of an LWR "fleet" supported by a TRU burning FR with the additional burden of reducing the legacy TRU. For these cases, the "legacy material" vector assumed is a steady supply of Pu and MA's from the reprocessing of UNF LWR's which top-up the actinides recovered via reprocessing of the FR's discharged fuel. The multi-tier cases are shown schematically in Figure 2.

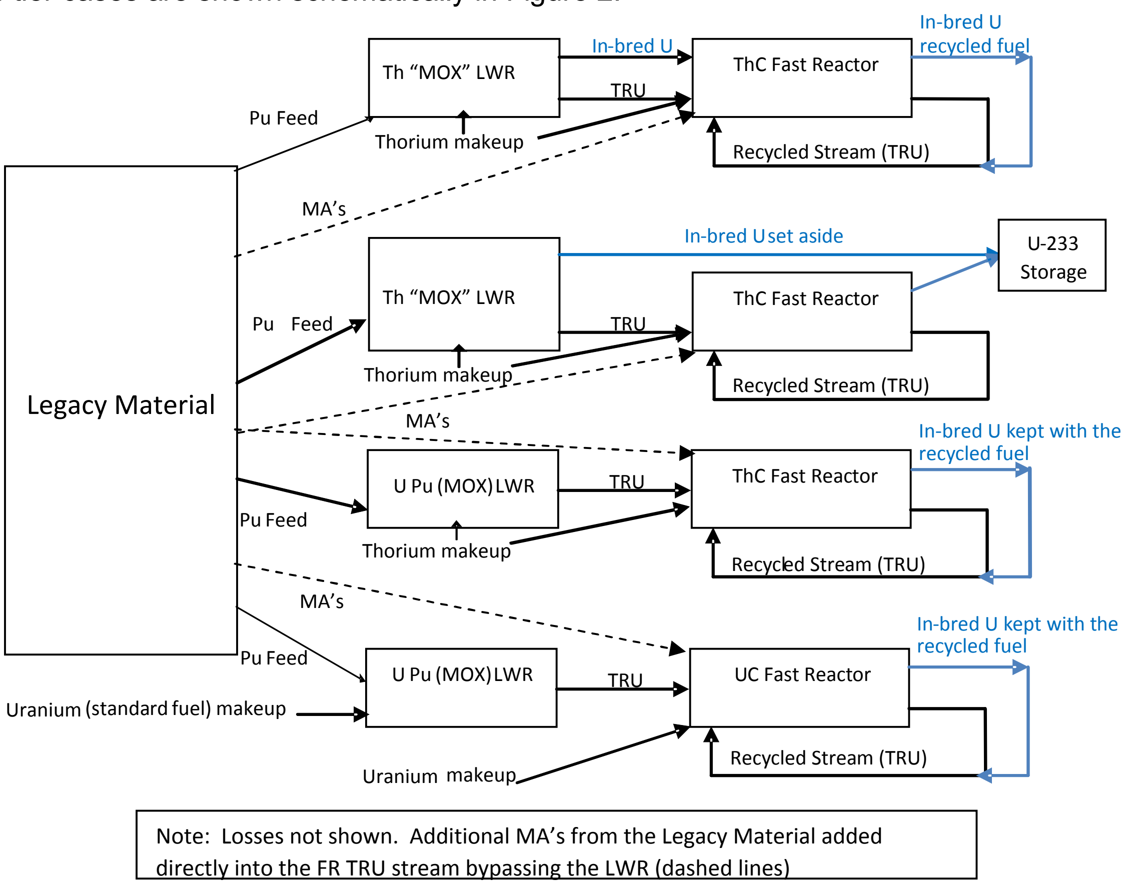

Fig 2. Additional Multitier Scenarios (cases 9-12 from top to bottom)

Transition Scenario to Closed Th-based Fuel Cycle

Results for a plausible transition from TRU burning to a closed Th fuel cycle will also be presented. The single and multi-tier scenarios previously discussed assume a steady supply of legacy TRU and therefore utilize a suitable core design (e.g. no blankets, relatively low internal breeding). In order to remain sustainable without a TRU feed, a U breeder design is envisaged for the later transmutation phase. The ARR model was modified as a first attempt at such a design [7].

The resulting modified core has a heterogeneous design with radial and axial blankets to enhance the breeding. The core features 294 fuel assemblies and 139 radial blanket assemblies, with the latter divided into four rings (a horizontal schematic of the reactor midplane is shown in Figure 3). The fuel selected for this preliminary investigation is $Th^{15}N$ fuel, based on the higher breeding potential shown with respect to the other fuels analyzed.

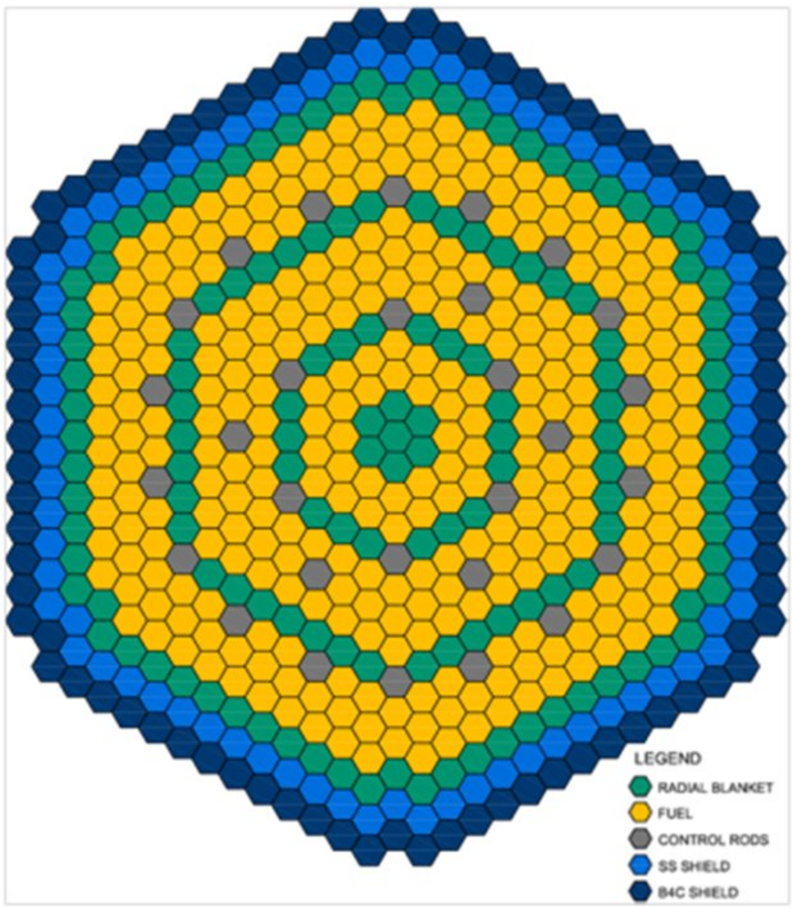

Fig 3. Radial view of the heterogeneous ARR breeder design

For the first 60 Effective Full Power Years (EFPY), the reactor is assumed to operate using the legacy TRU external supply as the primary fissile feed and thorium as the fertile make-up ("Phase I"). The in-bred U is assumed to be partitioned out of the recycled fuel during Phase I, conceivably to be employed in a symbiotic cycle and/or to startup new reactors. Accordingly, during Phase I the TRU burning rate is maximized while also achieving a high U breeding due to the presence of the blankets. Alternatively, at least a portion of the blanket assemblies could be used for heterogeneous transmutation of Am/Cm in target assemblies during Phase I.

At 60 EFPY, a second phase starts ("Phase II"). During this phase the TRU external supply is assumed to be extinguished. The in-bred U is now kept with the recycled fuel to provide the necessary fissile requirement lost from the exhaustion of the external TRU supply. Given the interruption of the external TRU supply, the TRU present in the core inventory begins to decrease as a result of transmutation by neutron reactors or decay. After sufficient operation under the new fuel management scheme, an isotopic equilibrium state typical of the thorium-closed fuel cycle is reached, ("Phase III"). A schematic representation of the various phases and fuel management is given in Figure 4.

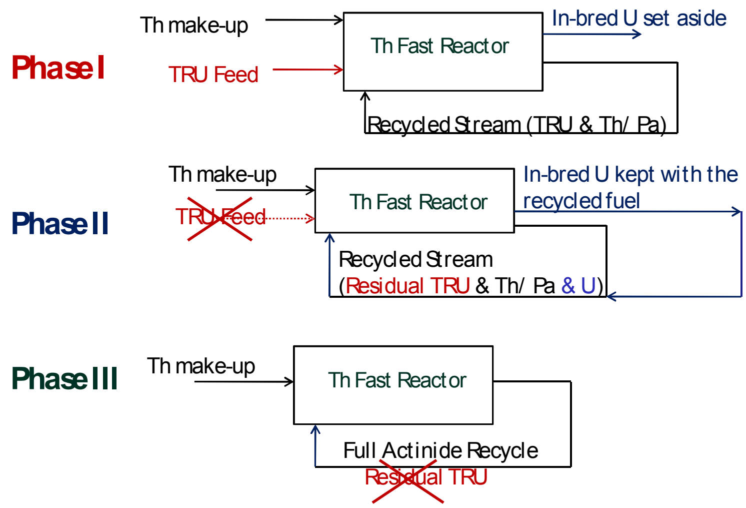

Fig 4. Schematic depiction of the 3-phase simulation to transition from TRU burning to closed Th-cycle

Simulation Details

The core physics analysis for the all scenarios studied has been performed with the fast reactor code suite ERANOS 2.2. 3D hexagonal geometry is utilized with 33 energy-groups. The VARIANT nodal diffusion method is utilized as the flux solver. ECCO with JEFF 3.1 neutronic libraries has been employed for the cell calculations [8]. Simulations cover the period from the start-up core to 60 Effective Full Power Years (EFPY) of depletion for the TRU burning cases (cases 1-12), where the metrics compared for each case have practically reached equilibrium Out-of-core cycle-to-cycle operations (decay, separation, manufacturing of new fuel with recycled actinides plus fertile and fissile top-up) have been accounted for in the simulations. The transition scenario case simulates 60 EFPY for phase I, upon which an additional 240 EFPY are simulated to ensure an equilibrium state is achieved.

RESULTS AND DISCUSSION

Single Tier TRU Burning Analysis

A summary of the main results obtained for cases 1-8 for the various fuels is given in Table III. The reference ARR design with U-TRU-Zr metal fuel achieves a core-average TRU burning rate of ~117 kg/GWt-yr. The Th fuels analyzed under the assumed partition of the in-bred U show very similar TRU burning rates, in the 330-340 Kg/GWt-yr range. The highest TRU burning rate pertains to Th oxide, followed in decreasing order by carbide, metal, nitride with natural N and N-15 enriched (i.e. with 95% N-15 in N). Overall, the TRU needed for 60 Effective Full Power Years (EFPY) of operation of the Th-fueled ARR is approximately 24.0 MT including the start-up core. The amount of TRU to be made available to the ARR from the reprocessed LWR fuel on a per thermal energy basis, i.e. 60 GWt-yr, corresponds to ~7 PWRs operating on typical reloading scheme and discharge burnup.

A general behavior notable in Table III is the TRU core inventory increases from start-up to equilibrium for all the Th fuels analyzed with partitioning of the in-bred U, predominantly due to the degradation with irradiation of the fissile quality of the recycled TRU. The differences in the TRU inventory observed for the various fuels are a consequence of the different HM density, internal breeding and to a minor extent differences in the spectrum. The slightly larger TRU consumption in the carbide and oxide follows from the smaller HM density and lower internal breeding of U and comes at the expense of a higher relative content of TRU in the core inventory and larger reactivity swing during the cycle. Due to their higher HM density, nitride fuels, and N-15 enriched in particular due to the more favorable neutron economy, show the largest internal breeding of U. As a result Th-TRU-^{15}N has the smallest relative content of TRU accumulated in the core inventory and the more beneficial (flatter) reactivity swing during the cycle.

Comparing the full recycle cases studied, the thorium cases (metal and carbide, cases 2 and 8 respectively in Table III) clearly can still burn TRU at a significantly faster rate compared to the uranium metal counterpart (case1). Also, the TRU fraction in the thorium based fuels (metal and carbide) reduces throughout core life while it virtually stays the same for the uranium metal case, although the uranium-based fuel TRU fraction starts and ends lower than both of the thorium fuel cases studied.

Thorium based fuel shows a distinct advantage over uranium based fuel when simultaneously burning TRU and recycling in-bred U-233, since the addition of U-233 reduces the TRU loading and does not contribute significantly to additional MA production, while improving the safety coefficients . As a result, thorium based fuel appears to have more flexibility for simultaneous TRU burning and breeding (of U-233).

Table III. TRU transmutation performance of the ARR burner core with various fuels

Case	1	2	3	4	5	6	7	8
	U-TRU-Zr	Th-TRU-Zr	Th-TRU-Zr	Th-TRU-O_2	Th-TRU-^{14}N	Th-TRU-^{15}N	Th-TRU-C	Th-TRU-C
Fuel Form	Metal	Metal	Metal	Oxide	Nitride	Nitride	Carbide	Carbide
Fuel density [g/cm^3]	15.85	12.01	12.01	10.42	12.53	12.62	11.70	11.70
Smeared density, %	75	75	75	85	85	85	70	70
Actinides Recycled	All	All	All but U-233	All but U-233	All but U-233	All but U-233	All but U-233	All
Make-up fertile/fissile	U/TRU	Th/TRU	Th/TRU	Th/TRU	Th/TRU	Th/TRU	Th/TRU	Th/TRU
Core HM loading [kg/GWt]	13099	10073	10073	9514	12378	12360	9391	9390
TRU Start-Up Core [kg/GWt]	3161	3579	3579	3974	4099	3834	3367	3367
TRU, % of HM (startup)	24.1%	35.5%	35.5%	41.8%	33.1%	31.0%	35.9%	35.9%
HM at equilibrium [kg/GWt]	12678	9668	9666	9109	11959	11939	9016	8987
TRU Eq. Core [kg/GWt]	3041	2680	3808	4075	4357	4185	3962	2822
TRU, % of HM (Eq.)	24.0%	27.7%	39.4%	44.7%	36.4%	35.0%	43.9%	31.4%
TRU Burned [kg/GWt-yr]	117.4	234.8	335.3	338.4	333.4	329.6	337.6	238.8
U bred, stored [kg/GWt-yr]	-	-	111.2	109.7	138.6	146.0	104.1	-
Reactivity Swing % delta k	3.09%	5.09%	3.50%	3.19%	1.95%	1.63%	3.60%	5.03%
TRU need, 60 EFPY [MT]	9966	16549	23597	24050	24035	23639	23887	16922
Residual TRU, 60 EFPY [MT]	2924	2462	3482	3747	4028	3860	3633	2596

Note: Th-TRU-^{14}N is thorium nitride fuel with natural N. Th-TRU-^{15}N is thorium nitride fuel with 95% N-15 in N.

It should be noted that at the end of the reactor life span, assumed to be on the order of 60 EFPY, there is a considerable amount of residual TRU accumulated in the core inventories, ~3.5 – 4.0 MT, for the Th cases with partitioning of the in-bred U and ~2.5 – 3.0 MT for the cases with U-233 recycling. To avoid direct disposal, these TRUs need to be recovered via reprocessing and burned in another cycle of transmutation. This can occur in a reactor with a similar burner design and feed scheme, but it will need an adequate external TRU supply. If the final goal is to transition the reactor fleet to a closed thorium cycle, such TRU external supply will eventually be extinguished. In such an eventuality, a breeder reactor design should be adopted as previously discussed to generate the required amount of fissile feed to complete the burning of the residual TRU core inventory and sustain a closed thorium cycle.

Multi-Tier TRU Burning Analysis

Selected results from cases 9-12, additional carbide cases with differing feed strategies from potential multi-tier scenarios, are presented in Table IV. Due to the multi-tier aspect of the scenarios, the results of these cases are less straightforward to interpret than the single-tier cases.

Table IV. TRU transmutation performance of the ARR burner core for carbide fuel multi-tier FR scenarios

Case	9	10	11	12
	Th-TRU-C	Th-TRU-C	Th-TRU-C	U-TRU-C
Fuel Form	Carbide	Carbide	Carbide	Carbide
Smeared density, %	70	70	70	70
Actinides Recycled	All FR, no LWR	All FR but U-233, no LWR	All FR, no LWR	All FR, no LWR
Make-up fertile/fissile	TRU-U233 (Th "MOX" LWR), MA (UOX LWR)	TRU (Th "MOX" LWR), MA (UOX LWR)	TRU(MOX) (U-Pu LWR), MA (UOX LWR)	TRU(MOX) (U-Pu LWR), MA (UOX LWR)
Core HM loading [kg/GWt]	9438	9440	9341	11103
TRU Start-Up Core [kg/GWt]	2609	3578	3145	3145
TRU, % of HM (startup)	27.6%	37.9%	33.7%	28.3%
HM at equilibrium [kg/GWt]	9029	9004	8917	10677
TRU Eq. Core [kg/GWt]	2784	5001	3760	3958
TRU, % of HM (Eq.)	30.8%	55.5%	42.2%	37.1%
TRU Burned [kg/GWt-yr]	173.1	342.5	248.4	165.0
Reactivity Swing % delta k	5.10%	2.60%	4.27%	3.21%
TRU need, 60 EFPY [MT]	12989	25218	18414	13680
Residual TRU, 60 EFPY [MT]	2603	4669	3508	3779

For case 10, since the U-233 from the LWR and FR is partitioned and set aside, the TRU burning potential nearly doubles compared with case 9. This scenario can be advantageous if one aims at utilizing the U-233 stock as seed for other Th LWR's or FR's which could yield "TRU free" fuel. Case 11 results show that a Th-TRU-C FR burner design with TRU feed from LWR's fueled with traditional U-Pu MOX fuel may have a higher TRU burning potential than that of a Case 9 where the LWR TRU feed is obtained from LWR's fueled with Th-Pu (Th MOX). However, one needs to account also for the Pu burned in the Th-MOX LWR, which is higher than for a U-MOX LWR, for a comprehensive comparison. In addition, residual TRU at 60 EFPY is significantly lower for the Th based LWR case (case 9).

Note that since results are per unit power or energy, the term “fleet” may be misleading and is used in a generic sense. Results from case 12 indicate significantly better FR transmutation performance for Th-TRU-C vs U-TRU-C (Case 11) if the TRU FR feed is obtained from traditional MOX fueled LWR’s at the expense of a larger reactivity swing and higher TRU fraction at equilibrium..

Potential of Transition to a Closed Thorium Cycle

The TRU and U core inventories characterizing the phases from TRU burning to a thorium closed cycle are shown in Figure 5, together with the TRU feed (Phase I) and in-bred U feed from the blanket to the driver fuel.

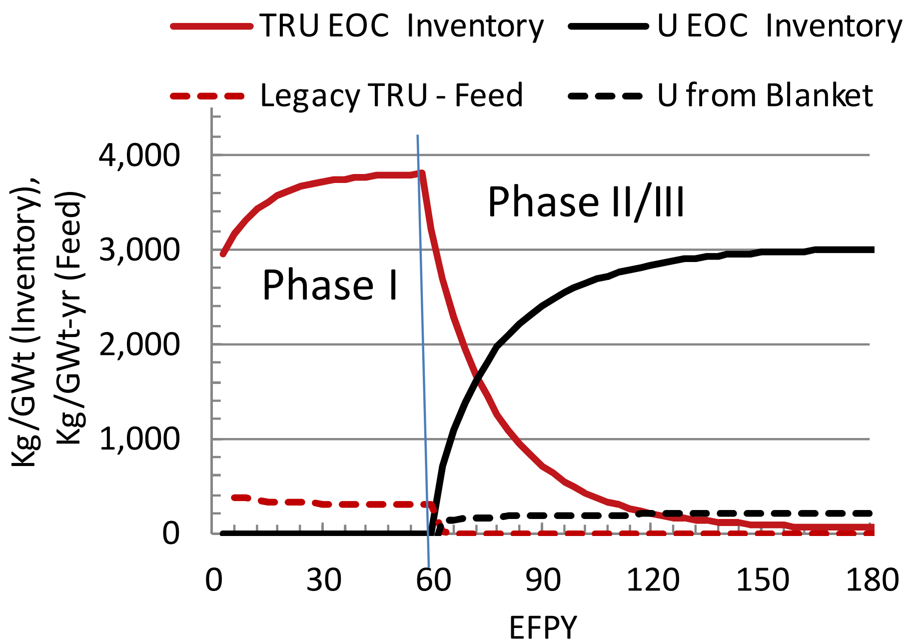

Fig 5. Trend in TRU and U core inventory and feed requirements from TRU burning to closed Th-cycle

During the 60 EFPY of Phase I, TRU are fed at a 318 kg/GWt-yr average rate, and burned at an average of 304 kg/GWt-yr, leading to a total increase of ~800 kg in the EOC TRU core inventory at the end of the 60 EFPY. At the same time the reactor with the heterogeneous core design is producing ~300 kg/GWt-yr of U, which for this initial phase of the simulation are assumed to be partitioned out. As Fig. 5 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 during Phase II. The TRU core inventory is 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 can be appreciated in Fig. 6, showing the ingested radiotoxicity index of 0.1% actinide waste from (i.e. 0.1% losses assumed during reprocessing) from the transmutation fuel at representative times during the various phases.

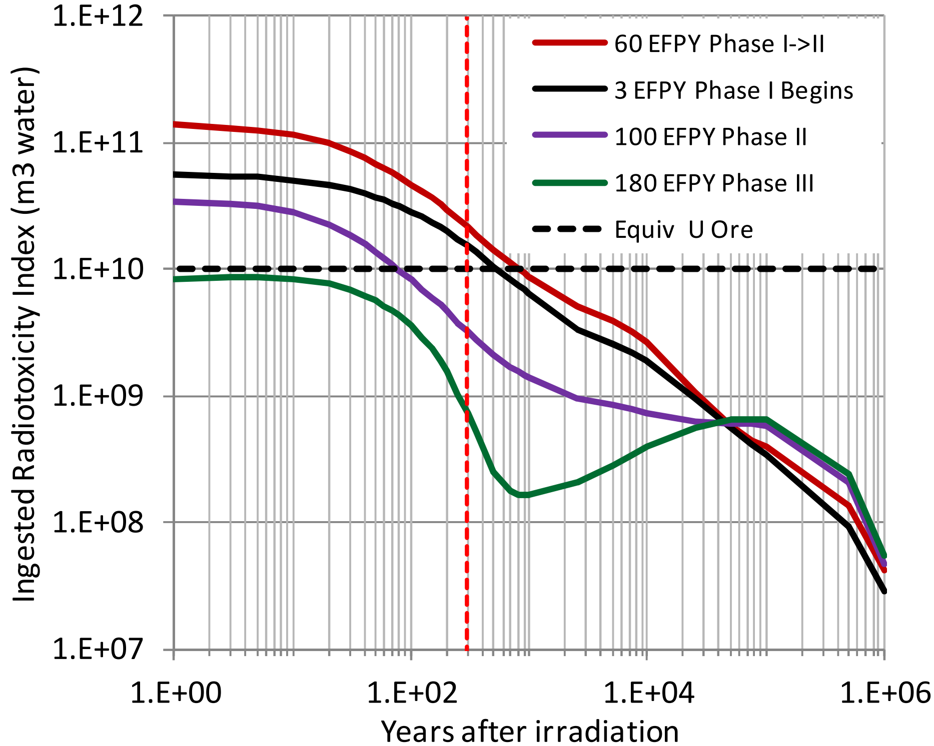

Fig. 6: Trend in TRU and U core inventory and feed requirements from TRU burning to closed Th-cycle

Figure 6 shows that under the assumed U partition strategy 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 proportionately in the actinide process losses. The radiotoxicity peaks and plateaus at ~ 60 EFPY, the beginning of the transmutation phase II. Due to the high radiotoxicity of the fuel during Phase I, it is beneficial to reduce the peak waste radiotoxicity and the overall cumulative radiotoxicity incurred throughout the phase. To minimize the cumulative radiotoxicity during this "high radiotoxicity" waste phase, a design which has the highest net TRU burning potential may be advantageous which corroborates using thorium to expedite the legacy TRU consumption.

The radiotoxicity 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 radiotoxicity approaches the characteristically low level emblematic of a Th-closed cycle [9-11]. It should be noted that it takes several tens of years before the transmuting fuel and resulting HLW will achieve the low radiotoxicity typical of the Th cycle. Therefore, a strong, long-term commitment to TRU transmutation and transition to the thorium fuel cycle should be ensured upon embarking on such undertakings. Nevertheless, TRU burning in any FR scenario studied promotes an overall reduction in disposed waste radiotoxicity and also takes an equal amount of far sightedness and long-term commitment.

Finally, the ingested radiotoxicity of the 0.1% actinide waste at 300 years after the fuel discharge is shown in Fig. 7. As the curve reveals, satisfying the 300-year waste criterion during the transmutation phase and the subsequent ~20 years is likely an unrealistic goal, demanding actinide waste losses below 0.1% of the core inventory. Note, however, that although the 300-year radiotoxicity is very high relative to the final Phase III resulting waste, the TRU inventory burned translated into a very significant reduction of the legacy waste to a fraction of its original amount.

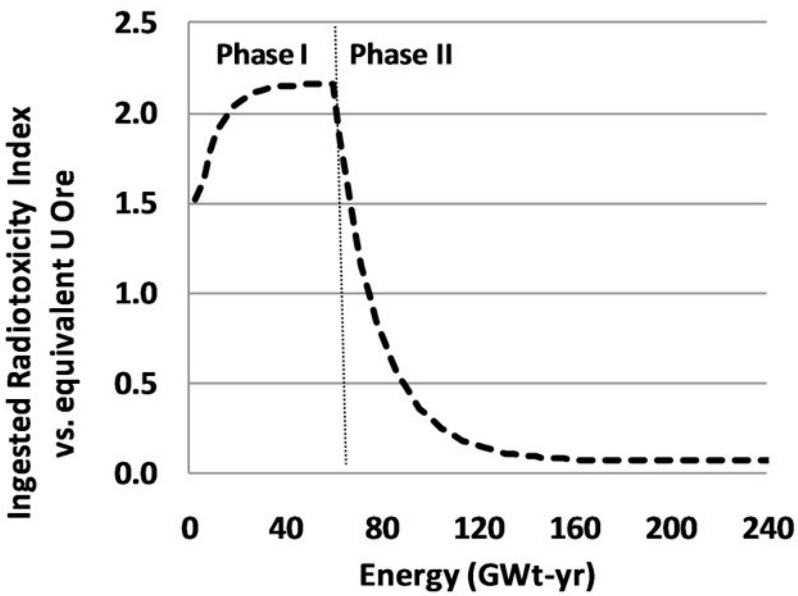

Fig. 7: Ingestion radiotoxicity index at 300 years, relative to the equivalent U ore, versus energy produced

CONCLUSION

A comprehensive “back-to-front” approach to the fuel cycle has recently been proposed by Westinghouse which emphasizes achieving “acceptable”, low-radiotoxicity, high-level waste, with the intent not only to satisfy all technical constraints but also to improve public acceptance of nuclear energy. Following this approach, the thorium fuel cycle, due to its low radiotoxicity and high potential for TRU transmutation has been selected as a promising solution. Additional studies not shown here have shown significant reduction of decay heat [12].

The TRU burning potential of the Th-based fuel cycle has been illustrated with a variety of fuel types, using the Toshiba ARR to perform the analysis, including scenarios with continued LWR operation of either uranium fueled or thorium fueled LWRs. These scenarios will afford overall reduction in actinide radiotoxicity, however when the TRU supply is exhausted, a continued U-235 LWR operation must be assumed to provide TRU makeup feed. This scenario will never reach the characteristically low TRU content of a closed thorium fuel cycle with its associated potential benefits on waste radiototxicity, as exemplified by the transition scenario studied.

At present, the cases studied indicate ThC as a potential fuel for maximizing TRU burning, while ThN with nitrogen enriched to 95% N-15 shows the highest breeding potential. As a result, a transition scenario with ThN was developed to show that a sustainable, closed Th-cycle can be achieved starting from burning the legacy TRU stock and completing the transmutation of the residual TRU remaining in the core inventory after the legacy TRU external supply has been exhausted. The radiotoxicity of the actinide waste during the various phases has been characterized, showing the beneficial effect of the decreasing content of TRU in the recycled fuel as the transition to a closed Th-based fuel cycle is undertaken.

Due to the back-to-front nature of the proposed methodology, detailed designs are not the first step taken when assessing a fuel cycle scenario potential. As a result, design refinement is still required and should be expected in future studies. Moreover, significant safety assessment, including determination of associated reactivity coefficients, fuel and reprocessing feasibility studies and economic assessments will still be needed for a more comprehensive and meaningful comparison against other potential solutions. With the above considerations in mind, the potential advantages of thorium fuelled reactors on HLW management optimization lead us to believe that thorium fuelled reactor systems can play a significant role in the future and deserve further consideration.

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