USE OF THORIUM FOR TRANSMUTATION OF PLUTONIUM AND MINOR ACTINIDES IN PWRS

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Abstract

The objective of this work was to assess the potential of thorium based fuel to minimise Pu and MA production in Pressurised Water Reactors (PWRs). The assessment was carried out by examining destruction rates and residual amounts of Pu and MA in the fuel used for transmutation. In particular, sensitivity of these two parameters to the fuel lattice Hydrogen to Heavy Metal (H/HM) ratio and to the fuel composition was systematically investigated. All burn-up calculations were performed using CASMO4 – the fuel assembly burn-up code. The results indicate that up to 1 000 kg of reactor grade Pu can potentially be burned in thorium based fuel assemblies per GW_eYear. Up to 75% of initial Pu can be destroyed per path. Addition of MA to the fuel mixture degrades the burning efficiency. The theoretically achievable limit for total TRU destruction per path is 50%. Efficient MA and Pu destruction in thorium based fuel generally requires a higher degree of neutron moderation and, therefore, higher fuel lattice H/HM ratio than typically used in the current generation of PWRs. Reactivity coefficients evaluation demonstrated the feasibility of designing a Th-Pu-MA fuel with negative Doppler and moderator temperature coefficients.

Introduction

Plutonium and Minor Actinides (MA) in spent nuclear fuel represent a considerable nuclear proliferation concern and have a major contribution to the long-term radiotoxicity of nuclear waste. Extensive research is currently in progress aimed at reduction of existing Pu and MA in the spent Light Water Reactors (LWR) fuel stockpiles. However, many of the proposed solutions require significant development effort and very likely high costs. For example, many accelerator driven and critical fast spectrum systems use advanced materials and components that have yet to be proven economically. Alternatively, use of U-Pu MOX fuel in LWRs is less costly to implement but the production of Pu from uranium in the fuel reduces the effectiveness of Pu destruction.

In order to accelerate Pu and MA destruction, the amount of uranium loaded into the core must be minimised. Two options seem to be promising in that respect – fertile-free and thorium based fuels. The utilisation of the existing PWR fleet makes both of these options economically attractive.

Fuel cores based on fertile-free fuels exhibit a large reactivity swing. Cores with mixed fertile free and UO_2 fuel may have high power peaking and impose some additional requirements on reactor control. As a result, only a limited number of fertile-free assemblies can be placed in the core.

Thorium-based fuels can potentially reduce the reactivity swing due to the continuous build up of ^{233}U and would have a more favourable Doppler reactivity coefficient. At the same time, similar to non-fertile fuels, thorium as a primary fertile material in the core allows effective burning of Pu and MA because virtually no Pu and MA are generated from thorium. ThO_2 is the preferable form to be used as a fuel due to substantial accumulated experience, mostly in the 70s and 80s, as well as its compatibility with light water coolant.

The effectiveness of TRU transmutation in thermal reactors can be argued by the fact that MAs have large capture cross-sections in thermal spectra. In such spectra, MAs can be rapidly transmuted by neutron capture to fissile isotopes with high fission cross sections, and thus eventually destroyed. In addition, the thermal spectrum cross sections for neutron absorption are 200-300 times larger than for fast neutrons. Thus, at a given power level a thermal spectrum system requires a significantly smaller actinide inventory, even though fast systems operate at higher neutron flux levels than thermal systems. This ultimately implies that thermal spectrum systems will discharge a smaller amount of minor actinides for reprocessing and, therefore, potentially reduce reprocessing costs. However, this is to be evaluated against particular designs of both the manufacturing and reprocessing facilities (for example, IFR may have less costly reprocessing).

In this work, we focus on establishing the practical limits for Pu and MA burning efficiency and on the feasibility of thorium based fuel in PWRs. The main parameters of interest are the rate of total Pu and MA destruction and residual fraction of transuranic nuclides (TRU) in discharged fuel. The former parameter is, effectively, the number of kilograms of TRU that are burnt per unit energy produced by the fuel. The latter parameter indicates the amount of TRU that will have to be recycled or disposed of in the nuclear waste repository.

The fuel composition (relative amounts of Th, Pu, MA and U in the fuel) and lattice geometry will affect both of these indices: the burning efficiency and rate of TRU destruction. Therefore, the study reported here consists of several parts. First, homogenous reactor grade PuO_2-ThO_2 mixtures are studied covering a wide range of possible compositions and geometries. Then, the effect of the addition of a small amount of natural uranium to the fuel was investigated. This option is important for the once-through TRU burning scenario where the discharged fuel will be sent directly to the

repository. In this case, ^{233}U generated from ^{232}Th has to be isotopically diluted (denatured) in order to eliminate potential nuclear proliferation threats. Next, MAs were also considered as part of the fuel and the efficiency and destruction rates of Pu, MA and total TRU were investigated.

The PWR fuel lattice allows a certain degree of freedom in optimisation of the fuel to moderator volume ratio. This ratio defines the degree of neutron moderation and, therefore, absorption and fission reaction rates in different HM nuclides in the fuel. For that reason, a scooping study was carried out to evaluate the effect of the fuel lattice geometry on Pu and MA destruction performance for each fuel composition considered.

Finally, the feasibility of utilisation of TRU-loaded thorium based fuels in the current generation of PWRs was studied by a comparative analysis of the reactivity coefficients and soluble boron worths for a number of realistic TRU-Th cases, typical MOX and conventional all-U fuel.

Methodology and description of calculated cases

All burn-up and criticality calculations in this study were performed using the CASMO4 fuel assembly burn-up computer code, [1] which uses a 70 energy group neutron cross-section library. Benchmark calculations reported in [2] demonstrated that CASMO4 is suitable for scooping studies of thorium – plutonium based fuel designs. It predicts reasonably well criticality, evolution of the fuel composition with burn-up and fuel reactivity coefficients. The results obtained with CASMO4 fall within the uncertainties of other codes evaluated in the benchmark.

However, careful evaluation of the accuracy of different computational tools for fuel design with large loading of MA has yet to be performed. It should also be noted that the accuracy of currently available nuclear data for MA nuclides is limited to a considerable extent. For example, the differences in thermal cross-sections of some MA between major nuclear data files can range up to 30%. [3]

The burn-up calculations were performed for a fuel pin cell geometry of a typical PWR. The reference fuel pin cell geometry and operating parameters used in the calculations are summarised in Table 1.

Table 1. **Reference pin-cell geometry and operating parameters**

Fuel pellet diameter, mm	8.192
Gap thickness, mm	0.082
Outer Cladding diameter, mm	9.500
Lattice Pitch, mm	12.6
Fuel temperature, K	900
Coolant temperature, K	583
Power density, kW/l	104
Reference H/HM ratio	3.64

The effect of differences in the neutron energy spectrum was studied by changing the hydrogen to heavy metal atom ratio (H/HM). Different H/HM ratios were simulated by varying water density in the fuel pin cell of fixed reference geometry. For the purposes of current study, this approach of varying H/HM can be considered neutronically equivalent to other more realistic options as demonstrated in [4]. The H/HM ratios were varied in a wide range from about 0.002 to about 70. All fuel compositions analysed in this study are summarised in Table 2.

In cases with zero MA loading, the isotopic composition of the Pu vector that was used is shown in Table 3. This composition corresponds to Pu in the spent fuel from a typical LWR, using all-U fuel with initial ^{235}U enrichment of 4.5% and irradiated to about 50 MWd/kg, immediately after discharge. Four different initial Pu loadings of 7, 9, 11 and 15w/o relative to total HM in the fuel (cases 1 through 4 in Table 2) were analysed to cover the whole range of possible fuel cycle lengths.

In cases 5 through 8 in Table 2, 15w/o of natural uranium was added to the initial Pu-Th fuel composition in order to assure that the uranium proliferation index in the discharged fuel is smaller than 0.12. The uranium proliferation index is defined as: [5]

$$\frac{\text{Weight of } ^{233}U + 0.6 \times \text{Weight of } ^{235}U}{\text{Total Weight of Uranium}} < 0.12 \qquad (1)$$

The initial Pu and MA isotopic composition of the Pu-MA-Th fuel (cases 9 through 11 in Table 2) is shown in Table 4. This composition corresponds to the isotopics of 4.2% enriched conventional UO_2 fuel irradiated to 50 MWD/kg and then decayed for 10 years. Three different loadings of TRU in Th were studied, again, to cover a broad range of possible fuel cycle lengths. In the reference fuel pin cell geometry these three fuel compositions will result in 12, 18 and 36 months operating cycle lengths respectively.

In this part of the study, the amount of natural uranium added for denaturing of bred ^{233}U was chosen to be about 20% relative to the amount of thorium in the fuel. It was assumed that all MAs in the fuel have the chemical form of $(MA)O_2$ with densities equal to the theoretical density of PuO_2.

Table 2. **Summary of studied fuel compositions**

Fuel comp.	**Description**	**Th** (w/o)	**Natural uranium** (w/o)	**Pu (w/o)**	**MA** (w/o)	**Isotopic vector**
1	Pu-Th unden.	93.0	–	7.0	–	Table 3
2	Pu-Th unden.	91.0	–	9.0	–	Table 3
3	Pu-Th unden.	89.0	–	11.0	–	Table 3
4	Pu-Th unden.	85.0	–	15.0	–	Table 3
5	Pu-Th den.	78.0	15.0	7.0	–	Table 3
6	Pu-Th den.	76.0	15.0	9.0	–	Table 3
7	Pu-Th den.	74.0	15.0	11.0	–	Table 3
8	Pu-Th den.	70.0	15.0	15.0	–	Table 3
9	Pu-MA-Th den.	63.58	13.54	19.82	3.05	Table 4
10	Pu-MA-Th den.	61.89	13.18	21.60	3.32	Table 4
11	Pu-MA-Th den.	58.51	12.47	25.15	3.87	Table 4
12	MOX	–	93.00	7.00	–	Table 3
13	All-U	–	100 (4.5% ^{235}U)	–	–	–

Core leakage was neglected in these scooping studies and the reactivity limited single batch burn-up (BU1) and fuel cycle length were estimated by calculating the burn-up at which kind of the fuel equals unity. The discharge fuel burn-up was estimated using a 3-batch linear reactivity model, as 1.5×BU1. [6]

Table 3. **Initial Pu isotopic composition in Th-Pu fuel**

Isotope	**Weight** (%)
^{238}Pu	2.883
^{239}Pu	54.602
^{240}Pu	21.150
^{241}Pu	15.300
^{242}Pu	6.064

In current PWRs, only reasonably moderate changes in the fuel assembly configuration are possible in order to optimise fuel performance parameters. Additionally, denaturing of bred ^{233}U is a required constraint for a practical design. In light of these two considerations, only denatured cases with H/HM ratios between the reference case and the reference +40% case were evaluated in terms of reactor operational characteristics.

The Doppler reactivity coefficient (DC), Moderator temperature coefficient (MTC), Void coefficient (VC) and Soluble Boron Worth (BW) were calculated for the compositions 5 through 11 in Table 2 at 3 different H/HM ratios and at 3 time points: beginning (BOL), middle (MOL) and end (EOL) of fuel irradiation. In order to simulate close to realistic operating reactor conditions, all reactivity coefficients were calculated assuming that the soluble boron concentrations are 1 000 ppm, 500 ppm, and 0 ppm at BOL, MOL, and EOL respectively.

The reactivity coefficients were calculated as follows.

$$MTC = \frac{\Delta K}{K_1 \times K_2 \times \Delta T_m} \tag{2}$$

where ΔT_m is the moderator temperature difference between two moderator temperatures T_1 and T_2 and K_1 and K_2 are infinite medium neutron multiplication factors corresponding to temperatures T_1 and T_2, respectively.

$$DC = \frac{\Delta K}{K_1 \times K_2 \times \Delta T_f} \tag{3}$$

where ΔT_f is fuel temperature difference between two fuel temperatures T_1 and T_2.

$$VC = \frac{\Delta K}{K_1 \times K_2 \times \Delta V} \tag{4}$$

where ΔV is the difference between two coolant void fractions V_1 and V_2.

$$BW = \frac{\Delta K}{K_1 \times K_2 \times \Delta C} \tag{5}$$

where ΔC is boron concentration difference in ppm.

Table 4. **Initial Pu isotopic composition in Pu-MA-Th fuel**

Isotope	**Weight** (%)
^{234}U	0.0001
^{235}U	0.0023
^{236}U	0.0019
^{238}U	0.3247
^{237}Np	6.641
^{238}Pu	2.7490
^{239}Pu	48.6520
^{240}Pu	22.9800
^{241}Pu	6.9260
^{242}Pu	5.0330
^{241}Am	4.6540
^{242m}Am	0.0190
^{243}Am	1.4720
^{242}Cm	0.0000
^{243}Cm	0.0050
^{244}Cm	0.4960
^{245}Cm	0.0380
^{246}Cm	0.0060

Results and discussion

Pu-Th cases

One of the most important characteristics of the fuel designed for Pu disposition is the Pu destruction rate; namely, the number of kilograms of Pu destroyed per unit energy produced by the fuel. Figure 1 shows Pu destruction rates normalised per 1 GWeYear for both the denatured and un-denatured cases. The Pu destruction rate is relatively insensitive to the Pu loading and to the H/HM ratio in the neighbourhood of the reference H/HM value.

The rate of Pu destruction for low Pu loadings at low H/HM ratios (in epithermal energy spectra) exhibits an increase since the fuel cycle length in this region is relatively short whereas fissile ^{239}Pu burns out rather rapidly at the beginning of fuel irradiation, increasing total Pu destruction rate. Although high Pu destruction rates in this H/HM region can be achieved, very low fuel cycle length and, thus, frequent reprocessing makes these cases impractical and uneconomical. In contrast, the rate of Pu destruction for the fuel with high Pu loading monotonically decreases as H/HM ratio decreases (Figure 1). In this case, energy from fission of ^{233}U is substantial due to effective breeding in the epithermal and fast spectra. The initial Pu loading is high enough to sustain core criticality until a significant amount of ^{233}U is generated. As a result, the Pu destruction rate is reduced because of the competition between neutron absorption in Pu and ^{233}U, although high burn-up, in general, results in deeper Pu burning as shown in Figure 2. However, the calculated achievable burn-up is an overestimate since neutron leakage was not considered. Additionally, due to the harder neutron spectrum, leakage is expected to be higher in Pu containing cores than in all-U core.

Figure 1. **Energy normalised Pu destruction rate**

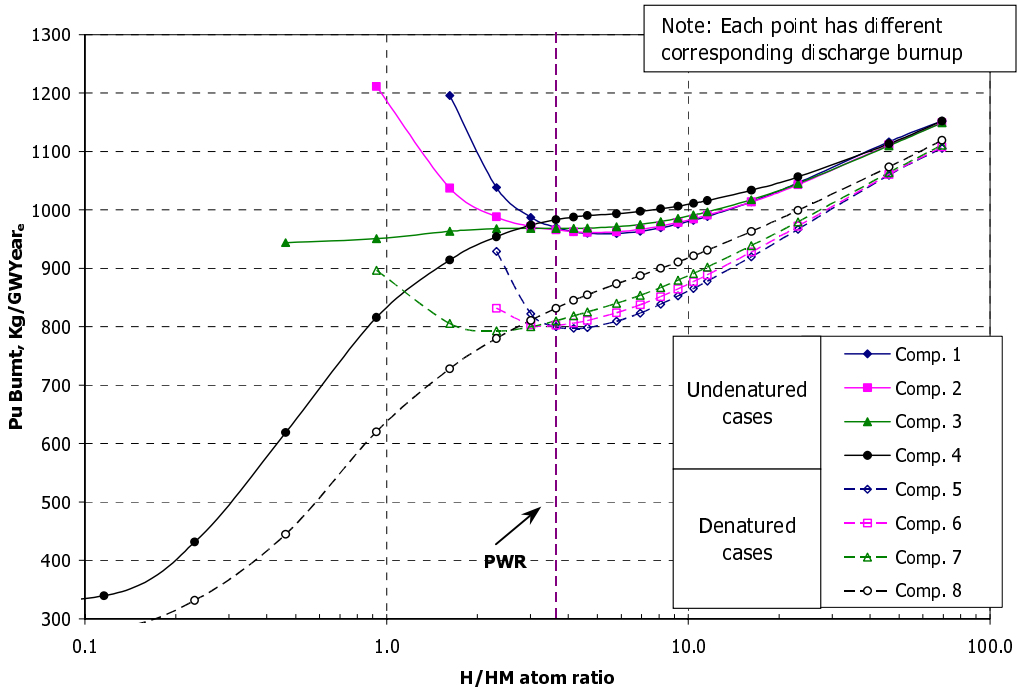


Figure 2 also suggests that deeper Pu burning (that is, to minimise the fraction of residual Pu in discharged fuel) in a PWR core cannot be increased substantially by the variation of H/HM ratio. However, there is an improvement from 67% up to 75% of initially loaded Pu can be potentially destroyed by increasing the H/HM ratio from 3.64 to about 7 for undenatured fuel compositions (cases 1 through 4 in Table 2). Nevertheless, at high H/HM in a given core volume, the total initially loaded Pu will be smaller.

Addition of uranium to the fuel decreases Pu destruction rate as expected. Figure 2 illustrates this fact. At the reference H/HM ratio point, the addition of 15w/o of natural uranium reduces the rate of Pu destruction by about 20%, although this relative reduction in the destruction rate becomes smaller for “wetter” than reference fuel lattices. Even at the reference H/HM, 50% Pu destruction is possible.

At the reference H/HM ratio, denaturing can almost double the amount of residual Pu (Figure 2). However, at higher than reference H/HM ratios, the difference between the denatured and undenatured cases becomes smaller and even vanishes for highly over-moderated lattices. This is partially due to the fact that denatured cases in the over-moderated region achieve slightly higher burn-up due to higher BOL reactivity and smaller conversion ratio. Additionally, the sensitivity of residual Pu fraction to H/HM ratio is notably greater for denatured than for undenatured cases. The increase of H/HM from the reference value to about 10 can reduce the residual Pu fraction nearly by the factor of 2.

Figure 2. **Residual Pu fraction**

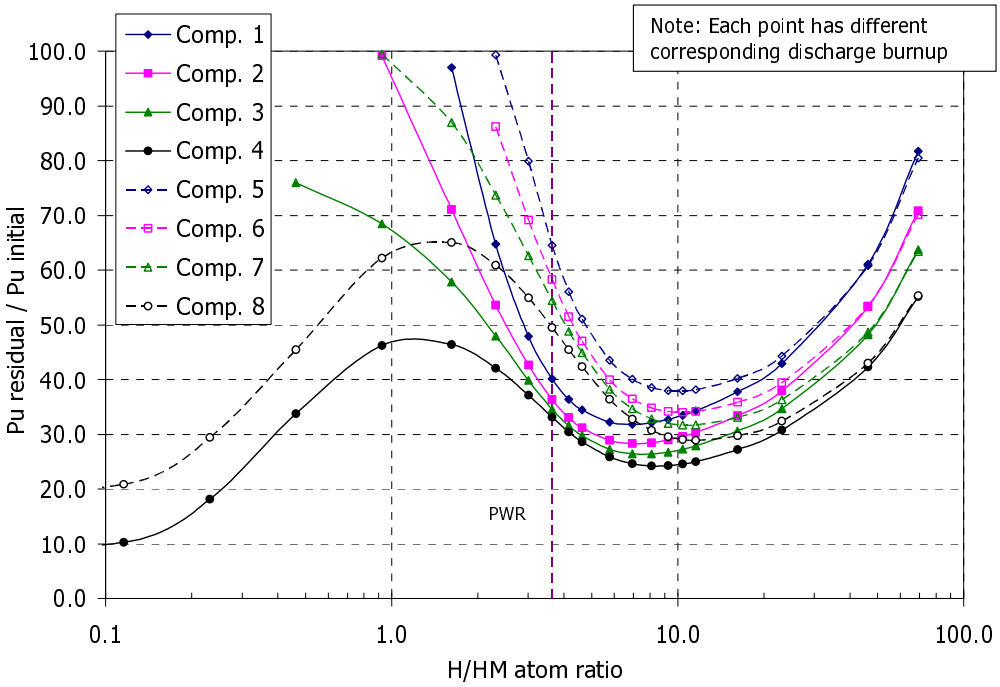


Figure 3. **Uranium proliferation index**

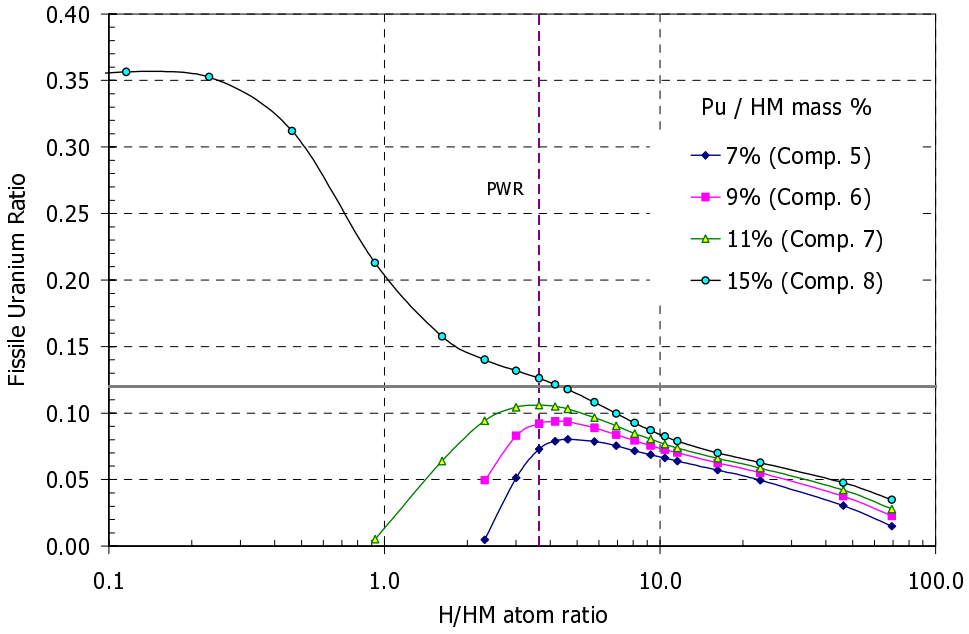


Figure 3 shows the uranium proliferation index as a function of H/HM for denatured cases. Addition of 15 w/o of natural uranium seems to be enough to assure the proliferation resistance of uranium in discharged fuel for most of the calculated cases. In fact, the uranium proliferation index decreases with H/HM which indicates that the amount of natural uranium can be reduced for wetter fuel lattices, which also improves Pu burning performance.

Pu-MA-Th cases

The potential of TRU destruction is an important feature of innovative fuel designs which can help the effort to reach sustainable fuel cycles. Only systems that utilise fuel which burns more TRU than originally loaded have the ability to reach an equilibrium state in a completely closed fuel cycle with zero net generation of TRUs.

Thorium based fuels used for disposition of Pu and MA, although they do not create a new generation of Pu and MA, produce noticeable amounts of actinides originating from ^{232}Th. The most valuable nuclide for the sustainable closed fuel cycle scenario is ^{233}U. It typically constitutes over 90% of all Th chain isotopes. It has a large thermal fission cross-section; thus, it can be efficiently recycled. However, small amounts of other Th chain nuclides are long-lived and radioactive. For example minute quantities of ^{232}U can significantly complicate fuel reprocessing and fabrication because of the presence of strong γ-emitters in its decay chain. [7]

Finally, all nuclides produced by neutron capture from ^{232}Th and subsequent decay have been added to the TRU waste. Therefore, in a once-through fuel cycle scenario, with the main objective being to maximise the consumption of TRU per path, Th chain nuclides have to be included in the total balance of actinides discharged to the repository.

Figure 4 reports TRU destruction rates normalised per 1 GWeYear for 3 different initial TRU loadings that in the reference PWR fuel pin cell geometry will result in 12, 18 and 36 month fuel cycle lengths. In this part of the study we report the TRU destruction rates and their residual amounts with and without including the Th chain nuclides in the total balance, since both indexes are of interest.

The following observations are made.

- The TRU destruction rates monotonically increase with increasing H/HM ratio over the whole investigated range of fuel lattice geometries. Therefore, it is always beneficial to keep H/HM as high as possible from the TRU destruction rate viewpoint.
- The destruction rates of TRU without Th chain nuclides are not sensitive to the initial TRU loading.
- The contribution of Th chain nuclides to total TRU destruction rate varies with H/HM and initial TRU loading. This variation originates in the fact that the efficiency of ^{233}U build-up depends on H/HM as well as on other actinide inventories.

Figure 4. **Energy normalised TRU destruction rate**

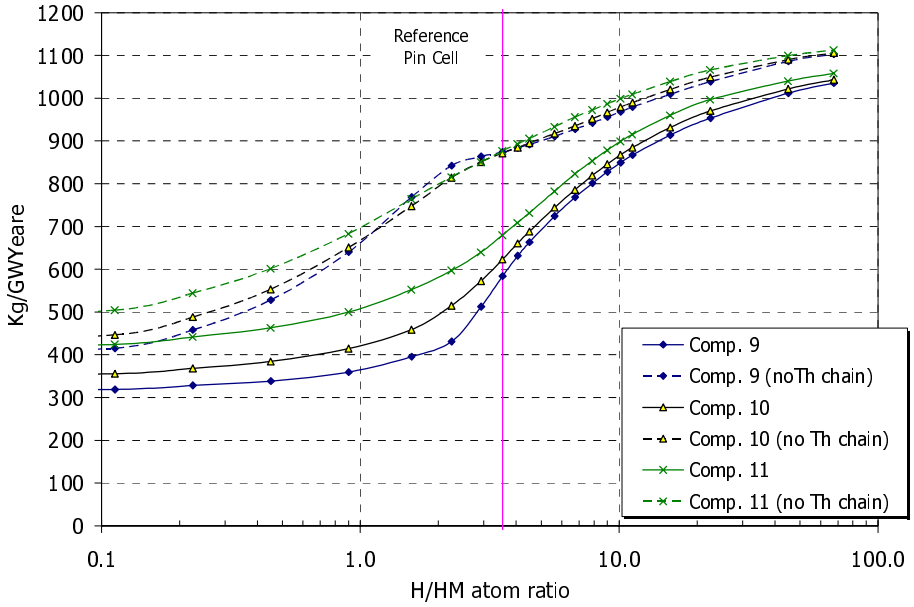


Figure 5. **Energy normalised MA destruction rate**

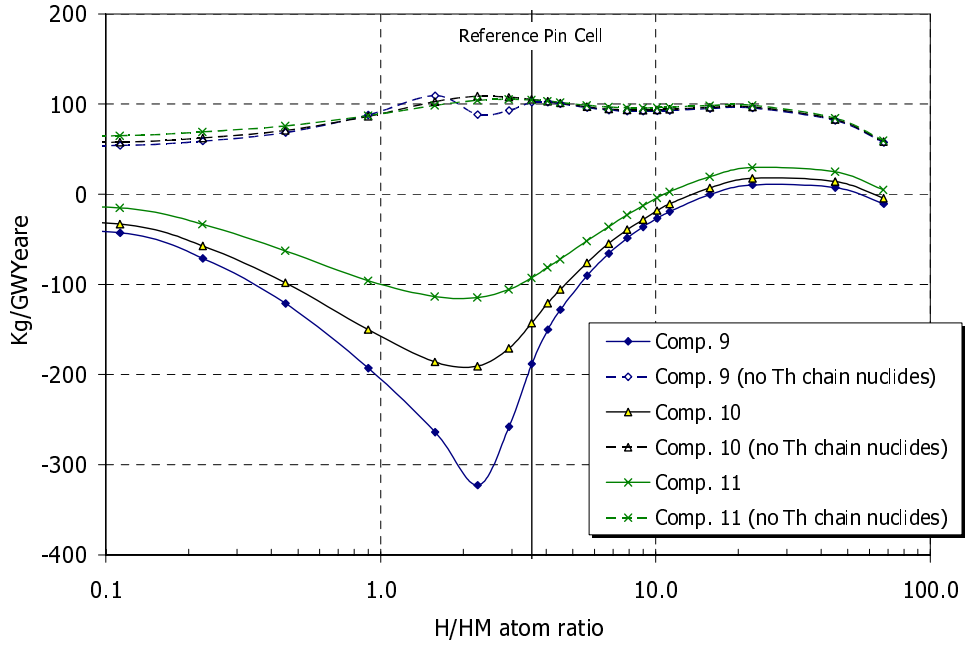
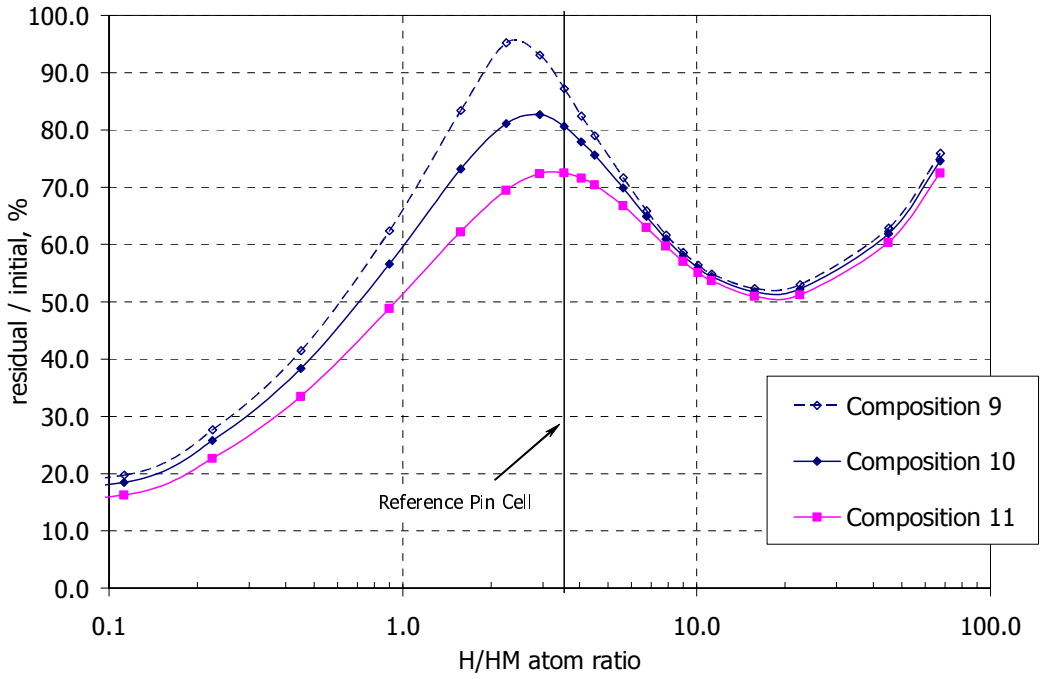


Figure 5 shows the MA-only contribution to the total TRU destruction rate. As can be observed from Figure 5, the actual reduction in MA inventory can be achieved only for highly over-moderated lattices if Th chain nuclides are included in the balance. If Th chain nuclides are not considered, the reduction of MA inventory is possible with a rate of about 100 kg per GWeYear. This rate appears to be remarkably insensitive to the initial TRU inventory and H/HM ratio in the range of practical interest (from 1 to 10).

The fraction of residual TRU in spent fuel not including Th chain nuclides is shown in Figure 6. The data plotted in Figure 6 suggests that the reference pin cell geometry is highly unfavourable from the effectiveness of TRU destruction standpoint. Higher initial TRU loadings are preferable as they result in deeper TRU burnout for H/HM ratios close to the reference one. However, this difference vanishes as H/HM approaches 10. The maximum theoretically achievable degree of TRU burnout is about 50% of initial loading at H/HM of about 11.

Figure 6. **Residual fraction of TRU (No Th chain nuclides)**



Reactivity coefficients

The results of the analysis presented above suggest that higher than reference H/HM ratios are preferable for effective Pu destruction. Therefore, reactivity coefficients were evaluated at H/HM values ranging from the reference PWR fuel pin cell to reference + 40% H/HM.

All reactivity coefficients were calculated on the basis of a pin cell geometry. Core average reactivity coefficients would be somewhat different as a core is composed of fuel assemblies with different accumulated burn-up. The pin cell based calculations, however, can be used for comparison of different fuel designs with different compositions and H/HM ratios against reference UO_2 fuel evaluated on the same basis.

Selected results of reactivity coefficient as well as soluble boron worth calculations are summarised in Table 5. All fuel compositions presented in Table 5 correspond to the 18 months cycle length currently widely accommodated by the nuclear industry.

MOX fuel provides somewhat stronger Doppler fuel temperature reactivity feedback (DC) than all-U fuel, while Pu-Th fuel has more negative DC than MOX and all-U. Wetter lattice yields slightly less negative DC than the reference one, nevertheless, Pu-Th fuel in wetter lattice has still more negative DC than reference All-U fuel.

Strongly negative DC is beneficial for transients associated with fuel temperature increase as it provides stronger negative reactivity feedback, however it results in larger reactivity insertion in start-up and shutdown scenarios. Stronger DC may also be a disadvantage in the reactor's response to sudden cool-down scenarios, such as a steam generator depressurisation event.

Calculated Moderator temperature and Void coefficients (MTC and VC respectively) for Th based fuels are negative and exhibit smaller variation with burn-up than All-U and MOX fuel. The absolute values of MTC and VC of Pu-Th cases are close to those observed for the typical MOX fuel while Pu-MA-Th fuels have MTC and VC values close to those of the All-U case. The calculated values of MTC and VC are consistent with those previously reported in [8] and [9]. The effect of increased H/HM ratio is not particularly significant for Th based cases. All reactivity coefficients stay negative over the entire investigated range of H/HM values.

Table 6 shows an example of the BOL reactivity control requirements and soluble boron worth (BW) for a number of calculated cases. The BOL whole core excess reactivity was estimated assuming a 3 batch core with linear burn-up-reactivity dependence for each batch. 3% of $\Delta\rho$ was allowed for leakage. No burnable poisons were considered. The BW of partially burned batches was assumed to be equal to the fresh batch BW, which is a conservative assumption since BW, generally, increases with the burn-up.

Although Pu-Th and Pu-MA-Th fuels require much smaller initial excess reactivity to control, the soluble boron worth is much smaller than that of the All-U fuel. As a result, the soluble boron concentrations required to control the initial excess reactivity are comparable to All-U fuel and in some cases considerably higher. Increasing the loading of TRUs in Th based fuels leads to harder neutron spectra and, therefore, lower soluble boron worth. Higher than reference H/HM increases neutron moderation and, as a result, increases soluble boron worth.

In general, the relatively hard neutron spectrum in all TRU containing fuels necessitates that special attention be devoted to the design of reactor control. Utilisation of enriched boron or gadolinium in control rods or as a burnable poison might be necessary to satisfy reactor safety criteria for Th-TRU fuel designs.

Summary and conclusions

The present study established potential limits for the efficiency of Pu and MA destruction in Th based fuels of PWRs. We primarily focused on two performance indexes: the rate of TRU destruction and residual fraction of TRU relative to initial TRU loading.

The results of the study showed that Th based fuel designs can be effectively used to reduce existing stockpiles of TRU in PWRs and, theoretically, can be part of a sustainable closed fuel cycle system with zero net generation of TRUs.

The reasonably achievable rate of TRU destruction in Th based fuel is about 1 000 kg of TRU destroyed per 1 GWeYear, while up to 50% of initially loaded TRU can, theoretically, be destroyed per path.

Denaturing of generated ^{233}U with natural uranium degrades the efficiency of Pu destruction. However, denaturing is required only for the once-through fuel cycle. In that case, denaturing reduces Pu destruction rates by approximately 20%. The difference in the destruction rate and the residual Pu fraction between the denatured and un-denatured cases decreases for wetter than reference lattices.

Table 5. **Reactivity coefficients: selected results**

Comp. No.	Description	Reference H/HM			Reference + 40% H/HM		
		BOL	MOL	EOL	BOL	MOL	EOL
DOPLER COEFFICIENT (pcm/K)							
6	Pu-Th den.	-4.32	-4.65	-5.04	-3.43	-3.78	-4.22
9	Pu-MA-Th den.	-2.98	-3.02	-3.15	-2.63	-2.80	-3.02
12	MOX	-2.92	-3.09	-3.20	-2.36	-2.57	-2.70
13	All-U	-2.20	-2.93	-3.33	-1.82	-2.31	-2.75
MODERATOR TEMPERATURE COEFFICIENT (pcm/K)							
6	Pu-Th den.	-49.05	-58.68	-73.47	-38.91	-50.40	-66.73
9	Pu-MA-Th den.	-18.53	-17.69	-23.40	-29.57	-33.17	-44.86
12	MOX	-40.63	-54.65	-73.78	-32.37	-46.92	-66.39
13	All-U	-22.17	-51.62	-77.79	-2.21	-26.00	-50.07
VOID COEFFICIENT (pcm/%void)							
6	Pu-Th den.	-128.0	-156.8	-198.3	-104.8	-142.9	-190.4
9	Pu-MA-Th den.	-42.8	-41.4	-51.7	-70.8	-85.3	-115.8
12	MOX	-104.8	-145.3	-200.7	-86.0	-130.8	-190.8
13	All-U	-62.5	-145.7	-228.0	-10.8	-83.5	-164.8
SOLUBLE BORON WORTH (pcm/ppm)							
6	Pu-Th den.	-1.95	-2.28	-3.02	-2.82	-3.60	-5.15
9	Pu-MA-Th den.	-1.05	-1.03	-1.24	-1.73	-1.90	-2.24
12	MOX	-1.96	-2.37	-2.76	-2.88	-3.70	-4.85
13	All-U	-4.80	-5.22	-6.23	-6.65	-8.15	-11.90

Table 6. **Soluble boron requirements for reactivity control at BOL**

Fuel Comp.	Description	K-inf (BOL), Pin cell	Core average reactivity (BOL), pcm	SB worth pcm/ppm	ppm needed to control
Reference H/HM					
5	Pu-Th den.	1.119	4 098	-2.41	1 699
6	Pu-Th den.	1.146	5 183	-1.95	2 664
7	Pu-Th den.	1.170	6 136	-1.66	3 703
8	Pu-Th den.	1.216	7 849	-1.24	6 322
9	Pu-MA-Th den.	1.062	1 533	-1.05	1 456
10	Pu-MA-Th den.	1.078	2 281	-0.97	2 358
11	Pu-MA-Th den.	1.109	3 672	-0.81	4 525
12	MOX	1.206	7 473	-1.96	3 804
13	All-U	1.380	12 953	-4.80	2 698
Reference H/HM×1.4					
5	Pu-Th den.	1.195	7 092	-3.41	2 080
6	Pu-Th den.	1.216	7 858	-2.82	2 788
7	Pu-Th den.	1.235	8 501	-2.42	3 512
8	Pu-Th den.	1.269	9 631	-1.92	5 022
9	Pu-MA-Th den.	1.100	3 289	-1.73	1 903
10	Pu-MA-Th den.	1.111	3 765	-1.62	2 320
11	Pu-MA-Th den.	1.133	4 680	-1.41	3 324
12	MOX	1.275	9 829	-2.88	3 415
13	All-U	1.440	14 528	-6.65	2 185

The calculated reactivity coefficients and their comparison with MOX and All-U fuel indicate the potential feasibility of Th based fuels utilisation for transmutation of TRU in PWRs.

Somewhat wetter fuel lattices than present PWRs are favourable from the TRU destruction efficiency and reactivity control perspectives. Pu and MA containing Th based fuels have significantly harder neutron spectra than for typical all-U fuel, which reduces control materials worth and imposes additional requirements on the design of reactor control features.

In the future, other strategies for increasing the actinide burning rates will be explored. This will include heterogeneous core configurations with fuel assemblies containing different Pu to MA ratios. Additionally, non-fertile fuel matrixes will be evaluated and compared to Th based homogeneous and heterogeneous designs, MOX fuels, and conventional All-U fuel.

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