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IMPROVING BURNUP PERFORMANCE OF FAST SODIUM COOLED REACTOR BY UTILIZING THORIUM BASED FUELS

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ABSTRACT

To study the improvement of fuel burnup for fast reactors, thorium based fuels are investigated. In order to ensure the projected expansion of nuclear power is achieved in conjunction with reduced risk of nuclear weapons proliferation, new conventional sources of fuel will have to be made available. Thorium fuel cycles have many incentives such as the reduction of plutonium generation and consumption of LWR actinides, the provision of high performance burnup, and the conservation of ^{235}U resources. This work examined the burnup reactivity loss and depletion analysis of thorium versus uranium based metal fuels. When compared the thorium based metallic fuel outperformed uranium based fuel with respect to higher actinide burnup and higher depletion rate of plutonium isotopes.

Key Words: Transuranics, S-PRISM, Burnup, Fast Reactors, Sodium-Cooled

1. INTRODUCTION

The purpose of the work reported in this paper was to perform a comparative analysis of the characteristics of uranium and thorium based fuels based on the objectives of the Advanced Fuel Cycle Initiative (AFCI). It is believed that there are enough uranium resources to sustain nuclear power for the next 100 years at the current global energy demand [1]. The energy demand is expected to grow exponentially in developing countries. As nuclear power becomes a popular option as a clean, economical, and safe alternative source of energy, there are challenges that must be addressed in order to increase the sustainability of the nuclear power generating option for further development. With the global expansion of nuclear power, it is important to utilize alternative resources to meet the increasing global energy demand. The management of nuclear waste associated with the spent fuel is a challenge that must be resolved in order for nuclear power to resonate with the general public. The next generation of nuclear reactor systems should meet the requirements of the AFCI to make fuel treatment technologies more efficient, less waste-intensive and more proliferation resistant. Reducing the inventory of long-lived radioactive species, radio-toxicity of discharged fuel elements and overall heat load on final

disposal systems makes nuclear power more sustainable. Thorium based fuels have distinctive features for next generation reactors that provide enhanced waste minimization and more proliferation resistance.

Thorium-based fuel is an attractive option due to the fact that fewer transuranics (TRU) are produced compared to uranium-based fuels. Fast spectrum reactors with plutonium-thorium or TRU-thorium fuel suggest that thorium-based fuels can efficiently reduce the plutonium stockpile while maintaining acceptable safety and control characteristics of the reactor system. Thorium is three times more abundant in nature compared to uranium and provides greater advantages to plutonium incineration and burnup potential.

Large amounts of nuclear waste containing plutonium and minor actinides (Am, Np, Cm) have been produced during the operation of light water nuclear power plants. There has been a renewed interest in sodium cooled fast reactors to meet modern-day needs to burn these actinides. Fast spectrum reactors are being investigated as part of the AFCI program to enable their repeated recycling since this is an effective way of transmuting and burning actinides. The sodium cooled fast reactor has been one of six candidates chosen by the U.S. Generation IV Initiative for the management of actinides and production of energy.

Since advanced fast reactors are very effective at transmutation, their use will help to reduce such inventory by burning transuranics from Light Water Reactor (LWR) spent fuel. Improving the utilization of fertile material in fast reactors is vital.

Studies have shown that thorium-based fuels in fast spectrum systems can efficiently perform the task of reactor-grade and weapon-grade plutonium stockpile reduction while maintaining acceptable safety and control characteristics of the reactor system [2]. However, the database and experience of thorium fuels and the thorium fuel cycles are very limited as compared to other fuels [3]. Previous investigations performed in test and power reactor experiments; modular high temperature reactor [4], Boiling Water Reactor (BWR) [5], LWRs [6], have all demonstrated that thorium based fuel, whether in combination with uranium, plutonium, or uranium/plutonium have many attractive features including the possibility of reduction of long-term radio-toxicity of discharged spent fuel, breeding of fissile material (^{233}U), burning of plutonium, transmutation of minor actinides, and improvement of the proliferation resistance aspects [7].

The overall modeling for this fuel study is based on the advanced sodium cooled fast reactor, S-PRISM, fueled by recycled spent LWR fuel (PRISM was developed during the DOE's Advanced Liquid Metal Reactor program). The configuration of the S-PRISM core, which is examined in this study, is shown in Fig. 1.

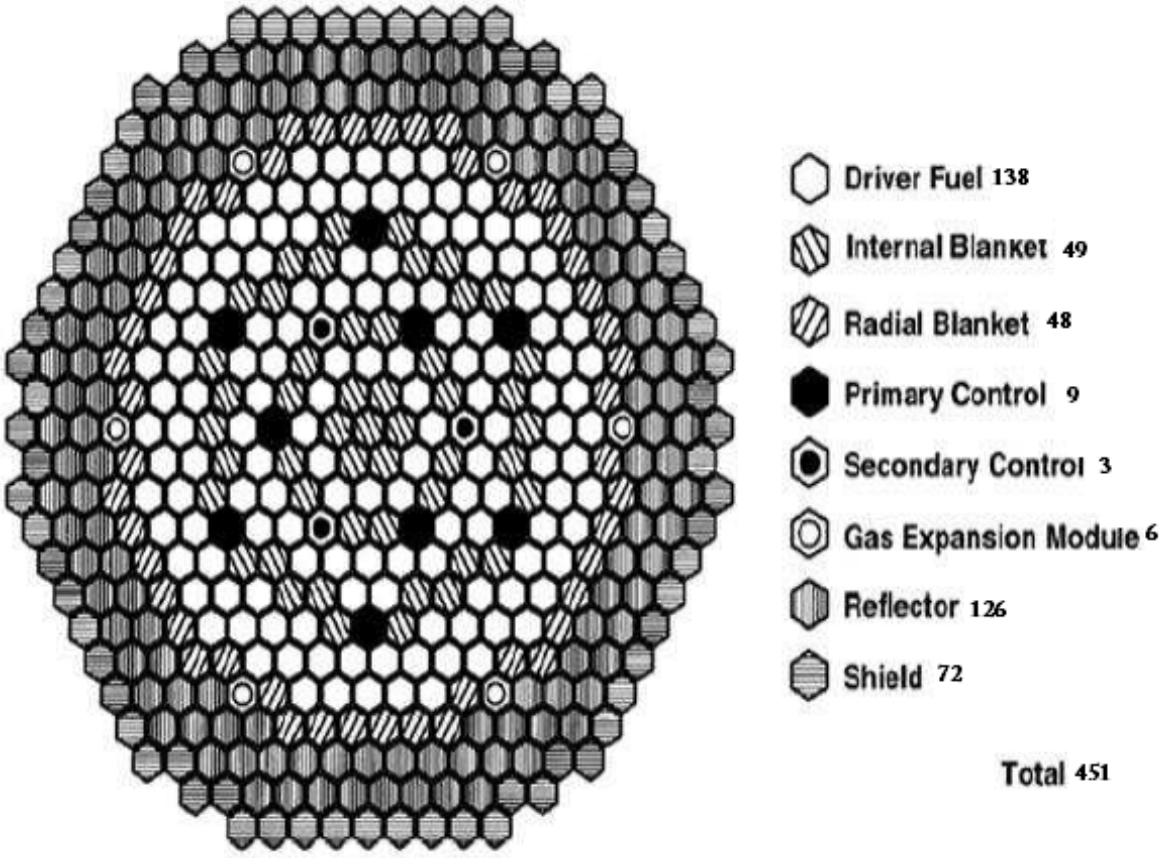

Figure 1. S-PRISM metal core configuration [8]

2. COMPUTATIONAL TOOLS

A number of analytical tools are used to accomplish this study. The continuous energy Monte Carlo method has the capability of modeling with high accuracy core environments with increased material heterogeneity and geometry complexity. First, an S-PRISM core physics model was built in MCNP5 [9] and results were obtained with this model for actinide burning using Th-Zr-TRU fuel. The analysis is then performed with the same MCNP5 core model using U-Zr-TRU matrix fuels of varying composition and the obtained results compared to the Th-Zr-TRU fuel results. The ENDF/B-VI MCNP libraries provided with the MCNP5 code at isothermal cold conditions (293.6K) were used. Subsequently, depletion calculations are performed using MONTEBURNS2.0 [10], which couples MCNP and the ORIGEN2.2 [11] computer codes to calculate coupled neutronic and isotopic results for this reactor core study and produce a large number of criticality and burnup results based on various specifications. Results obtained provided data on a comparative basis regarding actinide burning of uranium versus thorium-based fuel.

In order to evaluate the efficiency of thorium based fuel matrices in sodium-cooled fast reactors the reference model must first be replicated and validated with benchmark results. The first step in the validation process is to model the pin cell and fuel assembly having a repeating S-PRISM lattice. These models and results were summarized in [12]. Once these calculations were

performed and validated the work presented in this paper included modeling of remaining assemblies and core sector of symmetry.

3. REFERENCE CORE DESIGN

The simulation model for this fuel study is based on the advanced sodium fast reactor design, S-PRISM design, fueled by recycled spent LWR fuel. The metal fuel bundles use 271 pins per hexagonal fuel assembly and 127 pins for the blanket bundles with 16.142 cm assembly pitch. The pin-cells within the fuel assembly have a 1.191 pitch-to-diameter ratio with a 0.5477 cm diameter pellet and a 0.744 outer pin diameter. The active fuel height is 101.6 cm with an upper axial plenum of 191.14 cm and the core power is 1000 MWt. These dimensions are summarized in Table I.

Table I. Pin dimensions (Drive Fuel) for the S-PRISM design

Parameter	Value
Fuel OD	0.5477 cm
Gap Thickness	0.0423 cm
Cladding Thickness	0.0559 cm
Cladding material	HT9
P/D	1.191
Active Fuel Height	101.6 cm
Fission Gas Plenum Height	191.14 cm

The reflector assemblies consist of pin bundles of solid HT9. In the perimeter of the S-PRISM metal core configuration there are six GEM (Gas Expansion Module) assemblies. GEM assemblies differ from the other assemblies in their components and are designed to enhance neutron leakage and negative reactivity feedback upon loss of primary flow coolant. In the current study the GEM assemblies were replaced by liquid sodium due to the lack of available information about the material and dimensional configurations. However, comparisons between the thorium and uranium based fuels were made with identical core configurations.

Modeling a reactor core requires more detail than a fuel assembly model and requires more computational time. Therefore, one-sixth of the core is modeled using reflective boundaries in the radial direction with control rods withdrawn. Fig. 2 presents the radial layout of the reference core model. Figure 3 shows a close up schematic of the core emphasizing the level of detail in the modeling.

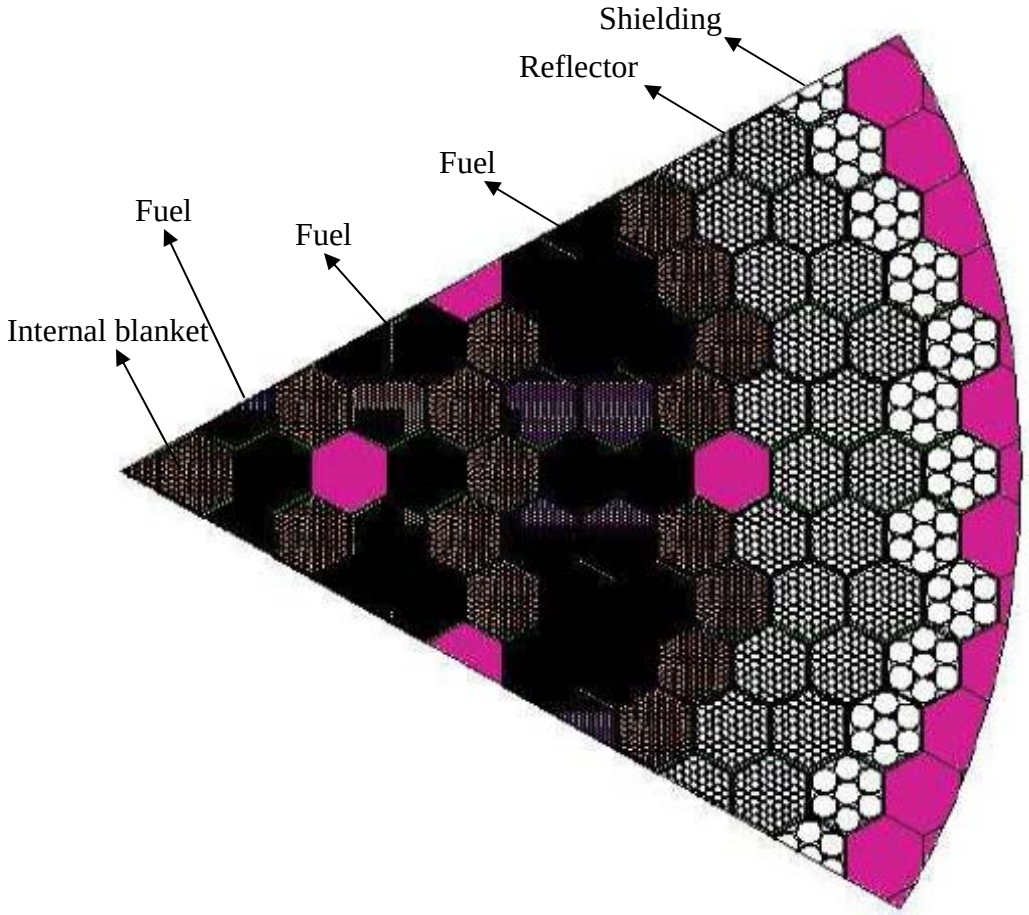

Figure 2. MCNP5 generated schematic of the one-sixth symmetric core showing core regions, radial and axial blankets, shield, reflective and driver fuel assemblies

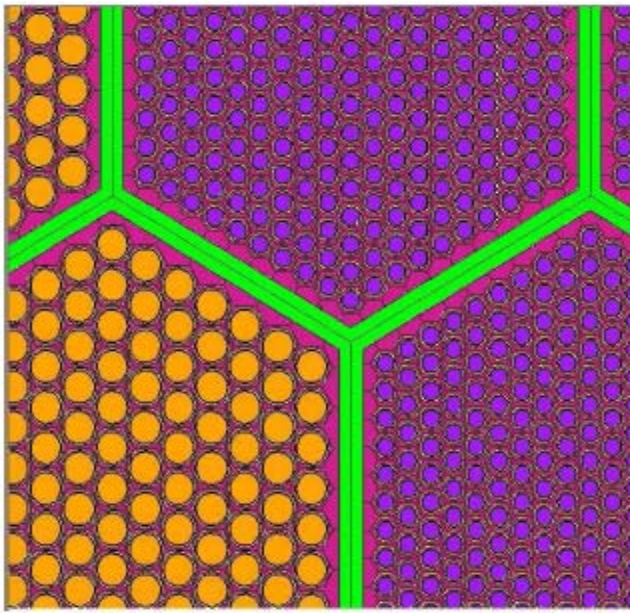

Figure 3. A close up of the one-sixth core model depicting the difference in the size of pins between the driver fuel assemblies and blankets

4. COMPARISONS OF REACTIVITY AS FUNCTION OF TIME

In the current study, it is of interest to track the reactivity with respect to core operation until criticality is lost. The fuel burnup was calculated at a constant linear power as a function of time without any outages. A comparison of the reactivity of the two fuels seen in Figure 4 show that uranium based fuel has a longer fuel cycle life. The thorium based fuel begins with a higher BOL reactivity than the uranium based fuel but loses criticality sooner. The uranium based fuel has a less stepper curve and longer fuel cycle life. The isotopic composition of the Uranium OXide (UOX) Spend Nuclear Fuel (SNF) used in the study is listed in Table II.

To stay within current fuel technology bases the limits for the metal fuel are 30 wt% TRU enrichment and 150 MWd/kgHM [8]. The isotopic content of the fuel for the thorium based fuel was increased from 20% to 30% in order to make its reactivity more comparable with the uranium-based fuel. Several MCNP calculations indicated that using the same fuel composition was not sufficient to sustain criticality when modeling the core. Therefore, the enrichment zone strategy was used to increase Beginning of Life (BOL) reactivity and help flatten the power profile. Therefore, in this study three different levels of enrichment were employed in the initial core. The TRU fractions used for the core analysis are listed in Table III. Though TRU fractions above 30% exceed the design criteria, it serves as a qualitative assessment of the two fuels, which is main objective in this study.

Table II. Isotopic composition for UOX SNF discharged from LWR.

Isotope	Weight percent
Np-237	5.46%
Pu-238	2.47%
Pu-239	45.79%
Pu-240	22.61%
Pu-241	13.18%
Pu-242	7.05%
Am-241	0.50%
$Am\text{-}242^{m}$	0.01%
Am-243	1.92%
Cm-242	0.18%
Cm-243	0.01%
Cm-244	0.78%
Cm-245	0.04%
Cm-246	0.00%

Table III. Fuel composition when using TRU fractions for core model

Fuel	Location	TRU fraction	Total Plutonium wt%	Fissile ^{239}Pu enrichment
Th-TRU-Zr	Inner	30%	27.33	13.74%
	Mid	32.24%	29.37%	14.76%
	Outer	34.48%	31.41%	15.79%
U-TRU-Zr	Inner	20%	18.22	9.158%
	Mid	22.24%	20.26	1.18%
	Outer	24.48%	22.30	11.21%

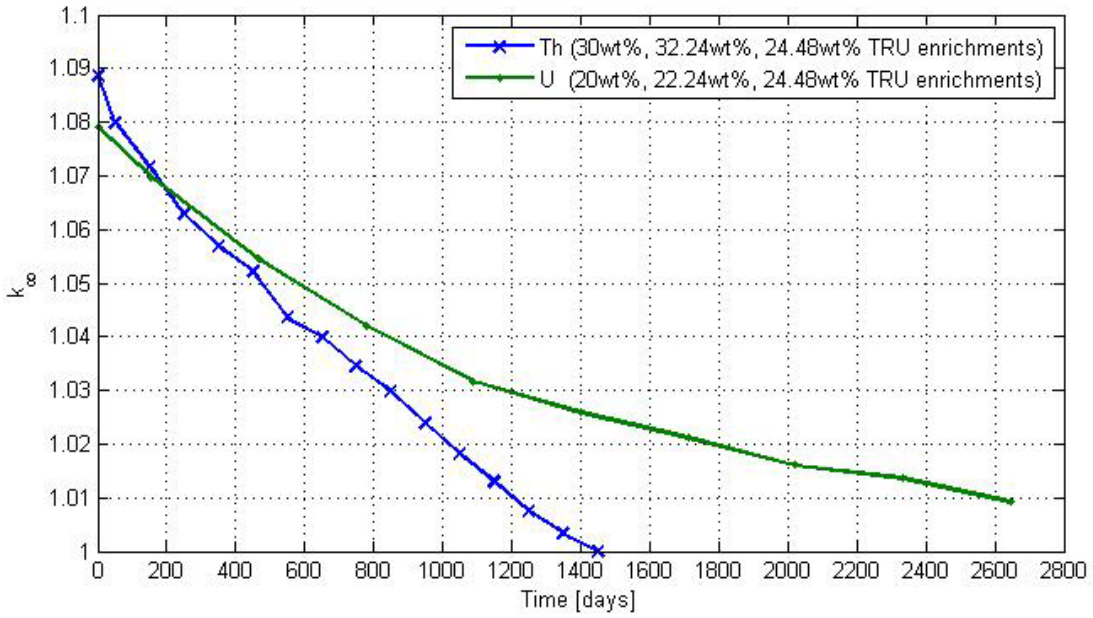

Figure 4. Reactivity as function of time for the thorium and uranium based fuels using three TRU fractions for the core model.

5. DEPLETION ANALYSIS

In this section the isotopic composition at the end of cycle is studied. One of the objectives of the advanced fuel cycle initiative for new generation fuels is to reduce the proliferation potential associated with the weapons usable materials inherent in the fuel at discharge. Therefore, MONTEBURNS was used to demonstrate the capability of each fuel type to eliminate the percent of transuranic weapons-usable materials at discharge. A relatively higher total net isotopic destruction rate, -1.0384 g/MWd, is achieved when using the thorium based fuel (Fig. 5) than the uranium based fuel, -0.3206 g/MWd (Fig. 6). In particular, the destruction rate of the ^{239}Pu isotope in the thorium based fuel is about three times greater.

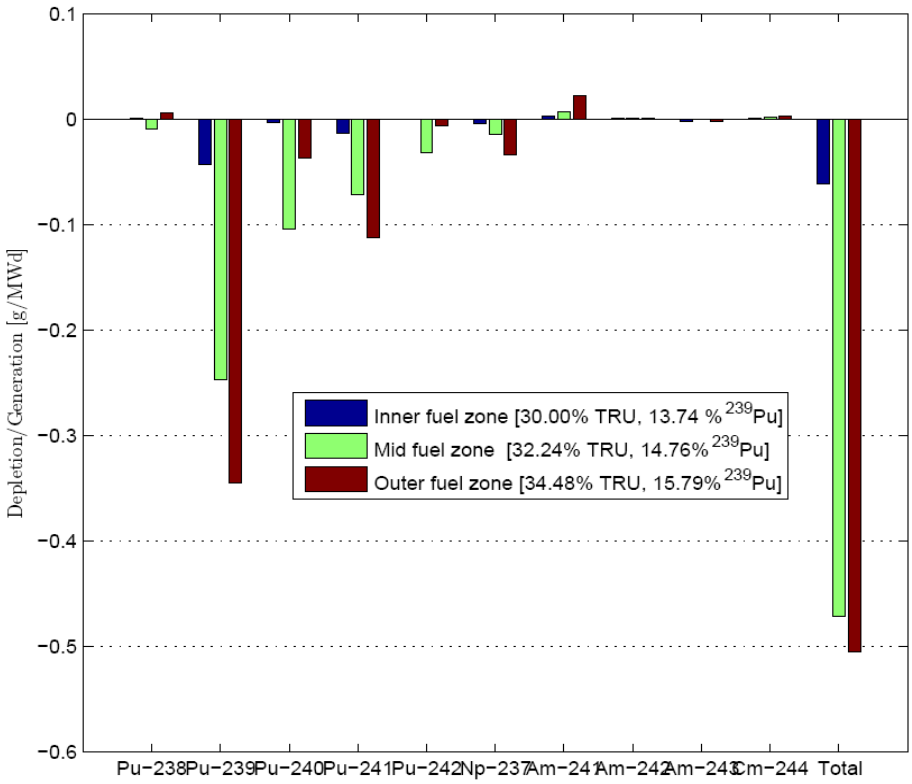

Figure 5. Burnup rate for the net change in TRU of the driver fuel assemblies for the thorium based fuel enrichment zones

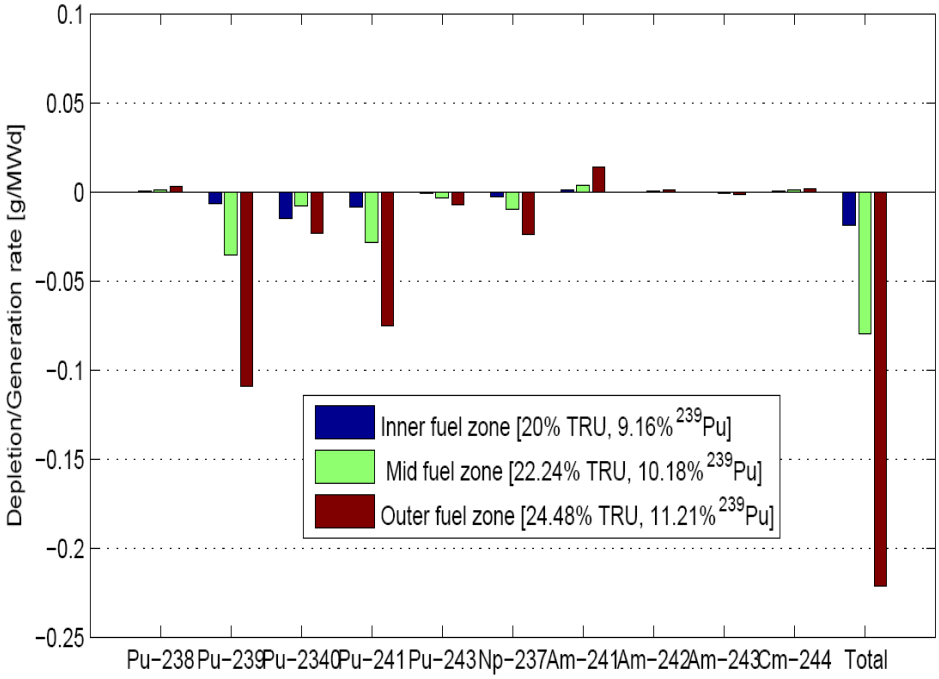

Figure 6. Burnup rate for the net change in TRU of the driver fuel assemblies for the uranium based fuel enrichment zones

The plutonium isotopic fraction at the End of Life (EOL) was used to determine the proliferation potential of the fuel. The thorium based fuel depletes the ^{239}Pu and ^{241}Pu while ^{238}Pu, ^{240}Pu, ^{242}Pu content increases (Table IV). As for the uranium based fuel there is no significant change in composition of ^{239}Pu at EOL when compared to the composition at BOL (Table V). Similar studies reported a 0.2 to 5.4% reduction at EOL [13].

Table IV. EOL Plutonium fraction of the driver assemblies for each thorium based enrichment zone

	BOL Plutonium fraction				
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
	2.70%	50.37%	24.72%	14.46%	7.74%
	EOL Plutonium fraction				
Inner fuel zone	4.87%	39.38%	34.20%	10.47%	11.09%
Mid fuel zone	4.87%	39.38%	34.20%	10.47%	11.09%
Outer fuel zone	4.49%	41.43%	32.76%	10.66%	10.66%

Table V. EOL Plutonium fraction of the driver assemblies for each uranium based enrichment zone

	BOL Plutonium fraction				
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
	2.70%	50.37%	24.72%	14.46%	7.74%
	EOL Plutonium fraction				
Inner fuel zone	3.99%	52.81%	28.84%	5.91%	8.45%
Mid fuel zone	4.15%	51.06%	29.85%	6.05%	8.89%
Outer fuel zone	4.24%	49.86%	29.88%	6.75%	9.27%

6. CONCLUSIONS

Over the past decades the advantages of using thorium based fuels were overlooked since there are large deposits of uranium and its utilization has been improved. However, due to geopolitical changes there has been an interest to use thorium for developing countries around the world for improved waste management and proliferation resistance. In this study an initial assessment on the use of thorium instead of uranium as the basis for transmutation fuel was investigated. An evaluation of thorium and uranium based metallic fuels using the same coolant and design parameters were compared. The two fuel options were evaluated and compared using the S-PRISM as the core reference design. The thorium and uranium based fuels varied in the amount of TRU loaded while using the same core configuration. When compared the thorium based metallic fuel outperformed uranium based fuel in terms of higher actinide burnup, discharging higher proliferation resistant fuel, and the depletion of plutonium isotopes. A higher total net isotopic destruction rate, -1.0384 g/MWd, is achieved when using the thorium based fuel as compared to the uranium based fuel, -0.3206 g/MWd. The increase in ^{238}Pu and ^{240}Pu content at the EOL can make the fuel more proliferation resistant since these isotopes are fertile; they produce larger decay heat and spontaneous neutrons. Fuels containing thorium are preferred over uranium to meet many aspects of the AFCI objectives. It is important to note that during the thorium fuel cycle ^{233}U is produced, which is a proliferation concern. Continued work needs to be done to ensure that such fuels when used in fast reactor designs provide acceptable safety

characteristics. The difference in TRU enrichments between the three radial zones, arbitrary chosen in this study, may cause uneven burnup. Further iterations in determining the optimal TRU enrichment and fuel shuffling should be studied. Furthermore, the thorium fuel cycle cost needs to be assessed to ensure that there will be no significant decreases in the economic competitiveness of nuclear electricity.

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