A Comparative Study on the Proliferation Resistance of Nuclear Fuel Cycles

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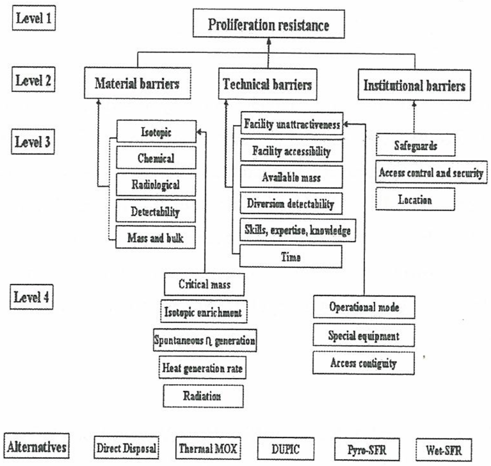
1. Introduction

A methodology based on Multi-Attribute Utility Theory (MAUT) [1] and Analytic Hierarchy Process (AHP) [2] is being developed at Korea Atomic Energy Research Institute (KAERI) to examine the proliferation resistance of nuclear fuel cycles, with the aim of discovering inherent vulnerability in fuel cycles before they are designed and built. The methodology has been applied to five different nuclear fuel cycles: Once-through fuel cycle, Thermal mixed-oxide fuel cycle (Thermal MOX), DUPIC fuel cycle, Pyroprocessing-Sodium-cooled Fast Reactor fuel cycle (Pyro-SFR), and an advanced wet reprocessing-SFR fuel cycle (Wet-SFR). The potential diversion of nuclear material by a state from the back-end of the fuel cycle has been considered in the analysis because all of the five nuclear fuel cycles have in common such steps as mining, conversion, enrichment, fuel fabrication, etc. Diversion target materials were identified as spent fuel (Once-through), PuO_2 powder and fresh MOX fuel (Thermal MOX), fresh DUPIC fuel (DUPIC cycle), transuranics (TRU) ingot and SFR TRU ingot (Pyro-SFR and Wet-SFR), respectively.

2. Evaluation Methodology

Proliferation resistance was assessed by defining and applying three objective barriers based on the characteristics of the fuel cycle as reported by many proliferation resistance studies, including the Nuclear Energy Research Advisory Committee's Task Force on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) [3]. Protection levels are achieved through a combination of these three barriers, i.e., intrinsic features of the material qualities, technical impediments, and extrinsic features related to materials accounting, security, adherence to international norms, etc. The metrics considered in the assessment are shown in the Table below and the metrics are mutually utility independent and additive independent. Attributes important for determining the effectiveness of the isotopic barrier and the facility accessibility are also shown in the table at the 4th level.



u_i	2nd level	weighting factor	3rd level	Weighting factor	4th level	Weighting factor
1	Material barriers	0.441	Radiological	0.278		
2			Detectability	0.233		
3			Mass and bulk	0.111		
4			Chemical	0.165		
5			Isotopic	0.213	Critical mass	0.114
					Pu purity	0.278
					Spontaneous neutron generation	0.284
					Heat-generation rate	0.180
					Radiation	0.144
6	Technical barriers	0.222	Facility unattractiveness	0.191		
7			Facility accessibility	0.168	Operation mode	0.714
					Special equipment	0.139
					Contiguity frequency	0.147
8			Available mass	0.073		
9			Diversion detectability	0.318		
10			Skills, expertise, knowledge	0.132		
11			Time	0.118		
12	Institutional barriers	0.336	Safeguards	0.579		
13			Access control and security	0.346		
14			Location	0.075		

The utility for the proliferation resistance of a nuclear fuel cycle, u, can be expressed as:

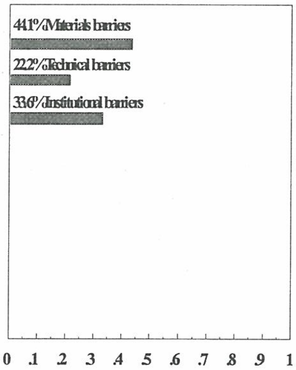
$$u(x_1, x_2, x_3, \ldots\ldots x_{14}) = \sum_{i=1}^{14} w_i u_i(x_i)$$

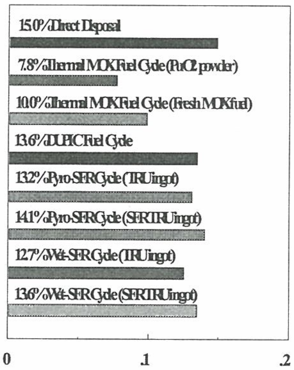
and the utility function was assigned to each of the metrics based on the MAUT theory using a 50-50 lottery and expert elicitation. The weighting factors of the metrics, w_i, were obtained using the AHP process and shown in the table above. All the consistency indices were well below 0.1, satisfying the acceptance limit.

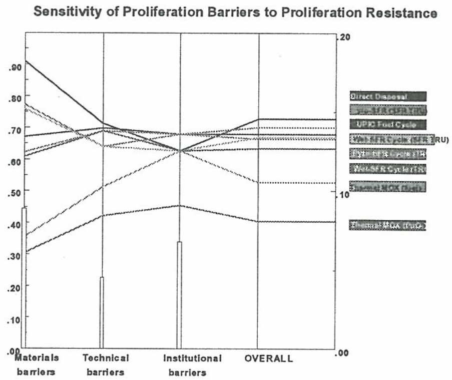
3. Proliferation Resistance Analysis and Discussion

The utilities for the five nuclear fuel cycles were calculated as follows: 0.810 for the once-through fuel cycle, 0.399 for Thermal MOX cycle (PuO_2 powder), 0.522 for Thermal MOX cycle (fresh MOX fuel), 0.729 for DUPIC cycle, 0.708 for Pyro-SFR cycle (TRU ingot), 0.750 for Pyro-SFR cycle (SFR TRU ingot), 0.676 for Wet-SFR cycle (TRU ingot), and 0.718 for Wet-SFR cycle (SFR TRU ingot).

However, many factors are subjective in the assessment of proliferation resistance of nuclear fuel cycles: the choice of metrics, the form and structure of the utility functions, the weighting factors, proliferation threats, the safeguards regime, etc. Of these subjective components, the weighting factors have the greatest potential to change the outcome of the analysis because the weighting factors aggregate all utility functions and produce the final utility for proliferation resistance. The figures below show contributions of three barriers (2^{nd} level) to the proliferation resistance of the nuclear fuel cycles. Sensitivity analyses can be performed to see how the proliferation resistance of nuclear fuel cycles changes with respect to each of the barriers, from the 2^{nd} level to the 4^{th} level, as well as how sensitive the proliferation resistance is to changes in the weighting factors of the metrics.







4. Summary

The preliminary quantitative analysis of proliferation resistance for the five nuclear fuel cycles demonstrated that the thermal MOX fuel cycle is most vulnerable to proliferation due to the presence of pure PuO_2 in the fuel cycle, while the once-through fuel cycle has the highest proliferation resistance. The innovative next generation fuel cycles such as Pyro-SFR and Wet-SFR were found to have similar levels of proliferation resistance to that of the DUPIC fuel cycle which is believed to have proliferation resistance strong enough for commercial deployment. The sensitivity analysis also demonstrated the effectiveness of the proposed methodology in applying to existing and/or newly developing nuclear fuel cycles so as to improve the proliferation resistance characteristic of the fuel cycle systems.

References

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3. Nuclear Energy Research Advisory Committee (NERAC), "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power System", International Workshop on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power System (TOPS), Washington, D.C. 2000.