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Title:	An Assessment of the Attractiveness of Material Associated with Thorium/Uranium and Uranium Closed Fuel Cycles from a Safeguards Perspective
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AN ASSESSMENT OF THE ATTRACTIVENESS OF MATERIAL ASSOCIATED WITH THORIUM/URANIUM AND URANIUM CLOSED FUEL CYCLES FROM A SAFEGUARDS PERSPECTIVE

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ABSTRACT

This paper reports the continued evaluation of the attractiveness of materials mixtures containing special nuclear materials (SNM) associated with various proposed nuclear fuel cycles. Specifically, this paper examines two closed fuel cycles. The first fuel cycle examined is a thorium fuel cycle in which a pressurized heavy water reactor (PHWR) is fueled with mixtures of plutonium/thorium and ^{233}U/thorium. The used fuel is then reprocessed using the THOREX process and the actinides are recycled. The second fuel cycle examined consists of conventional light water reactors (LWR) whose fuel is reprocessed for actinides that are then fed to and recycled until consumed in fast-spectrum reactors: fast reactors and accelerator driven systems (ADS). As reprocessing of LWR fuel has already been examined, this paper will focus on the reprocessing of the scheme's fast-spectrum reactors' fuel. This study will indicate what is required to render these materials as having low utility for use in nuclear weapons. Nevertheless, the results of this paper suggest that all reprocessing products evaluated so far need to be rigorously safeguarded and provided high levels of physical protection. These studies were performed at the request of the United States Department of Energy (DOE). The methodology and key findings will be presented.

INTRODUCTION

The United States Department of Energy (DOE) requested an assessment of the attractiveness, from an international safeguards and domestic physical protection perspective, of the special nuclear materials (SNM) (*i.e.*, Pu, ^{233}U, and ^{235}U), alternate nuclear materials (ANM) (*i.e.*, ^{237}Np and Am), and other actinides that have a critical mass (*e.g.*, Cm) that are associated with reprocessing and are handled in forms largely decontaminated of fission products. Each potential malefactor is unique in the material to which he has access and in the degree of sophistication he could utilize in weaponizing the material. Collectively, proliferant States and sub-national groups could consider a broad spectrum of SNM and ANM to be attractive for use in a nuclear explosive device. Although earlier studies [1,2] developed two figures of merit (FOM) that were intended to explain material attractiveness or preferences across a span of credible nuclear adversaries, this study exclusively uses one of these, called FOM_1, which covers the broadest range of adversaries and represents the most prudent basis for safeguards and security design.

A credible nuclear threat from a sub-national group is different than that from a proliferant State. On the one hand, the perceived threat from a sub-national group is more dependent upon the fact that a device may produce any nuclear yield than it is upon the actual amount of yield. Even in a low technology, low quality device, any nuclear yield will, in most cases, exceed the conventional explosive yield. Thus, any device capable of generating a nuclear yield in the hands of a sub-national group would meet their requirements. On the other hand, a proliferant State is likely to have a preference for materials that are more easily and efficiently fabricated into higher yield

nuclear weapons than those materials of interest to a sub-national group. All SNM and ANM should be protected and safeguarded according to the highest level of attractiveness derived from both of these threats.

METHODOLOGY

The primary factors of material attractiveness are the bare critical mass, the internal heat generation, and the radiation dose rate. Our approach is to combine these separate factors into a single analytic formula that provides an overall metric for material attractiveness. This metric is given in Eq. (1), which represents the bounding case for evaluating the weapons utility of SNM or ANM to various potential adversary groups (see Ref. 1 or 2).

$$FOM_1 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10}2}}\right) \quad (1)$$

where M is the bare critical mass of the metal in kg, h is the heat content in W/kg, and D is the dose rate of $0.2 \cdot M$ evaluated at 1 m from the surface in rad/h. In the context of safeguards, the bare critical mass and the heat content are of the purified element after it has been removed from the used fuel. In the context of security, the bare critical mass and heat content are of an impure alloy that is derived from the used fuel but not chemically purified.

In this study, the dose rate for SNM contained in used fuel assemblies is calculated after the material has been processed for potential weapons use; it is not of the starting item. This is a conservative approach to accounting for the effect of the dose rate. This basically means that the adversary has access to shielded hot cells or equivalent handling facilities. If the adversary does not have access to these capabilities, then credit can be taken for the size and mass of the fuel assembly. In this case, the dose rate would be taken from the used fuel assembly and the M/50 term would be replaced with an N/10 term, where N is the net weight of the fuel assembly in kg.

The basic concept of FOM_1 is to relate candidate nuclear material to accepted standards. The well-established standards are: 1) the threshold for low enriched uranium (*i.e.*, ^{235}U enrichment less than 20%), 2) radioisotope thermoelectric generator plutonium (*i.e.*, ^{238}Pu enrichment greater than 80%), and 3) a self-protecting dose rate (*i.e.*, 500 rad/h at 1 m [3,4]).

FOM_1 was reviewed by nuclear weapons experts at both LANL and LLNL. While it was determined that there are a number of smaller factors that are not captured, it was agreed that FOM_1 captures the dominant factors quite nicely in an unclassified format.

Table 1 gives the meaning of FOM_1 in terms of weapons utility, and materials attractiveness in a safeguards and security context. To make a material unattractive for use in a nuclear device, FOM_1 must be less than 1. Table 1 does not distinguish between degrees of proliferation resistance that might characterize a nuclear material or mixture. Table 1 reflects the fact that while a particular nuclear material might be preferable for use in a nuclear weapon or explosive device, the design and construction of effective nuclear weapons from any of the materials with $FOM_1 > 1$ is theoretically possible. For example, plutonium from typical civilian used fuel could be used in a nuclear device [5]. As this paper will show, plutonium with ^{239}Pu content ranging above 90% (often characterized as low proliferation resistance) or between 50% and 20% (often characterized as high proliferation resistance) both have a FOM > 1. The fact that potential proliferant States or sub-national groups might "prefer" one material over another should not imply that either material in question is "proliferation-proof," or that any reduction in international safeguards and national physical

protection requirements can be justified. It should be noted that the lower the FOM_I the better. Even though a material may still need to be safeguarded and secured, a process that produces a material with a FOM_I of 1.1 should be encouraged over a process that produces a material with $FOM_I = 2.5$.

Table 1. The Meaning of FOM_I When Applied to Metals or Alloys

FOM_I	Weapons Utility	Materials Attractiveness	Attractiveness Level [6]
> 2	Preferred	High	~B
1-2	Attractive	Medium	~C
0-1	Unattractive	Low	~D
< 0	Unattractive	Very Low	~E

The FOM represents a small but important part of the overall proliferation and security risks that are posed by various materials and processes in the nuclear fuel cycle. To contextualize the FOM, it overlaps strongly with one of the six proliferation resistance measures (Fissile Material Type) that is identified in the PR&PP methodology [7], and it overlaps strongly with the material attractiveness criteria which is a key part of the DOE graded safeguards table [6]. So in the case of proliferation resistance there are five other factors that need to be considered, *e.g.* proliferation technical difficulty, proliferation cost, proliferation time, detection probability, and detection resource efficiency. In the case of physical protection, there are two other factors that need to be considered, *e.g.* material quantity and security category.

THORIUM RESULTS

For many years India has promoted the long term goal of a sustainable fuel cycle based on ^{233}U and thorium. With the discovery of its own large thorium reserves, the United Sates has taken a renewed interest in this fuel cycle. The current worldwide fleet of light and heavy water reactors breeds reactor-grade plutonium which is weapons usable primarily because the bare critical mass is small. The impurities in the plutonium, ^{238}Pu and ^{240}Pu, increase the heat content and the intrinsic neutron rate, respectively, making the material slightly less attractive. A new generation of light or heavy water reactors based on thorium will produce ^{233}U, which is also weapons usable because of its small critical mass. The primarily impurity in the uranium, ^{232}U, substantially increases the dose rate of the material. The high dose rate arises from intense high energy gamma-ray decay from ^{208}Tl, a daughter product of ^{232}U. This study evaluates the attractiveness of the ^{233}U that is produced in thorium-based fuel cycles and compares it to other nuclear materials of interest.

For the purpose of this study, the reactor design is assumed to be that of the advanced heavy water reactor (AHWR) that has been proposed by India [8]. The AHWR is a vertical pressure tube type reactor cooled by boiling light water and moderated by heavy water. The reactor is designed for a sustainable thorium-based fuel cycle. The used fuel is reprocessed to extract and recycle the ^{233}U. The reactor uses fuel assemblies comprised of 16 ^{233}U-Th rods in the inner fuel zone and 20 Pu-U rods in the outer fuel zone.

This analysis evaluates the attractiveness of three different materials: 1) the Pu-Th in the inner zone, 2) the ^{233}U-Th in the outer zone, and 3) the total ^{233}U-Pu-Th in the assembly. The isotopic compositions of the used fuel were determined using SCALE [9]. The physical properties of the materials for the FOM calculations were determined using MCNP-X [10].

Used fuel is characterized herein by its burn-up, expressed in MW·d/kg of initial heavy metal, and its age at the time of reprocessing. For each of the three materials, the FOM_I is calculated as a function of age, measured from insertion into the reactor. Initially the material is irradiated in the reactor for the first two and a half years. This corresponds to a burn-up of 20 MW·d/kg. Then the remaining age is cooling time out of the reactor. The FOM_I is calculated for ^{233}U and Pu when separated from the Th fuel matrix. In all cases, the FOM_I of an impure alloy derived from the discharged fuel has a value of $-\infty$. The Th-based fuel at charge even in metal form does not have a critical mass unless it is heavily moderated.

For the outer Pu-Th rods, the inventory of Pu (~50 kg of heavy metal at charge) is 2.58 kg and the inventory of ^{233}U and Pu at discharge is 0.35 and 1.82 kg, respectively. For the inner ^{233}U-Th rods, the inventory (~30 kg of heavy metal) of ^{233}U at start-up is 2.20 kg and the inventory of ^{233}U and Pu at discharge is 2.04 kg and 0.3 mg, respectively. For the combined ^{233}U-Pu-Th rods, the inventory of ^{233}U and Pu (~80 kg of heavy metal) per the entire assembly at start-up is 2.20 and 2.58 kg, respectively. The inventory of ^{233}U and Pu at discharge is 2.38 and 1.82 kg, respectively. Total mass of a typical assembly is 181 kg, which includes cladding, pressure tube, *etc.* The equilibrium concentration of ^{232}U in the ^{233}U in a closed, sustainable fuel cycle will be between 700 and 1,000 ppm.

Figure 1 shows the FOM_I for the SNM component in the used nuclear fuel. All of these materials are very attractive for nuclear weapons use, except for the small amount of Pu in the ^{233}U-Th rods which is over 90% ^{238}Pu. Only the Pu in the Pu-Th rods displays any significant change for the time period shown. For both cases, the Pu FOM_I drops while in the reactor because ^{239}Pu is consumed. After discharge, the Pu FOM_I increases because initially ^{241}Pu is decaying away and then ^{238}Pu. For comparison the FOM_I of weapons-grade (WG-Pu) and reactor-grade (RG-Pu) plutonium, high (HEU – 93 % ^{235}U) and low (LEU – 20 % ^{235}U) enriched uranium, ^{237}Np, ^{233}U contaminated with 10 ppm ^{232}U, and a 80:20 mixture of ^{238}Pu and ^{239}Pu are shown on the left side of each figure.

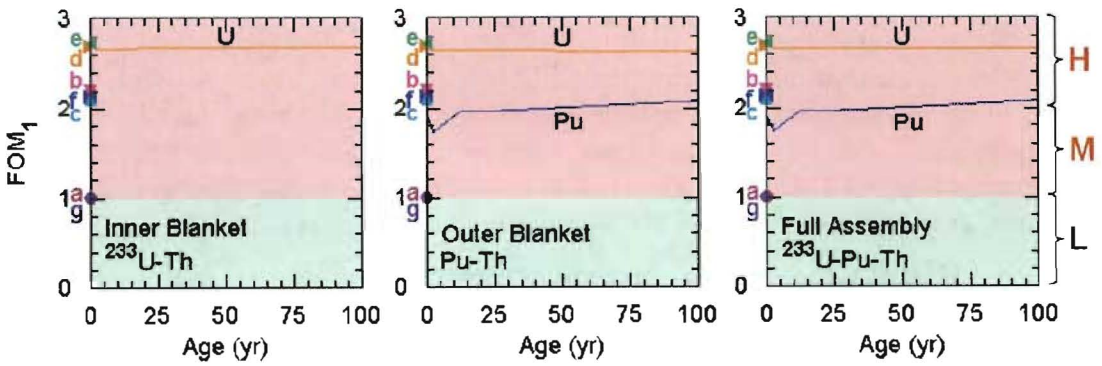

Figure 1. FOM_I *Versus* Age. The material is irradiated in the reactor for the first 2.5 years and then resides outside the reactor for the remaining years. The letters H, M, and L denote high, medium, and low attractiveness, respectively (see Table 1). Included for reference are the following data points: a – LEU (20%), b – HEU (93%), c – ^{237}Np, d – ^{233}U (10 ppm ^{232}U), e – WG-Pu, f – RG-Pu (45 MW·d/kg and cooled 10 years), and g – $^{238}Pu/^{239}Pu$ (80:20).

The thorium-based unprocessed discharged fuel is not substantially different in attractiveness than ordinary U-based used LWR or HWR unprocessed discharged fuel. In other words, any *unprocessed* discharged fuel is not attractive as long as the dose rate is on the order of 500 rad/h or

higher at one meter. A more detailed analysis of the attractiveness of unprocessed discharged fuel assemblies as a function of age is still needed to show how long these assemblies will remain self-protecting.

One can also examine the attractiveness of ^{233}U as a function of ^{232}U content and age. In Figure 2, the heat term (bare critical mass times heat content), the dose term, and FOM_1 are plotted as a function of age. The bare critical mass is independent of age and initial ^{232}U contaminant concentration for concentrations $\leq$ 3200 ppm at 15.5 kg. The material is the least attractive at an age of about 10 years. There is little difference in attractiveness for freshly purified materials and for very old materials. The curve with 800 ppm of ^{232}U most closely matches what is expected in these Th-based fueled reactors. In summary ^{233}U is very attractive at any practical concentration of ^{232}U and age. Furthermore, comparing reference points b (HEU – 93 % ^{235}U) and d (^{233}U contaminated with 10 ppm ^{232}U) in any figure indicates ^{233}U is significantly more attractive than ^{235}U.

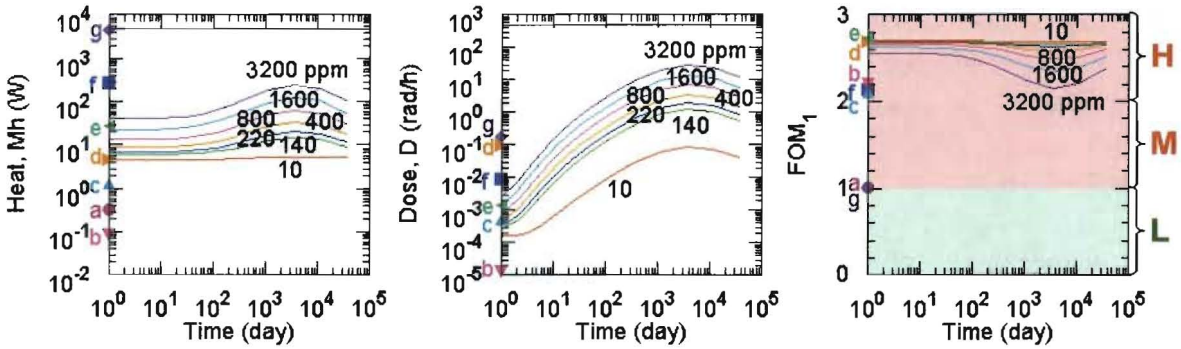

Figure 2. Heat, Dose, and FOM_1, as a function of decay time for various initial concentrations of ^{232}U in ^{233}U. See Figure 1 for explanation of H, M, and L and symbols a – g.

Table 2 provides the compositions at charge of three thorium fuel mixtures that were analyzed. The percentages of the mixtures constituents were determined by achieving the same average k_{eff} as a LWR (4.08% enriched) at a burn-up of 45 MW·d/kg.

Table 2. Compositions at Charge of Thorium Cases

Material	Pu (%)	$^{239}Pu/Pu$ (%)	U (%)	$^{235}U/U$ (%)	Th (%)
1	6.25	94	5.0	0.7	88.75
2	0.00	—	30.5	19.9	69.50
3	10.00	53	5.0	0.7	85.00

Figure 3 illustrates two concepts: 1) adding low enriched, natural, or depleted uranium (*i.e.*, ^{238}U) as a salting agent to mask ^{233}U production from thorium and 2) dilution of the fissile isotopes with Th to reduce the security threat. Comparison of the attractiveness of the U in Figure 1 with the undiluted U (*i.e.*, 0% Th concentration) in Figure 3 indicates **salting is an effective means to reduce the attractiveness of ^{233}U**. The effect of salting on Pu attractiveness is minor as seen in Figure 3 by comparing the undiluted Pu for material 3 with the reference point f (RG-Pu) or the RG-Pu curves in Figure 4, if a small (< 25%) amount of salting agent is used. Nevertheless,

burning thorium fuel produces smaller quantities of ^{239}Pu than burning uranium fuel. The FOM_1 results in Figure 3 are independent of time.

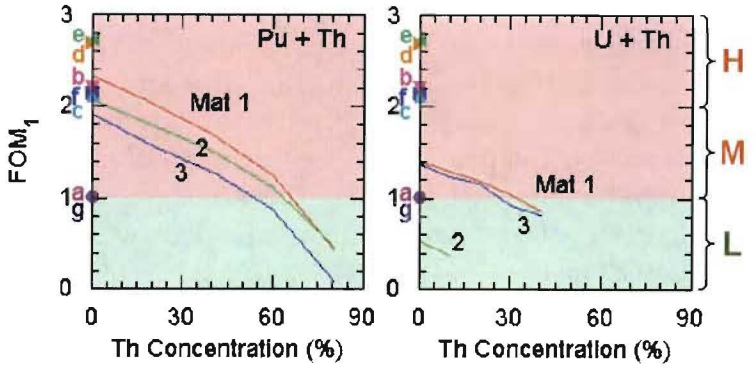

Figure 3. The FOM_1 of the Pu + Th (Left) and U + Th (Right) THOREX Products at Discharge of the Fuels Listed in Table III *Versus* Thorium Concentration. See Figure 1 for explanation of H, M, and L and symbols a – g.

Diluting the ^{239}Pu with used thorium requires the mixture to be > ~⅔ Th to achieve low attractiveness using Eq. (1). Diluting the ^{233}U with used thorium requires the mixture to be > ~⅓ Th to achieve low attractiveness, depending on the initial quantity and quality of the Pu in the thorium charge. If LEU is mixed with the thorium fuel at charge, then there is sufficient ^{238}U to mask the buildup of ^{233}U during its burn and to render the uranium unattractive at discharge.

Figure 3 also provides a gauge of the degradation in material attractiveness that result from materials being "burned" in a thorium-fueled reactor. The attractiveness of WG-Pu at charge is displayed as symbol "e" in Figure 3; whereas the attractiveness of that same plutonium at discharge and whatever plutonium is bred during burn corresponds to the undiluted Pu for Mat 1. Hence, burning WG-Pu in a thorium-fueled reactor degrades the attractiveness by ~0.4. Similarly, the attractiveness values for LEU and reactor-grade plutonium decrease by ~0.5 and ~0.2, respectively, by burning to 45 MW·d/kg in a thorium-fueled reactor.

FAST SPECTRUM REACTOR RESULTS

The term fast spectrum reactor (FSR) encompasses a large class of reactors with different physical characteristics (*e.g.*, coolant or burn-up). To capture the effect of this variability, this study analyzed the actinide compositions from Ref. 11, 12, and 13 (fission products were ignored, because FOM_1 is much less than zero with them for the time scales considered herein). Discharge compositions were subsequently aged (*i.e.*, allowed to decay) using ORIGEN2.2 [14] calculations.

FSR (*i.e.*, fast reactors and accelerator driven systems (ADS)) recycle all of their discharged transuranic elements, TRU. When this recycled TRU is fabricated into fresh fuel, any lost reactivity is compensated by topping the recycled TRU with higher-reactivity TRU from used uranium oxide (UOX) or mixed oxide (MOX) fuel discharged from LWR. FOM_1 results for candidate topping materials are shown in Figure 4 [1,2]. The FOM_1 of Pu and TRU decreases with increasing burn-up, because the concentration of ^{239}Pu decreases and the concentration of ^{238}Pu, which is an intense heat source, increases with increasing burn-up. The FOM_1 for TRU is strongly dependent on used fuel age, which is defined hereafter as the time between discharge and reprocessing; because ^{242}Cm and ^{244}Cm are intense heating sources and quickly decay away (their half lives are 163 days and 18 years, respectively).

The first set of FSR results is presented in Table 3 and is based on the isotopic compositions given in Ref. 11 for three transmutation approaches: 1) 1XT – an advanced liquid metal reactor (ALMR) that is topped with TRU from used MOX fuel (2nd MOX pass); 2) 3M – an ADS topped with TRU from used advanced LWR (ALWR) fuel; and 2) 3T – an ALMR topped with TRU from used ALWR fuel. These FSR use metal fuel, are sodium cooled, and recycle the TRU in their discharged fuel after cooling for 2 year. The actinides at charge and discharge for the ALMR fuel are unattractive because of a high uranium concentration (see Ref. 1 and 2). However, TRU (a safeguards and security concern) from used FSR fuel that has been cooled for 2 years is moderately attractive in all three cases, as is the TRU in the topping material. The TRU in the 3M charge is also moderately attractive because the ADS is driven and doesn't need uranium to maintain criticality. Note all of the Pu (a safeguards concern) ranges from moderately to highly attractive.

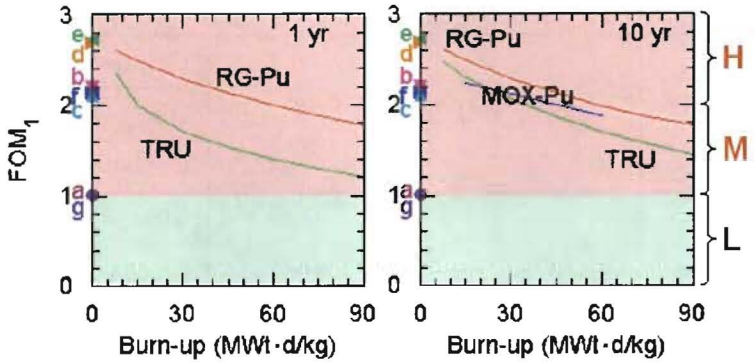

Figure 4. FOM_1 *Versus* Burn-up of Used-UOX Source of Topping Candidates Cooled 1 (left) and 10 (right) Years: RG-Pu (red curve), Pu from Used MOX (blue curve labelled MOX-Pu) Burned to 60 MW·d/kg, and TRU (green curve). RG-Pu is the MOX plutonium at charge. See Figure 1 for explanation of H, M, and L and symbols a – g.

Because the fuel in Table 3 is from an equilibrium cycle, the effect of cycle number was explored and is shown in Figure 5 for an ADS that burns fuel to 260 MWt·d/kg with conversion ratio (CR) ~ 0.25; tops with LWR discharges burned to 60 MWt·d/kg and cooled for 10 years; and immediately recycles discharged TRU. The FOM_1 of the discharged fuel reaches an equilibrium that is consistent with the 3M value in Table 3 within four cycles. The TRU from 2-yr old used ADS fuel is moderately attractive; whereas the Pu ranges from moderately to highly attractive. The first charge is also highly attractive.

The effect of varying CR on material attractiveness at equilibrium is shown in Figure 6. To decrease CR in the sodium-cooled, metal-fueled fast burner (CR < 1) design used in Ref. 13 with collocated reprocessing, pin radii were reduced to decrease the fuel volume fraction, resulting in reduced uranium concentration and increased burn-up, all to maintain criticality. To breed (*i.e.*, CR > 1), the reactor core was divided into TRU-bearing driver and uranium-only blanket regions (the average over the entire core, including any blankets, is shown as "<core>" in Figure 6). To increase breeding, more blankets and larger driver pin radii were used. No major reactor modifications were required to change CR. The fuel at charge and discharge is unattractive with the exception of the charge at CR = 0.01, because Cm provides a heat deterrent for CR < 1 and uranium dilutes the fissile isotopes for CR > 1. TRU from used fuel is moderately attractive for CR < 1 and highly attractive for CR > 1, because the Cm concentration decreases and the ^{239}Pu concentration increases as CR and ^{238}U concentration increase and the burn-up decreases. The Pu in the TRU is moderately

attractive for CR < 0.65 and highly attractive for CR ≥ 0.65. The ^{239}Pu concentration in the blanket is of particular concern, because it reaches a maximum concentration of 97.4 % of the TRU at CR = 1.7. Consequently, the SNM associated with all FSR must be safeguarded.

Table 3. The FOM_1 of the Actinides in the Fuel and TRU Extracted from Aged Used Fuel For Three Transmutation Approaches [11] and the Corresponding Topping Material.

Case	Reactor Type	Burn-up (MWt·d/kg)	CR	TRU Consumed (%)	State	U (%)	TRU FOM_1	Pu FOM_1
1XT	ALMR	119	~0.5	18	Charge	62	0.5	1.6
					Discharge	64	0.1	1.6
					Cooled 2 yr	0	1.1	1.6
3M	ADS	273	~0.25	29	Charge	2	1.2	1.7
					Discharge	2	0.5	1.6
					Cooled 2 yr	0	1.0	1.6
3T	ALMR	118	~0.5	19	Charge	68	0.8	1.9
					Discharge	70	0.3	1.8
					Cooled 2 yr	0	1.4	1.8
1XT Topping	ALWR	51	—	—	Cooled 2 yr	0	1.2	1.9
3M or 3T Topping	ALWR	51	—	—	Cooled 10 yr	0	1.8	2.1

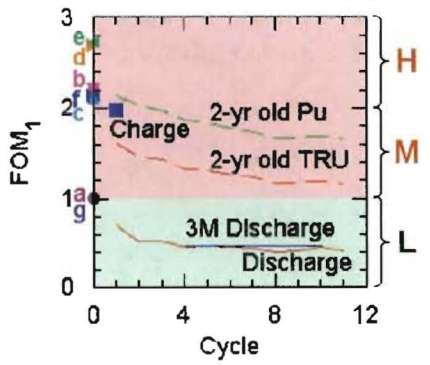

Figure 5.The FOM_1 of ADS Fuel at Charge (blue square), Discharge (red curve), and TRU (red dashed line) and Pu (green dashed line) from 2-yr Old Used ADS Fuel *Versus* Cycle Number. Also shown is the 3M discharge (blue line). See Figure 1 for explanation of H, M, and L and symbols a – g.

CONCLUSIONS

The thorium fuel cycle potentially produces two highly attractive materials: ^{239}Pu and ^{233}U. Both are of great concern from a safeguards perspective. The Pu product can be rendered unattractive to non-Host State actors by co-extracting a Pu-Th mixture that is > ⅔ Th. The ^{233}U product can be rendered unattractive to both Non-Host State and Host State proliferators by adding natural or depleted U to the fuel before irradiation, but may exacerbate the ^{239}Pu problem in the product. Additionally, the ^{233}U product can be rendered unattractive by co-extracting a U-Th mixture that is > ⅓ Th.

Nevertheless, diluted material can still be made attractive by purification, but this takes time and some degree of technical capability that is well within the capability of a Host State, but not necessarily within the capability of a non-Host State actor. The thorium fuel cycle is also a net consumer of plutonium [~40% of the initial plutonium inventory in the case of Material 3 (see Table 2)].

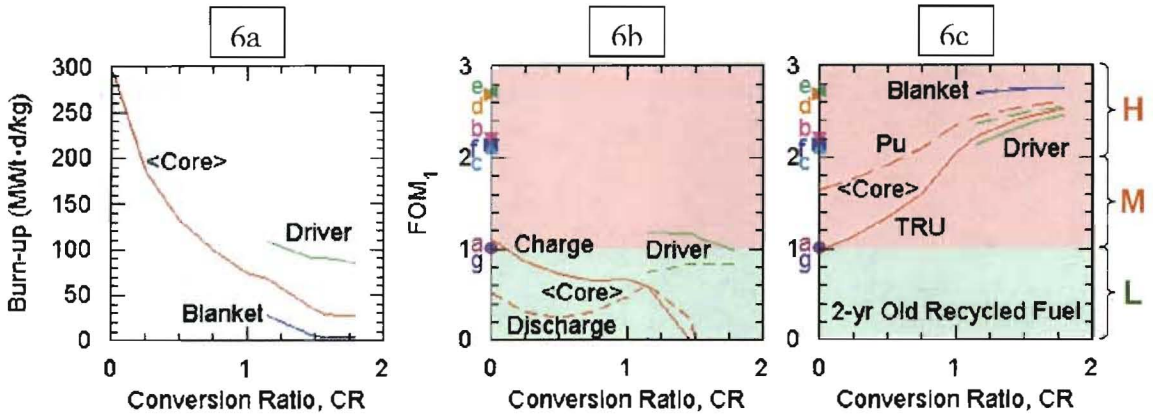

Figure 6. The Burn-up (6a); FOM_1 at Charge (Solid Line) and Discharge (Dashed Line) (6b); and FOM_1 for Pu (Dashed Line) and TRU (Solid Line) Obtained from Used Fast Reactor Fuel Cooled for Two Years (6c) *Versus* Conversion Ratio for the Blanket (Blue Line), Driver (Green Line), and Averaged Core (CR > 1) and for the Entire Averaged Core (CR < 1) (Red Line). See Figure 1 for explanation of H, M, and L and symbols a – g.

The ^{233}U that is produced has a substantial amount of ^{232}U. The presence of ^{232}U increases the dose of the material particularly at ages of about 10 years after irradiation. This is due to the in growth of ^{208}Tl which has an intense high energy gamma-ray emission. In terms of weapons utility or material attractiveness this dose rate is only a nuisance to the adversary. It is not anywhere near sufficient to incapacitate a dedicated adversary. So if long term health and safety is not a concern to the adversary, ^{233}U is one of the most attractive of all nuclear materials.

For FSR systems, lowing CR affords some security benefit for reprocessed TRU, but no safeguards benefit because the operator, design permitting, may be able to change the CR or reprocess for Pu. Even more of a concern is the possibility of introducing a Pu breeding blanket. The Pu obtained from such a blanket can be of very high quality, as has been shown.

Even though ^{233}U, RG-Pu, and TRU are moderately to highly attractive, they normally are not attractive while remaining within used nuclear fuel. The high dose rate of the used fuel in combination with the large mass of a used fuel assembly and the low concentration of SNM makes the material self-protecting for many years. However, the dose rate of any used fuel eventually will become low enough so as not to be an impediment to theft or reprocessing.

Consistent with other studies of fuel cycles, Th- and U-based materials and processes between enrichment and repository need high levels of safeguards and moderate to high levels of security. Full safeguards would be needed on all facilities handing greater than 8 kg of ^{233}U and/or Pu. However, security can be reduced for the used fuel while the dose rate is high enough for it to be self-protecting (*e.g.* Cat III), but security needs to be high in the recycling and fuel fabrication facilities (*e.g.* Cat I) and moderate to high in any fresh fuel handing facilities (*e.g.* Cat II or I).

We have not identified a "silver bullet" technology that would eliminate safeguards and security issues. None of the proposed flow sheets examined to date justify reducing international safeguards or physical security protection levels. All of the reprocessing or recycling technologies evaluated to date still need rigorous safeguards and high levels of physical protection. Rigorously safeguarding all relevant nuclear materials should further the development of nuclear energy around the world.

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