Proliferation Resistance Assessment of Different Fuel Cycles in the CANDU System

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Summary

(Th, U)O_2 fuel is regarded as an attractive option for CANDU reactors because of thorium's rich abundance in nature and its favorable neutron economy. This paper compares the proliferation resistance degree of the thorium fuel cycle with that of the natural uranium fuel cycle in CANDU reactor systems, based on the multi-attribute methodology (MAUA) [1] and Figure of Merit (FOM) method [2]. The results show that the proliferation resistance (PR) value changes with the fuel flowing through the whole cycle, from mining to final geological repository. The PR of natural uranium fuel cycle is slightly higher than that of thorium fuel cycle in all processes.

1. Introduction

Since the 1970s, several methodologies of proliferation resistance have been developed around the world [1-8]. Two popular projects are: Generation IV International Forum's (GIF) project on proliferation resistance and physical protection (PR&PP) of Nuclear Energy Systems (NESs) [3], and IAEA's Innovative Nuclear Reactors and Fuel Cycles (INPRO) project on developing a methodology for the holistic assessment of NESs [4]. Proliferation Resistance is defined as the characteristic of a NES that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other Nuclear Explosive Devices (NEDs) [3]. Although they are developed for different users, a common definition of proliferation resistance is shared and both give out hierarchal top down analytical structure as well as treat proliferation resistance as a function of multiple intrinsic features and extrinsic measures. Besides, they can be complementary to each other.

Other methodologies such as Technology Opportunities for Proliferation Resistance (TOPS) [5] and Japan Atomic Energy Agency's (JAEA) methods [6] are mainly dependent on expert judgment and generate qualitative assessments. PR&PP, MAUA, Fuzzy Logic method [7] and Risk-Informed Probabilistic Analysis (RIPA) [8] produce a quantitative value. The MAUA incorporates subjective and objective inputs to produce a PR value. Recently, the INPRO collaborative Project with GIF-Proliferation Resistance and Safeguardability Assessment Tools (PROSA) [9] is attempting to simplify the assessment process by performing it at three levels i.e. state level, NES level, and facility level.

CANDU reactors were originally designed to burn natural uranium fuel. (Th, U)O_2 is regarded as an attractive option for CANDU because of thorium's rich abundance in nature and its favourable neutron economy. When we compare two fuel cycles, we find that proliferation resistance is a key factor to be considered. The proliferation resistance assessment of CANDU has been researched by different methods. Intrinsic features and extrinsic measures of CANDU were considered and expressed with analytical results [10]. MAUA gave the PR value of 0.76 for the process in a CANDU reactor compared with 0.93 for PWR. The small fuel bundle and online refuelling scheme of CANDU are the main reasons for the smaller PR value. This work starts with the purpose of developing a quantified method to compare the proliferation resistance characteristics of different fuel cycles for CANDU reactors. The emphasis will be on the consideration of the whole fuel cycle: fuel mining & milling, refining, conversion, enrichment, burning in the reactor, discharging and cooling in the pool, dry cask storage and the final geological repository.

2. Methods

2.1 Multi-attribute Utility Analysis (MAUA) [1]

The multiattribute method was adopted to compare the proliferation resistance degree of each process for different fuel cycles. Fourteen attributes (J=14) were used to calculate the proliferation resistance value of process i by Eq. (1). Each attribute j has a utility function ($u_j\,(x_{ij})$) describing the relationship of its input (x_{ij}) and final function value. The utility functions come from experts' opinions that concentrated the effects of each input on the proliferation resistance of the material in process i. Each attribute also has a corresponding weight factor (w_j) that determines its importance in the overall assessment. Attributes like the attractiveness level, radiation dose rate, even plutonium fraction, physical barriers and inventory are considered as intrinsic while the frequency of measurement, measurement uncertainty, and probability of unidentified movement are considered extrinsic because they are carried out by institution and can be improved. We can track the PR value of a unit mass of material flowing through a fuel cycle instead of focusing on the facilities.

$$PR_i = \sum_{j=1}^{J} w_j u_j \left(x_{ij} \right) \tag{1}$$

2.2 Figure of Merit (FOM) [2]

The FOM method is used to calculate the attractiveness of Special Nuclear Material (SNM) or Alternative Nuclear Material (ANM). FOM value is determined by the bare critical mass (M), heat content(h) and dose rate (D), as shown in Eq.(2). If the FOM >2, the material is favourable for weapon use. Materials with 1<FOM <2 are potentially usable for nuclear weapons while materials with FOM <1 are impractical for weapon use but still theoretically possible. We suppose the Host State which runs the whole fuel cycle is technologically advanced and accept any yield factor, so the intrinsic neutron production rate was ignored here. FOM value represents a small part of the overall proliferation and security risks that are posed by the materials in the fuel cycle. It describes the material attractiveness with a fine-grain resolution while it doesn't take into account the difficulty of transforming the material into highly concentrated SNM metal, which is beyond the scope of FOM.

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

2.3 Calculation Procedure

The MAUA and FOM methods evaluate the proliferation resistance degree and nuclear material attractiveness respectively. The concentration of the nuclides, heat content and dose rate were prepared using the depletion package within SCALE- OrigenArp [11]. The bare critical mass was calculated with KENO [12]. Computations are carried out for 1 MT of heavy metal fuel and then the results are adjusted and analysed. For the natural uranium fuel cycle, it runs for 226.5 days to reach a burnup of 7927.5 MWd/MTHM. For the thorium fuel cycle, the same burnup was achieved with homogeneous fuel consisting of 30% thorium and 70% uranium (1.58% U-235). After discharge from the reactor, the spent fuel bundles stay in the spent fuel pool for 6 years, dry cask storage for 44 years and then into the geological repository.

3. Results and Discussion

3.1 MAUA Results

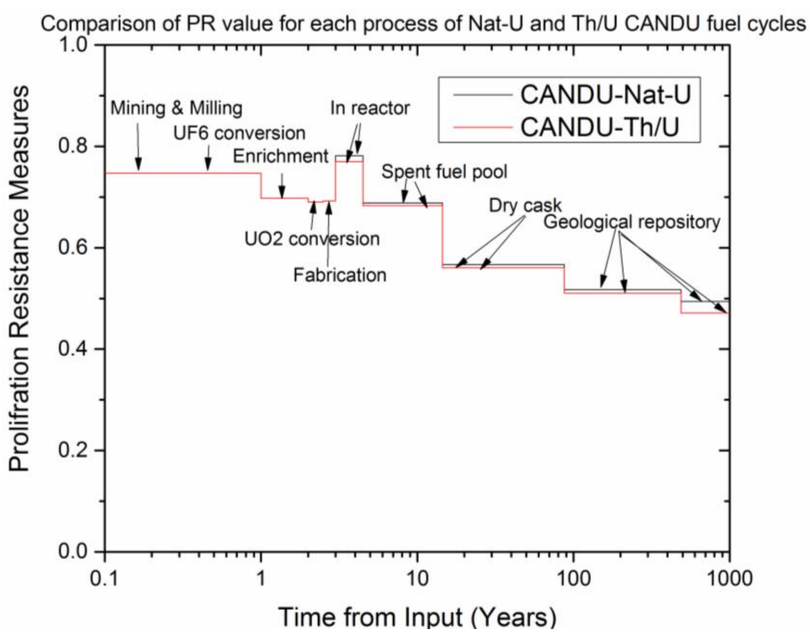

Figure 1 Comparison of PR value for each step of two fuel cycles.

The comparison of PR value for different fuel cycles is expressed in Figure 1. Two fuel cycles share a very similar trend in the fuel preparation process with the exception that there is no enrichment process in the natural uranium fuel cycle. When in the reactor, more plutonium was produced in the natural uranium fuel cycle which created more heat and larger even plutonium fraction, as a result the PR value is slightly higher than that of the thorium fuel cycle. When the spent fuel was stored in the spent fuel pool or dry cask, PR decreased. The main reason for this is the decreasing of measurement frequency and its accuracy. As the spent fuel goes into geological repository, the inaccessibility will increase PR value a little, and the lack of continuous inspections and lower radiation outside the site will decrease PR. PR may become an important criterion in the safety assessment of spent fuel disposal.

3.2 FOM Results

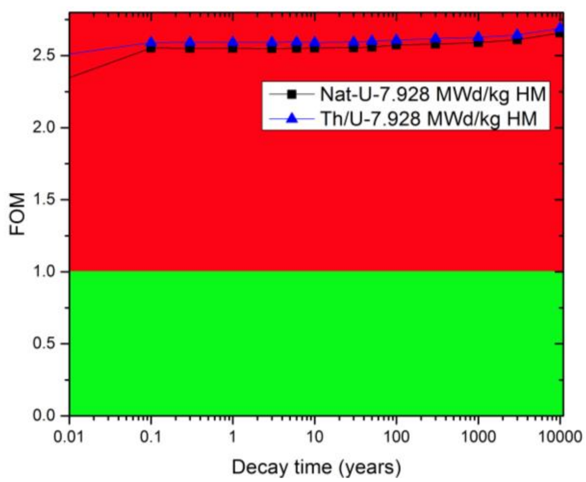

Figure 2 Comparison of FOM of Pu from spent fuel of two fuel cycles.

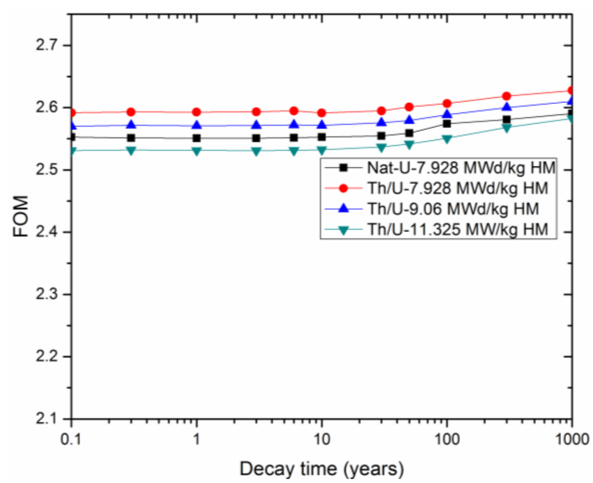

Figure 3 Comparison of FOM of Pu from spent fuel with different fuel burnup.

The proliferation risk with plutonium in spent fuel still exists although the plutonium only accounts for 0.33% weight in the natural uranium fuel cycle and 0.19% weight in the thorium fuel cycle after 50 years from discharged. As Figure 2 shows, Pu from spent fuel is favourable for nuclear weapon production with the FOM value larger than 2. As time increases, the FOM increases because the amount of fissile Pu increased and heat and dose rate from plutonium decreased. The natural uranium fuel cycle has a smaller FOM value because of relatively smaller heat content from plutonium, smaller dose rate and smaller Pu-239 fraction. Figure 3 shows that the FOM decreased with higher burnup. The increasing FOM induced by the decreased radiation dose rate and heat repeats the importance of proper reprocessing of spent fuel. It also emphasizes the need for more effective safeguards, which can be fulfilled by strengthening the extrinsic attributes.

4. Conclusions

MAUA and FOM were used to compare the proliferation resistance of different processes. As the nuclear wastes goes into temporary storage or final disposal, the intrinsic attributes of the nuclear waste such as the decay heat and dose rate, cannot serve as sufficient barriers to proliferation, the safety of nuclear waste could be a serious issue in the waste management process. The extrinsic attributes can affect the proliferation resistance degree more significantly and effectively than the intrinsic attributes. Strict inspection and material accounting systems could make the verification more reliable and thus could be used to make up for the decreased PR value.

5. References

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