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October 15, 2009

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The application of a figure of merit for nuclear explosive utility as a metric for material attractiveness in a nuclear material theft scenario

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1. Abstract

Effective integration of nonproliferation management into the design process is key to the broad deployment of advanced nuclear energy systems, and is an explicit goal of the Laser Inertial Fusion Energy (LIFE) project at Lawrence Livermore National Laboratory. The nuclear explosives utility of a nuclear material to a state (proliferator) or sub-state (terrorist) is a critical factor to be assessed and is one aspect of material attractiveness. In this work, we approached nuclear explosives utility through the calculation of a "figure of merit" (FOM) that has recently been developed to capture the relative viability and difficulty of constructing nuclear explosives starting from various nuclear material forms and compositions. We discuss the integration of the figure of merit into an assessment of a nuclear material theft scenario and its use in the assessment. This paper demonstrates that material attractiveness is a multidimensional concept that embodies more than the FOM. It also seeks to propose that other attributes may be able to be quantified

through analogous FOMs (e.g., transformation) and that, with quantification, aggregation may be possible using concepts from the risk community.

2. Introduction

Material attractiveness is defined as a measure of the desirability of a material for nuclear weapons use (Mladineo, 2003). The concept of material attractiveness is used in both the safeguards and the nonproliferation literature. As a safeguards concept, materials attractiveness is used to establish criteria for how well nuclear materials need to be protected from theft or insider diversion. In the graded safeguard table,(DOE, 2005) material is considered in a variety of forms including pure products (button ingots, recastable metal), high-grade materials (carbide, oxides), low grade materials (solutions, moderately irradiated materials), and others (highly irradiated forms, low enrichment).

In a nonproliferation context, material attractiveness is discussed in terms of intrinsic barriers. Bathke and coworkers (Bathke, 2009; Bathke, Jarvinen, 2008; Bathke, Wallace, 2008) use a figure of merit as a metric for material attractiveness considering the intrinsic barriers of bare critical mass, heat load, and radiation dose. Such studies often assume that the material has been processed to a product material (pure element or impure metal with fission products removed) that is intended for use in a nuclear explosive. But, Pilat has argued that material quality alone, as for example expressed by the figure of merit, does not account for contributions to attractiveness from intrinsic barriers posed by factors such as processing difficulty and high radiation levels (Pilat, 2009). In a recent paper,

Cavalieri et al. (Cavalieri d'Oro, 2009) pointed out that an attractiveness metric proposed by Saito (Saito, 2008), which is also a measure of material quality, constitutes only one of the possible measures of attractiveness.

The point of using attractiveness as a measure of proliferation resistance is that it should provide a clear way to communicate with stakeholders. Zentner et al. discuss the use and communication of information from proliferation resistance assessments (Zentner, 2009):

> *"Using information provided by proliferation resistance assessments, government officials should be able to understand the attractiveness of the technology or material inherent in a proposed nuclear energy system to potential proliferators for use in a weapons program. If the material or technology is or could be attractive to potential proliferators, then the officials should be able to determine if the nuclear energy system can be designed and operated in order to reduce this attractiveness and present an undesirable route for a possible proliferation effort."*

Attractiveness in this reference seems to encompass factors in addition to material quality alone. It seems that measuring attractiveness in a theft context is more complex compared with an international safeguards context because factors such as radiation dose and processing of materials may represent more significant barriers.

From the nonproliferation point of view, there is a need for a metric that enables quantitative comparisons of the attractiveness of materials from different advanced nuclear energy systems. The metric must be clear, communicable, robust, and defensible. In this paper, we discuss the application of the figure of merit as metric

for material attractiveness in a nuclear material theft scenario and demonstrate the need for integrating the FOM into a broader, multi-attribute measure of material attractiveness that also considers other salient factors in proliferation and theft scenarios.

3. Methodology

In a broader study (King, 2009), we analyzed the pertinent nuclear material theft scenario aspects of the disposition of WG-Pu via the Laser Inertial Fusion Energy (LIFE) (Moses, 2009; Kramer, 2009; Moir, 2009; Meier, 2009; Caird, 2009; Abbott, 2009; Peterson, 2009) hybrid fuel cycle, from fuel fabrication through spent fuel storage, for vulnerabilities (or lack of intrinsic barriers). The assessment was made relative to LWR WG-MOX fuel, e.g., see (Travers, 1999). The use of plutonium fuel in LIFE is a specialized case of the more general LIFE concept and is envisioned for use only in the United States or possibly other nuclear-weapon states (P-5 countries). Therefore, the present study focuses not on evaluating barriers to *state-directed* diversion or misuse, as in the usual definition of "proliferation resistance," but rather on resistance to theft and successful exploitation by individuals, terrorists, or other *non-state* actors.

3.1. Framework

We constructed the broader study based on a rich literature in the field of proliferation resistance and physical protection. We employed relevant aspects of methodologies such as PR&PP,(Bari, 2008; Bari, 2006, 2007; Bari, 2003 ; Bari, 2009; Bley, 2009; Cojazzi, 2009; Peterson, 2009; Zentner, 2009) the work of Cleary and coworkers(Cleary, 2007), the GNEP Nonproliferation Impact

Assessment(Anonymous, 2008), and recent work of Bathke et al. (Bathke, Jarvinen, 2008; Bathke, Wallace, 2008, 2008) on nuclear explosive utility, which has particular relevance for the non-host-state theft scenarios that form the focus of the current study. Although physical protection challenges within the PR&PP framework can include radiological sabotage by non-state actors, for the purposes of this work we examine only fuel theft and potential use of the stolen material. In this paper, we seek a better understanding of the elements that contribute to material attractiveness.

3.1.1. Proliferation issues, factors, and measures

3.1.1.1. Relation to PR&PP

A large and diverse community (the Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum) has been working for a number of years toward an evaluation methodology for proliferation resistance and physical protection (PR&PP) of Generation IV nuclear energy systems (Bari, 2006; 2007 ; Bari, 2009; Bley, 2009; Cojazzi, 2009; Peterson, 2009; Zentner, 2009). This methodology is well suited for a comprehensive study of a fully designed nuclear energy system.

3.1.1.2. Relation to DOE M 470.4-6

Because we are assessing a theft scenario, this paper relates more closely with physical protection (PP) rather than proliferation resistance (PR) as defined in PR&PP (Bari, 2006). For material attractiveness measures in a theft scenario, PR&PP appeals to the DOE graded safeguard table. Our approach borrows from the nuclear material control and accountability concepts implemented by the

Department of Energy that focus on material attractiveness, material quantity, and security requirements (DOE, 2005). In this paper, we discuss material attractiveness and material quantity and implement a figure of merit for nuclear explosives utility.

3.1.2. Stages of proliferation via theft

We adopted the so-called "stages of proliferation" with associated attributes and inputs from the methodology of Cleary et al. (Cleary, 2007) with the diversion stage substituted with a theft stage. The relevant stages for our analysis include theft, transportation, transformation, and nuclear explosive fabrication. The facility misuse stage is not considered to be relevant for the case of LIFE in a nuclear-weapon state. Several inputs have been added to those given by Cleary. The stages are described in detail in Appendix A. The decomposition of the scenario into stages facilitates the definition of attributes and inputs that are nearly independent. Conclusions were based on an assessment of material attractiveness and accessibility at each stage.

3.2. Fuel forms

The LIFE fission fuel in this study is based on the TRISO design (Del Cul, 2002). The LIFE TRISO particles are ~1mm in diameter. The kernels within the TRISO particles are 80 v/o ZrC + 20 v/o plutonium oxycarbide. The plutonium kernels will be coated with SiC. The use of oxycarbide kernels can suppress kernel migration and CO formation at high burnups (Lindemer, 2002). The TRISO particles are in a carbon matrix at ~30% packing fraction. In this analysis, the carbon matrix was doped with some Li^6 in order to act as a burnable poison early in time when the fissile material inventory is high. Each 2 cm diameter pebble (Figure 1) will contain 0.518g of WG-

Pu. A fuel load will comprise 1.32×10^7 pebbles with a mass of 6,840 kg of Pu. In this analysis, the intent was to load the fuel and then burn it to near 100% fissions per initial metal atom (FIMA).

In order to assess the nuclear material theft scenario risk attributes of a WG-Pu-fueled LIFE engine in context relative to alternative systems fueled with nuclear explosives fissile material, we compared this LIFE option with the burning of weapons-grade MOX in LWRs (Travers, 1999). The WG-MOX is 5 weight percent (of the total heavy metal) Pu. A summary of MOX fuel technology can be found in (Anonymous, 2003).

We modeled a Westinghouse AP1000 reactor consisting of 264 fuel pins per assembly and 157 assemblies, rated at 3.4 GWt full power (Anonymous, 2006). The fuel assembly has an active fuel length of 365 cm with a pitch of 21.4 cm and the nominal volume is 0.19 m^3 including all structural components. The mass of the assembly would include 461 kg heavy metal. Including the masses of oxygen, Zircaloy tubing, and other assembly hardware, yields a total of about 660 kg (Croff, 1979). For typical MOX fuel enrichments of 5-9% PuO_2/UO_2 ratio, one assembly would contain 3-4 significant quantities (SQs) of Pu.[1] The assemblies are then available to be loaded into a reactor for a period of three to four years. After this time, the assemblies are removed from the reactor and sent to a cooling pond for a period of about 5 years.

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[1] 1 SQ = 8 kg of WG Pu and scales with the bare critical mass as the Pu isotopics evolve.

4. Stages of proliferation via theft

The attributes and inputs for the theft, transportation, transformation, and nuclear explosives fabrication stages are given in Appendix A. Here we focus on the application of the figure of merit as part of the nuclear explosives fabrication stage.

4.1. Figure of merit for nuclear explosives utility

Recently, Bathke et al. (Bathke, 2009) have proposed a figure of merit for nuclear explosives utility that provides relative measures of the usefulness of a material for the production of a nuclear explosive. It accounts for three important characteristics: bare critical mass, heat content, and irradiation dose rate.

$$FOM = 1 - \log\left(M\left[\frac{1}{800} + \frac{h}{4500}\right] + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log 2}} \right)$$

Equation 1

where M is the bare critical mass of the metal product material (pure element or impure metal) that is intended for the nuclear explosive in kg, h is the heat content in W/kg, and D is the dose rate of a $0.2M$ sphere evaluated at 1 m from the surface in rad/h. Table I correlates the result for the FOM calculation with the material's nuclear explosive utility (Bathke, 2009). In this FOM, the heat source h and the dose rate D are those that result directly from the isotopic composition of the metal in its transformed state after removal of fission products. The bare critical mass M is the critical mass after the same transformation.

FOM for metals	Nuclear explosives utility
> 2	Preferred
1-2	Usable
0-1	Unusable
< 0	Unusable

Table I The correlation between the FOM and the utility of a material. A slightly different terminology is used here compared with (Bathke, 2009).

5. Results

5.1. Materials attractiveness and the FOM

We used data from our analyses for the bare critical mass, the heat content, and dose rate of $0.2M$ evaluated at 1 m from the surface to compute the figure of merit for transformed WG-Pu TRISO and for WG-MOX. Note that the dose rate D in the figure of merit calculation refers only to the dose from the actinides and their decay products (Figure 2), not the fission product dose rate that may be present prior to transformation (Figure 8). In this analysis, we took credit for that dose (Figure 8) in the assessment of the transformation stage.

Figure 3 shows the result of evaluation of Equation 1. Before irradiation, LIFE TRISO FOM (left plot) has a value that is consistent with the nuclear explosives utility of WG Pu ($\sim$2.6) and decreases to <2 after 4.5 years irradiation. This coincides with the decrease in the concentration of ^{239}Pu from 94% to 24% of the net Pu mass and the increases in ^{240}Pu, ^{241}Pu, and ^{242}Pu (Figure 4). The FOM continues to decrease until it finally reaches <1.5 leaving the Pu isotopics to be dominated by the long-lived isotope ^{242}Pu.

The decrease in the FOM after about 4 years is dominated by the increase in the heat term of Equation 1 due to the increasing concentration of ^{238}Pu that starts accumulating at about 4 years. The FOM does not fall below 1 indicating that the material is usable for a nuclear explosive (Table I). It is important to keep in mind that the FOM reflects the nuclear explosives utility of the Pu if extracted from the LIFE fuel and does not reflect the difficulty imposed by the radiation, the dilution of the Pu in the fuel, and/or the significant decrease in the Pu inventory in LIFE that occurs at these very high burnups (97% fissions per initial metal atom). This is a clear illustration that there is more to material attractiveness than the FOM alone. We address this in more detail below.

In contrast, Figure 3 also shows the FOM computed for WG-MOX burned in a light water reactor (LWR) (right plot). Note that in spite of the isotopic changes shown in the plot at right in Figure 4, the nuclear explosives utility remains high (2<FOM<3) even after its time in the reactor. The data ends at about 4 years since the fuel would be discharged to the spent fuel pool at that point. So, for the case of an actor who can accomplish the transformation stage, overcoming the issues associated with shielding the fission product dose rate, WG-MOX is highly nuclear explosives-usable material. (see Table I).

Figure 5 shows plots of the three terms of Equation 1. The bare critical mass term is $M/800$. The heat load term is $Mh/4500$. The dose term is $(M/50)(D/500)^{1/\log 2}$ (Bathke, 2009). This result indicates that the term that dominates the FOM calculation for LIFE is the heat load term.

To illustrate the multidimensionality of material attractiveness, Figure 6 plots the figure of merit as a function of the mass of LIFE pebbles and WG-MOX fuel assembly containing 1 SQ for various irradiation times. The plot, which combines two components of material attractiveness, illustrates how significantly the mass of fuel material required for 1 SQ increases as the FOM decreases for LIFE compared with WG-MOX. Because the Pu isotopics change with irradiation time, the mass of Pu per SQ was modified by the ratio of the bare critical mass of the current isotopics divided by that of WG-Pu (10.7 kg). After 5.75 years of irradiation, even though the material has some marginal nuclear explosives utility, it would require about 20 metric tonnes (MT) of LIFE pebbles to obtain 1 SQ of nuclear explosives usable material. In contrast, the mass and the FOM change significantly less for the WG-MOX case.

Another way to look at this is to plot the number of SQs in the LIFE engine or the reactor as a function of irradiation time. Figure 7 gives this result for WG-Pu TRISO in LIFE and WG-MOX in a LWR. A difference here is that LIFE inventory of Pu decreases throughout the irradiation time and after 6.9 years, there is less than 1 SQ remaining in the entire LIFE fuel load. WG-MOX burned in a LWR on the other hand decreases but still retains about 300 SQs in the fuel load when refueling is required.

Further, recall that the FOM as applied in Figure 3 and Figure 6 does not account for self protection of the irradiated LIFE-TRISO and the LWR-MOX fuels before they are reprocessed; the irradiated fuel will require significant decay times before they can be transported or handled as illustrated in Figure 8. The current thinking is that

material becomes self-protecting at 1,000 rad/h at 1 m (Coates, 2005). The self-protecting nature of both fuels would dominate the material attractiveness in a theft scenario. In our assessment, credit for the fuel being self-protecting was taken in the transformation stage. The radiation dose is an intrinsic barrier to theft of the material and would dominate the attractiveness of this fuel, for the time that the fuel is self-protecting.

6. Discussion

The above results illustrate the complexity and multi-dimensionality of the analysis of material attractiveness. In the following, we place the figure of merit in the context of the other inputs to material attractiveness.

6.1. Material Attractiveness and the FOM

While FOM is perhaps the most important consideration from the nonproliferation point of view, there are more inputs that must be considered before a proliferator can make the decision to steal material. An actor must assess attractiveness of the material across the stages of proliferation (theft) (see (Cleary, 2007)). Attractiveness should at least embody the following attributes that include both intrinsic and extrinsic barriers to theft:

- difficulty of handling material during theft or diversion
- difficulty of handling material during transportation
- difficulty of transforming the material
- figure of merit of nuclear explosives utility
- number of SQs available for theft or diversion

6.1.1. Quantification of the transformation stage

A key aspect of material attractiveness, especially should new proliferation resistant

fuel forms be developed in the future, is the challenge that will be presented during

the transformation of the material from its original form to the metal form,

particularly if the material is irradiated. This includes issues of shielding, exposing

the nuclear material, dissolving the material, and the relevant actinide chemistry

required to convert the material to metal. It is in this stage that hundreds or more

kilograms of materials need to be processed to obtain 1 SQ of nuclear explosives

usable material. These intrinsic barriers that affect material attractiveness are not

captured by the figure of merit.

6.1.2. Aggregation of nuclear explosives fabrication stage

A goal is to aggregate, first within stages and then across stages to yield a more

quantitative measure of material attractiveness and proliferation risk. As a first step

in that process, we propose to aggregate the inputs of the FOM and the number of

SQ available for theft within the nuclear explosives fabrication stage. This is

accomplished through a multiplicative factor to the FOM that takes the material

inventory into consideration. The aggregating function should asymptotically tend

toward zero at small fractions of an SQ, and asymptotically tend toward one at

many-SQ quantities. It should have its maximum slope in the region of 1 SQ. While

details are yet to be worked out, and different experts may choose different

particulars, a convenient functional form is the cumulative distribution function for

the normal distribution,

$$p(x) = \frac{1}{2} + \frac{1}{2} erf\left(\frac{x - \mu}{\sigma\sqrt{2}}\right)$$

where *x* is the number of SQs, μ=1 SQ, and σ is selected in this case to provide a near step function. Other values for σ and μ could be selected to reflect the scenario assumptions, for example, the type of adversary or whether the scenario is theft (abrupt or protracted), diversion, or breakout. μ could also be used to reflect the material yield of the transformation stage. Figure 9 shows this function plotted for the case of σ=0.25 SQs. One would then multiply the FOM by this function to carry out the aggregation as also illustrated in Figure 9 for LIFE.

The FOM is reasonably in hand to quantify static properties of materials compositions that complicate weaponization. However, no one has published a method to quantify and aggregate the other factors that must be included when dealing with real proliferation problems. Consequently, a quantitative metric for material attractiveness currently eludes the community. However, there are formalisms in the risk assessment community that may be applicable to achieve this aggregation, e.g., see (Edmunds, 2007). The use of the figure of merit and the result of Figure 9 are first steps toward this aggregation.

7. Conclusions

In this study, we compared WG-Pu burned in a LIFE engine with WG-MOX burned in a LWR for the purposes of assessing the relative theft resistance of a LIFE enterprise. We assessed a LIFE engine with a proof-of-principle or disposition mission sited in a P-5 nation. For this study, diversion by the host state was not taken to be the relevant threat, but rather theft and exploitation by outsiders,

insiders, or a combination of these. We assumed these actors to be well financed and well organized (Carlson, 2009). We assume that the actor has the resources and skills required to transform the stolen material to nuclear explosives usable form.

We used the so-called stages of proliferation proposed by Cleary et al. (Cleary, 2007). This proved to be a very useful construct in that the transformation stage and the nuclear explosives fabrication stage were clearly delineated. This enabled credit to be taken for the self-protecting nature and for the dilution of the material in the transformation stage and the application of the figure of merit in the nuclear explosives fabrication stage. This brings clarity to the definition of the figure of merit.

We point out the need to integrate the figure of merit for nuclear explosives utility into a broader group of attributes that make up material attractiveness in the context of a nuclear material theft scenario. We identified the importance of taking steps to obtain quantitative metrics for the other attributes so that they can be effectively aggregated to obtain a metric for material attractiveness.

The FOM calculation shows that in both the case of LIFE burning TRISO and a LWR burning WG-MOX, the Pu contained in the fuel has significant nuclear explosives utility at all times. Only in LIFE is the inventory of Pu decreased to the point that spent LIFE fuel is essentially useless for nuclear explosive production, i.e., less than 1 SQ is present in the entire LIFE fuel load. We added a new attribute "number of SQs available for theft" to the attributes and inputs of (Cleary, 2007) for the theft

(diversion) stage and the nuclear explosives fabrication stage and have proposed a function to aggregate within that stage.

We find the figure of merit to be a useful tool for quantifying nuclear explosives utility for theft scenarios. It provides discrimination among materials that have been transformed to product material (pure element or impure metal). It does not take into account the significant intrinsic barriers presented by material handling difficulty during diversion, transportation, or transformation and it does not account for the quantity of material available in the fuel, i.e., dilution. It represents one very important piece of the concept of material attractiveness. Therefore, we suggest using the term nuclear explosives utility, rather than material attractiveness, to describe the FOM in the nonproliferation context.

While it may be nearly impossible to come up with absolute quantitative measures of proliferation resistance of a particular advanced nuclear energy system, when applied consistently in an analysis comparing two or more advanced nuclear energy systems, quantitative measures such as the FOM become particularly powerful. This also gives hope that progress toward quantification of the other stages of proliferation coupled with a method of aggregation could lead to more objective and quantitative assessments in the future.

8. Acknowledgements

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Appendix A.

Table A-1, Table A-2, Table A-3, and Table A-4 respectively, list associated attributes and inputs used for these four stages. An asterisk indicates those attributes and inputs not suggested by (Cleary, 2007). Note that for the nuclear explosives fabrication stage, attributes are treated through the calculation of a "figure of merit" that recently has been developed to capture the relative viability and difficulty of constructing nuclear explosives starting from various nuclear material forms and compositions (Bathke, 2009; Bathke, Jarvinen, 2008; Bathke, Wallace, 2008).

Of course, not all of the stages, attributes, and inputs given by Cleary et al. (Cleary, 2007) are relevant to this discussion and so are not considered. Further, because LIFE is in the pre-conceptual design phase, relatively few details of the design are known, and therefore some inputs and attributes are treated only qualitatively or not at all.

A.1.   Attributes and inputs for theft

Theft
Material handling difficulty during theft
Mass/SQ
Volume/SQ
SQs available for theft*
Radiation level in terms of dose
Heat load
Process Temperature
Interruptions/changes (normal and unexpected) in material stocks and flows*
Difficulty of evading detection by the accounting system
Uncertainty in accountancy measurements
Difficulty of evading detection
Sensitivity and effectiveness of exit portal screening*
Sensitivity to detect power fluctuations due to fuel load changes*

Table A-1 The attributes and inputs for the theft stage (Cleary, 2007). Those attributes and inputs not suggested by (Cleary, 2007) are indicated by an asterisk.

A.1.1.   Input: SQs available for theft

For most advanced nuclear energy systems (ANES), the number of SQs of material at a site remains large. As in any ANES configured to burn actinides (rather than breed them), the number of SQs decreases as irradiation time increases. However, unique to neutron-driven systems like the LIFE engine, the total quantity of actinides can be driven below 1 SQ.

A.1.2.   Input: Interruptions/changes (normal and unexpected) in material stocks and flows

Processes such as fuel loading and maintenance can change accessibility of attractive materials compared with routine ANES operation.

A.1.3.   Input: Sensitivity and effectiveness of exit portal screening

This input addresses the issue of detection at the portal of protracted theft where the actor is removing small quantities of material, possibly in shielded containers, over a long time.

A.1.4.   Input: Sensitivity to detect power fluctuations due to fuel load changes

Removal of material, either irradiated or unirradiated, that results in a decrease in the total fuel load could give rise to power fluctuations. If these are significant, they could be an indicator of theft.

A.2. Attributes and inputs for transportation

Transportation
Difficulty of handling material during transportation 　　　Mass/SQ 　　　Volume/SQ 　　　Material form (solid, liquid, powder, gas) 　　　Radiation level in terms of dose 　　　Heat load
Difficulty of evading detection during transport 　　　Mass of material and transportation container 　　　Volume of material and transportation container 　　　Heat load of material 　　　Radiation signature from transportation container

Table A-2 The attributes and inputs for the transportation stage (Cleary, 2007). Those attributes and inputs not suggested by (Cleary, 2007) are indicated by an asterisk.

A.3. Attributes and inputs for transformation

Transformation
Facilities and equipment needed to process stolen materials 　　　Cost of facilities and equipment required for transformation 　　　Number of different types of specialized, nuclear-associated equipment and materials 　　　Minimum electrical requirement
Knowledge, skills and workforce needed to process stolen materials 　　　Highly trained technical experts needed to transform the material 　　　Advanced degreed scientists and engineers needed to transform the material 　　　Technicians needed to transform the material 　　　Labor workers needed to transform the material
Difficulty of evading detection of transformation activities 　　　Facility size 　　　Volume of non-naturally occurring gases emitted 　　　Undiluted volume of liquid emissions
Time required to transform the materials*

Table A-3 The attributes and inputs for the transformation stage (Cleary, 2007).

A.3.1. Attribute: Time required to transform the materials

In the case of discovery of an abrupt theft, the time for the actor to complete

transformation will become very limited.

A.4.   Attributes and inputs for nuclear explosives fabrication

Nuclear Explosives Fabrication

Figure of Merit for material nuclear explosives utility
 	
    Bare critical mass*
    Heat content of transformed material*
    Dose rate of transformed material
    SQs available for theft*

Knowledge and skills needed to design and fabricate   Knowledge and skill level for material/weapon type alternatives (direct input from a priori calculations)

Table A-4 The attributes and inputs for the nuclear explosives fabrication stage (Cleary, 2007). Those attributes and inputs not suggested by (Cleary, 2007) are indicated by an asterisk.

A.4.1. Input: Bare critical mass (kg)
Required input to FOM calculation.

A.4.2. Input: Heat content of transformed material (W/kg)
Required input to FOM calculation.

A.4.3. Input: Dose (rem/h)
Dose rate of $0.2M$ evaluated at 1 m from the surface.

A.4.4. Input: SQs available for theft
For most ANESs, the number of SQs of material at a site remains large. As in any ANES configured to burn actinides (rather than breed them), the number of SQs decreases as irradiation time increases. However, unique to neutron-driven systems like the LIFE engine, the total quantity of actinides can be driven below 1 SQ.

A.5.   References

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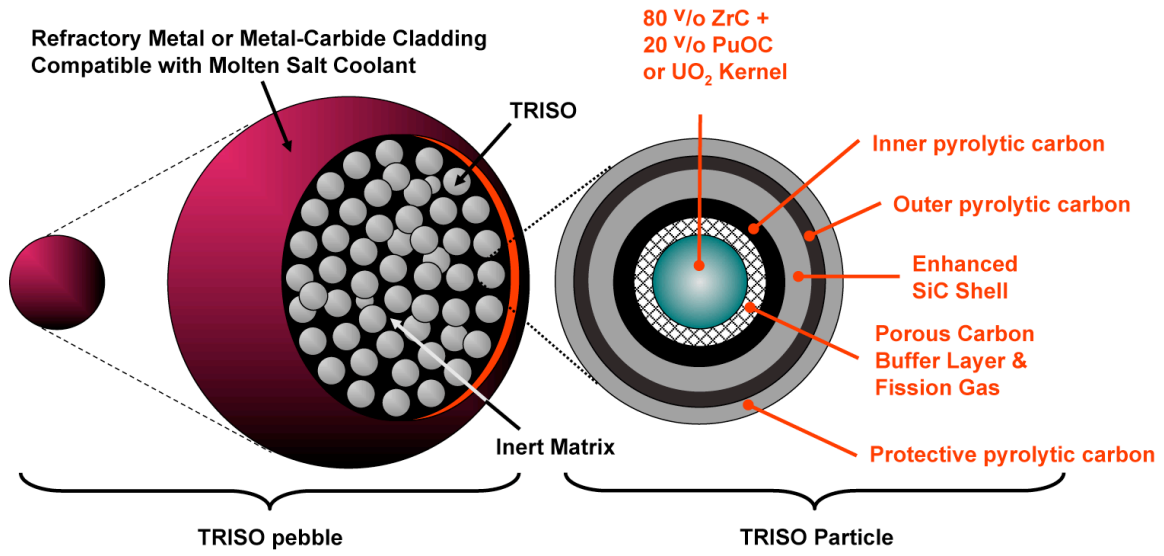
Figure 1 Schematic drawing of TRISO fuel.
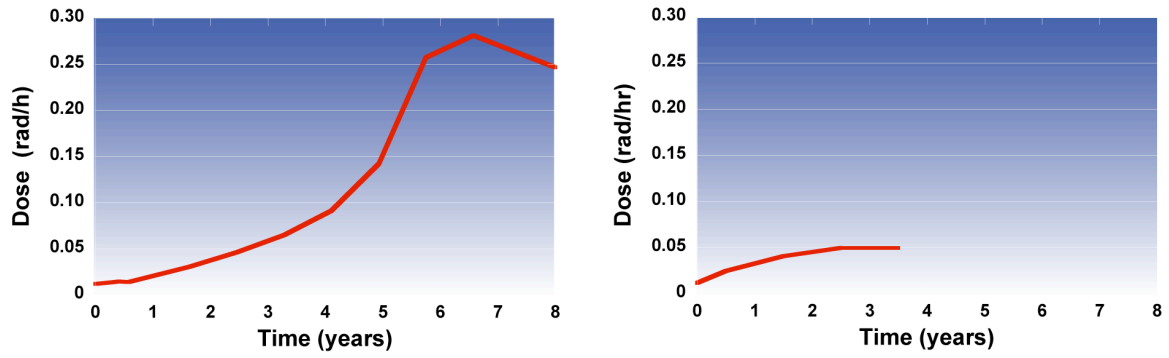
Figure 2 Dose contributions versus irradiation time of transformed WG-Pu TRISO (at left) and WG-MOX at right used in calculation of FOM. This refers only to the dose from the actinides and their decay products, not the fission product dose rate that was present prior to transformation (as seen in Figure 8).
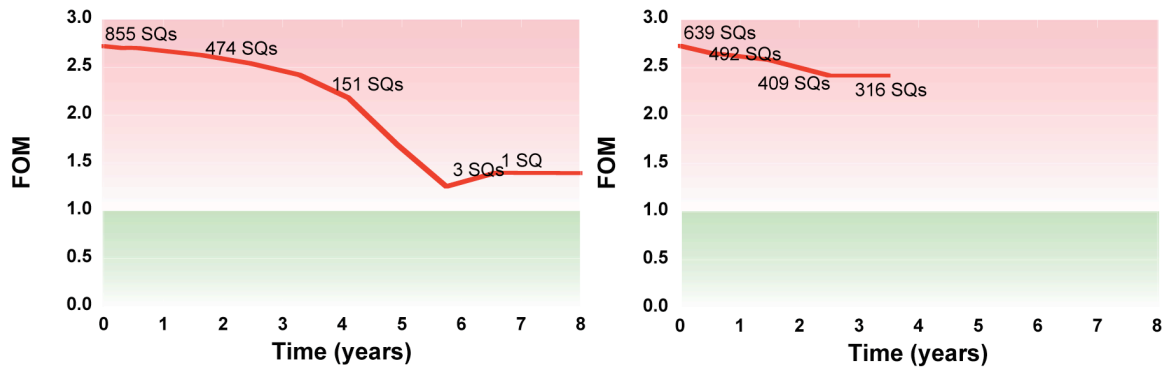
Figure 3 The figure of merit for WG-Pu LIFE fuel (at left) and WG-MOX fuel (at right) as a function of irradiation time in the LIFE engine and LWR reactor. (Note that the figure of merit here refers to the nuclear explosives utility of the plutonium *after* removal of any fission products and other materials, so that in the case of irradiated fuel, the dose rate *D* in the FOM calculation refers only to the dose from the actinides and their decay products, not the fission product dose rate that will be present prior to reprocessing. The red region delineates high and moderate nuclear explosives utility. The green region delineates the region of low nuclear explosives utility. The numbers on the curves indicate the number of SQs of Pu the systems as a function of irradiation time.
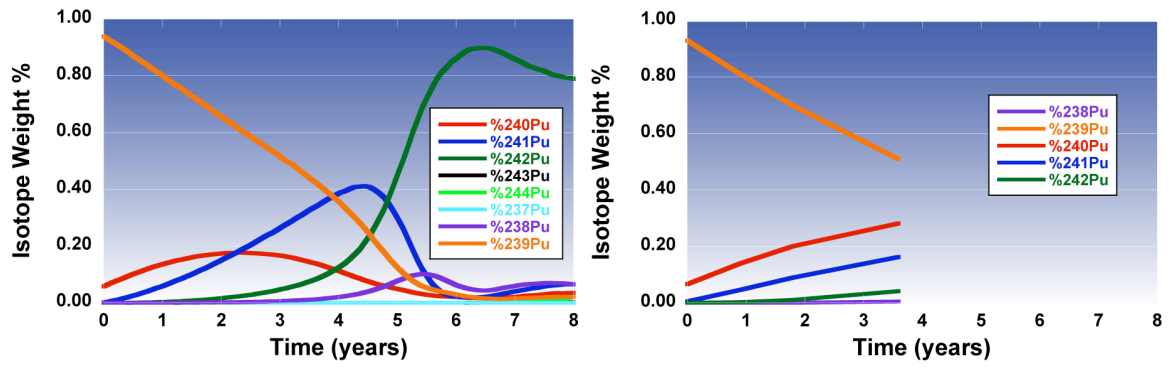
Figure 4 Burnup isotopics of WG-TRISO LIFE (at left) and WG-MOX at right as a fraction of the total Pu.
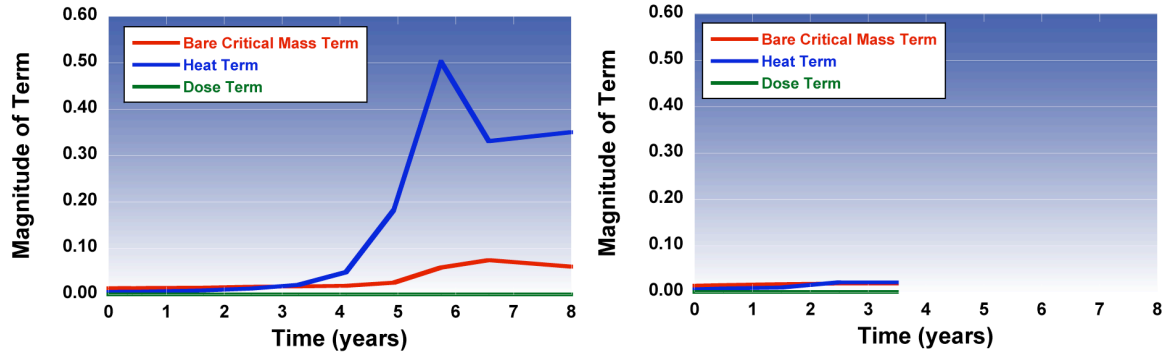
Figure 5 Plots of the three terms of Equation 1 for LIFE at left and WG-MOX at right.
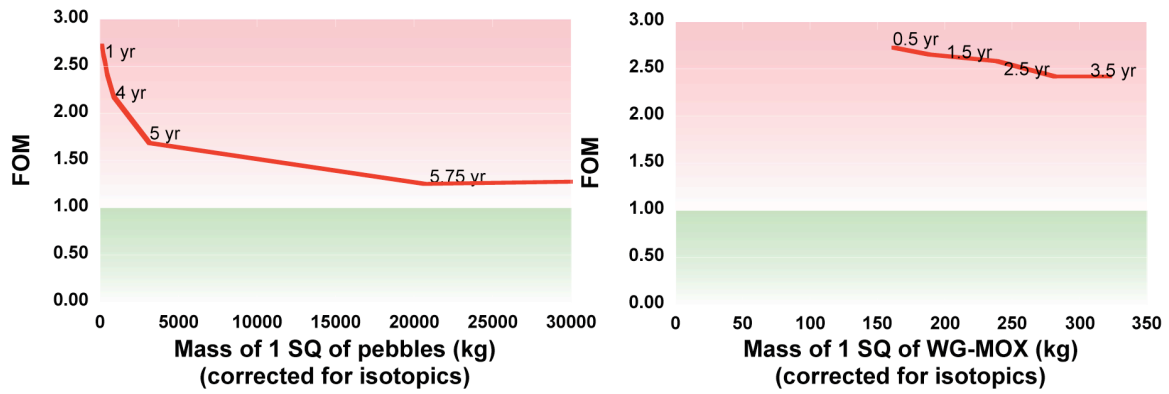
Figure 6 FOM plotted as a function of mass of LIFE pebbles (left) and WG-MOX fuel assembly (right) containing 1 SQ (corrected for isotopic changes). These plots illustrate the increasing processing and handling challenges arising from depletion of plutonium as the irradiation time increases. The numbers on the curves indicate the number of years of irradiation. The red region delineates high and moderate nuclear explosives utility. The green region delineates the region of low nuclear explosives utility. The green region delineates the region of low nuclear explosives utility.
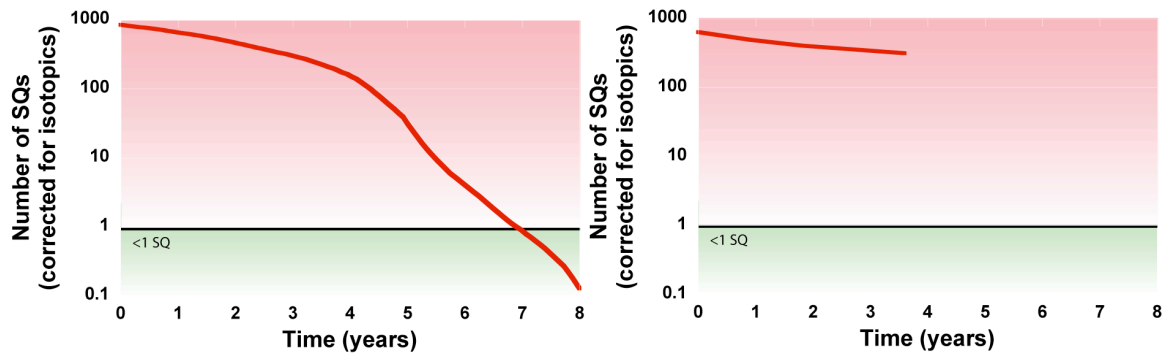
Figure 7 Number of SQs (corrected for isotopic changes) of Pu in the fuel load in a WG-Pu LIFE engine (at left) and in a WG-MOX LWR reactor facility (at right). Note that the inventory at the LWR site increases significantly when spent MOX fuel is moved to cooling ponds and fresh fuel is added. The red region delineates times when more than 1 SQ is in the fuel load. The green region delineates the region where <1 SQ remains in the fuel load.
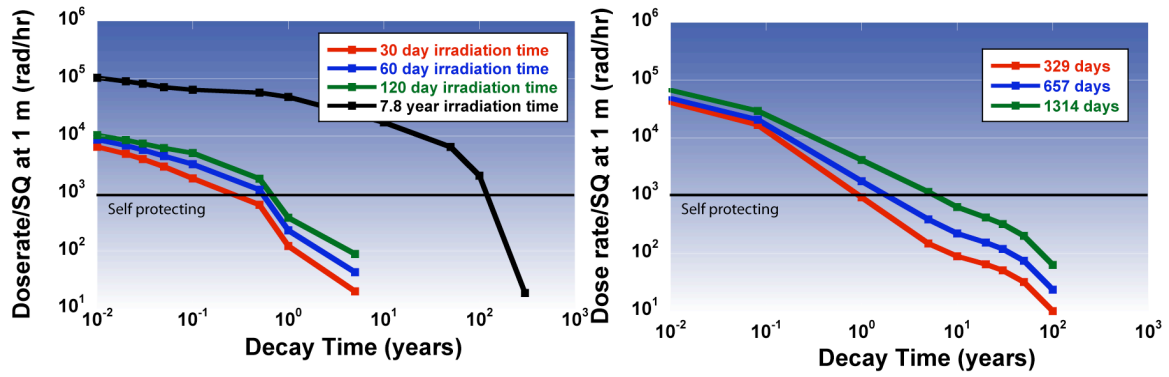
Figure 8 The radiation dose rate at 1 meter for 1 SQ of LIFE pebbles (at left) and for 1 SQ of LWR WG-MOX fuel assemblies (at right) containing 1 SQ of plutonium as a function of decay time for four different residency times in the engine or three in the reactor. LIFE fuel becomes self-protecting almost immediately. Note that unlike the FOM (as applied) these dose rates include contributions from fission products in the spent fuel that are present prior to separation.
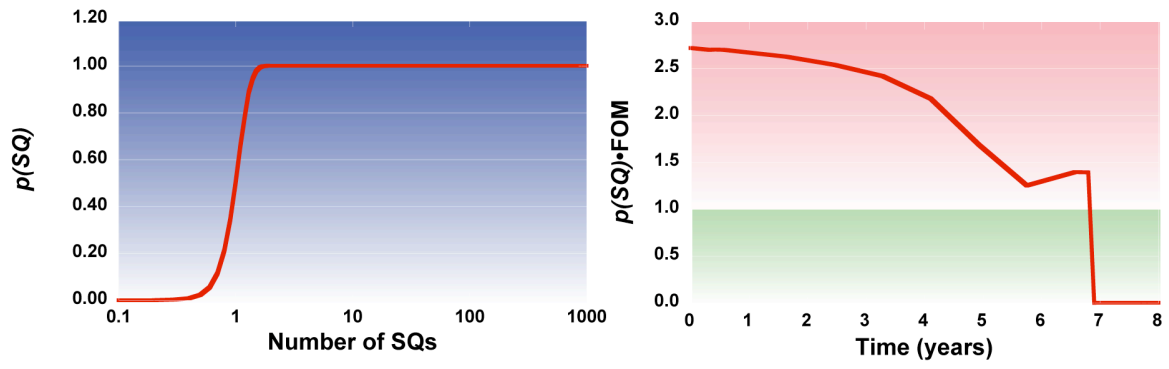
Figure 9 Equation 2 plotted with σ=0.25 SQs at left and the aggregation across the nuclear explosives fabrication stage for LIFE WG-TRISO. Compare this with the FOM in Figure 3.