Conference Paper

PROLIFERATION ATTRACTIVENESS OF NUCLEAR MATERIAL IN A SMALL MODULAR PRESSURE TUBE SCWR

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Proliferation Attractiveness of Nuclear Material in a Small Modular Pressure Tube SCWR

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1. Introduction

The SuperSafe© Reactor (SSR), has been recently proposed[1] as a small modular version of the Canadian supercritical water cooled reactor (SCWR)[2]. This reactor is a heavy water moderated, pressure tube reactor using supercritical light water as coolant. The current SSR design is to generate 300 MWe taking advantage of the expected high thermal efficiency (assumed 45%).

As one of the reactor types being considered by the Generation-IV International Forum, it is expected that this SCWR design will feature enhanced proliferation resistance over current generation technologies. Proliferation resistance assessments are wide-ranging, multidisciplinary efforts that are typically performed at a number of levels, from a state level down to a specific facility level. One small, but particularly important, sub-assessment is that of nuclear material attractiveness, that is, assessing the quality of nuclear materials throughout the fuel cycle for use in making a nuclear explosive device. The attractiveness of materials for three different SSR fuel options is examined in this work.

2. Material Attractiveness Metric

A figure-of-merit (FOM) formula for rating nuclear material attractiveness has been devised[3]. The formula takes into account the main factors that dictate the attractiveness of a material for use in nuclear explosives namely: critical mass, decay heat, and radiation dose rate. In addition to these, a second formula takes into account spontaneous neutron production. It is generally thought that high spontaneous neutron production from a material may impede only the relatively unadvanced nations or sub-national groups from producing a nuclear explosive. The two formulas are:

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

$$FOM_2 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{MS}{6.8(10^6)} + \frac{M}{50}\left[\frac{D}{500}\right]^{1/\log_{10} 2}\right)$$

Where M is the bare critical mass in kilograms, h is the decay heat in watts per kilogram, D is the dose rate in rem/hr at a distance of 1 m, and S is the spontaneous neutron generation rate in

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[1] R. Duffey, L.K.H. Leung, D. Martin, B. Sur, and M. Yetisir, "A Supercritical Water-Cooled Small Modular Reactor", Proc. of the ASME 2011 Small Modular Reactors Symposium, SMR 2011, Washington on Capitol Hill, Washington DC, USA, Sept 28-30, 2011.

[2] L.K.H. Leung, M. Yetisir, W. Diamond, D. Martin, J. Pencer, B. Hyland, H. Hamilton, D. Guzonas, and R. Duffey, "A Next Generation Heavy Water Nuclear Reactor with Supercritical Water as Coolant", Proc. of the Int. Conf. Future of HWRs, Canadian Nuclear Society, Ottawa, Ontario, Canada, Oct. 02-05, 2011.

[3] C.G.Bathke, et. al., "The Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios", Proc. Of Global 2009, Paris, France, Sept 6-11, 2009.

neutrons/second/kilogram. These quantities are calculated for metallic uranium or plutonium, that is, the material after it has been removed from the spent fuel and processed into weapons usable form. Thus, it is implied that reprocessing capability exists, whether it is included in the nuclear energy system or is a clandestine facility. The numerical result of the equation can then be used to describe the material attractiveness for weapons use according to Table 1.

Table 1: Material Attractiveness ranking by Figure of Merit

FOM	Weapons Utility	Material Attractiveness
>2	Preferred	High
1-2	Attractive	Medium
0-1	Unattractive	Low
< 0	Unattractive	Very Low

3. SSR Fuel Cycle Options

Three fuel options were investigated for this work: plutonium-thorium, lightly enriched uranium (LEU), and LEU-thorium, see Table 2. The SSR is a three-batch fuelled reactor, i.e. one third of the fuel is replaced at each fuelling outage, approximately every two years. The fuel assembly is based on 78-element geometry[2] and features a re-entrant coolant design[4].

Table 2: SSR fuel options

Fuel Type	Initial Composition	Initial Fissile wt % HE	Average Assembly Discharge Burnup (MWd/kgHE)
Pu-Th	13% RG PuO_2, 87% ThO_2 (Pu: Pu-238 2.75%, Pu-239 51.96%, Pu-240 22.96%, Pu-241 15.23%, Pu-242 7.10%)	8.6%	44.3
LEU	100% UO_2 (6 wt% U-235/U)	6%	44.2
LEU-Th	50% UO_2, 50% ThO_2 (13 wt% U-235/U)	6.5%	42.9

Fuel burnup calculations have been performed using the 2D lattice code WIMS-AECL v 3.1.2.1. Isotopic compositions for the uranium and plutonium in the fuel have been extracted at several points during the fuel burnup, roughly corresponding to the burnup seen at the refueling shutdowns. Compositions of uranium and plutonium have been averaged over five sections of the fuel assembly in order to account for axial variation in burnup. The figures of merit were then calculated for both uranium and plutonium.

4. Results and Discussion

Figure 1 shows the result of the FOM calculation for plutonium and uranium for the three different SSR fuel options. Plutonium remains highly attractive throughout the entire fuel burnup for all three fuel types. Only in the case of Pu-Th fuel does the FOM1 drop below 2 towards discharge burnup. The higher concentration of Pu-240 in the Pu-Th fuel leads to an unattractive rating when considering FOM2.

For uranium, FOM2 is practically identical to FOM1 due to the relatively low number of spontaneous neutrons produced and is not shown in the figures. The uranium produced in the Pu-Th fuel during irradiation is a proliferation concern as it is primarily (>90%) U-233. In the case of the LEU-Th fuel, the U-233 produced is “denatured” by the presence of U-238 and this is reflected in the unattractive (<1)

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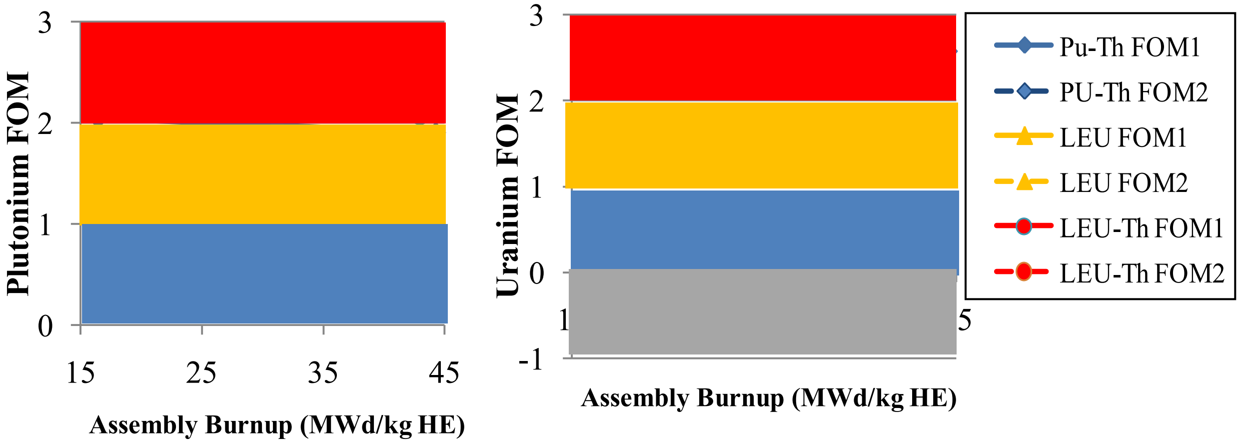
[4] J. Pencer, “Preliminary Core Physics Evaluation of a Small Modular Pressure Tube SCWR”, 2nd International Technical Meeting on Small Reactors, Ottawa, Canada, November 7-9, 2012.

FOM value. For the LEU fuel, the uranium in the fuel does not contain enough fissile material to create a critical mass and therefore unable to be used as weapons material.

Figure 1: Figures of Merit for plutonium (left) and uranium (right) for SSR Fuel Options



As the FOM evaluates only the quality of material, a separate assessment must be done on the quantity of material present. While a more detailed proliferation resistance assessment is to be performed as future work,

Table **3** lists the mass of plutonium and uranium in an assembly at discharge along with the bare critical mass for the respective compositions at discharge.

Table 3: Quantity of Materials per Assembly at Discharge

Fuel	Mass per 5 m long assembly at discharge (kg)	Bare critical mass of material at discharge (kg)
Pu-Th	Pu: 23.3	17.7
	U: 3.24	15.4
LEU	Pu: 2.7	14.1
	U: 290	infinite
LEU-Th	Pu: 1.4	13.5
	U: 136	11234

5. Conclusions

The proliferation attractiveness of uranium and plutonium produced in the SuperSafe reactor has been examined for three fuel types. It was found that in all cases the plutonium produced in the reactor is of high attractiveness for weapons use for state-sponsored clandestine activities. The plutonium produced in the Pu-Th fuel case is the least attractive, and less attractive for sub-national threats, however the uranium produced in this fuel type is relatively pure U-233 and represents a proliferation concern. The concern reduced slightly by the buildup of U-232 in this fuel which has a high gamma activity daughter Th-228. After separation from the spent fuel, the decay of U-232 will present challenges in handling the material. Further denaturing the uranium by adding LEU to fresh fuel is seen to make the uranium unattractive in all three fuels.

Although the LEU and LEU-thorium fuel types both produce weapons attractive plutonium, the amount of plutonium in the discharged fuel assembly is significantly less than in the Pu-Th fuel. In addition, both these fuels are found to contain low quality uranium throughout the fuel cycle. While a more thorough proliferation resistance assessment is to be performed in the future, the LEU and LEU-Th fuel options appear to be more appealing fuel options from a non-proliferation viewpoint.