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Examination of Proliferation Resistance of Small Modular Reactor by Using Non-proliferation Assessment Tool (NAT)

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1. Introduction

From the IAEA statistics, it is apparent that nuclear power plants (NPPs) provided more than one-quarter of the total electricity to 13 countries, and there are 446 NPPs are in operation [1]. In other words, nuclear energy makes a significant contribution to human life. Currently, a small nuclear reactor is a promising solution for a sustainable energy source in case of remote areas (for example: islands), or areas that have no access or have a lack of accessibility to the main electrical grids.

However, since the 11/9 event and especially in light of the current North Korea situation, nuclear weapons and nuclear proliferation are becoming serious world-wide issues. Civilian nuclear capability can be used directly or indirectly to facilitate nuclear weapon programs. In 2016, the International Atomic Energy Agency (IAEA) spent approximately 135 million euro, which equals to 37% regular budget of the IAEA, for safeguards activities in order to reduce the proliferation risk [2]. In this situation, proliferation resistance is clearly an essential element of civilian nuclear system.

2. Objective

Although there are many proposed methods for evaluation of PR value, there is very few research regarding quantitative assessment of proliferation resistance for SMRs. From this observation, three questions arise:

1) How is the proliferation resistance value of small nuclear reactor in comparison with other types of reactor?

2) How to increase the proliferation resistance value of small nuclear reactor? And

3) How can the safeguards burden be reduced when deploying SMRs?

To answer these questions, this study specifically focused on a small modular reactor designed by South Korea (System Integrated Modular Advanced Reactor - SMART). The proliferation resistance value of SMART was examined and compared with the value of a large scale PWR. Next, recommendations regarding SMART design are proposed in order to improve its proliferation resistance value. A nuclear fuel can be divided to many stages:

- Beginning of cycle: mining, milling, conversion, enrichment, fuel fabrication.
- Reactor operation: fresh fuel storage, irradiation, spent fuel handling and storage.
- Back-end: storage of spent fuel, reprocessing, final disposal.

In case of SMRs, which are supposed to be built in isolated areas, the reactor operation stage was taken into account.

3. Literature Review

Numerous proliferation resistance assessment methods were developed, and these methods can be classified into two group: attribute approach and scenario approach. Table 1 shows advantages and disadvantages of each approach.

Attribute approach bases on various attributes related to nuclear material diversion process. A multi-barriers framework, which was developed by the Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) Task Force, was widely used in order to evaluate the proliferation resistance [3]. This framework can be used to evaluate qualitatively the proliferation resistance of nuclear fuel cycles. By applying fuzzy logic and multi-attribution utility theory to this framework, quantitatively assessments were performed by Jun Li, and Steve Skutnik [4-5]. William Charlton used another set of attributes for quantitative proliferation resistance evaluation [6]. Each barrier has a weighting factor that represents the importance of each barrier, and a utility function that identifies the influence level or the contribution of each barrier to the proliferation attempt. This approach can be applied for conceptual analysis.

Scenario approach, on the other hand, identifies the potential diversion targets, diversion pathways, and then uses some measures to evaluate each pathway [8-9]. Quantitative results can be achieved by this approach. However, this approach has time consuming issue and requires more design information of nuclear fuel cycles when performing the assessment.

4. Methodology

Since SMART is in conceptual design stage at the moment, multi-attribution utility theory is obviously an effective method for quantitative assessment of its proliferation resistance. After W. Charlton study, a follow-up research was performed at the University of Texas at Austin with in collaboration with the Oak Ridge National Laboratory, and Non-proliferation

Assessment Tool (NAT) was the result of this research [7].

The study that is presented here used above tool to perform proliferation resistance analysis. This tool uses a series of attributes that include 05 groups: 1) attractiveness level, 2) concentration, 3) handling requirements, 4) type of accounting system, and 5) accessibility. Each group have its sub-attribute as shown in table 1 [7]. As can be seen in this table, these attributes include both intrinsic attributes that represent the inherent nature of the fuel cycle and extrinsic attributes that includes safeguards and security measures.

Each barrier j has a weighting factor (w_j), and a corresponding utility function (u_j). The proliferation resistance value of a nuclear fuel stage can be calculated by the following equation [7]:

$$PR_i = \sum_{j=1}^{15} w_j * u_j(x_{ij}) \quad (1)$$

Where:

- PR_i is the proliferation resistance value for process i;

- w_j and u_j are the weighting factor and utility function of attribute j respectively; and

- x_{ij} is the input value for the utility function for attribute j in stage i. This input data can be calculated by ORIGEN2.2 code that is integrated with NAT tool.

Table 1. 15 Attributes used in Non-proliferation Assessment Tool (NAT)

Group	j	Attribute
Attractiveness level	1	DOE attractiveness level
	2	Heating rate from Pu in material (W)
	3	Weight fraction of even Pu isotopes
Concentration	4	Concentration (SQs/tonne)
Handling requirements	5	Radiation dose rates (rem/h at a distance of 1m)
	6	Size/weight
Type of accounting system	7	Probability of unidentified movement of material
	8	Frequency of measurement
	9	Measurement uncertainty
	10	Separability
	11	Number of processing steps that change material form
	12	% of processing steps that use item accounting
Accessibility	13	Physical barriers
	14	Inventory
	15	Fuel load type (Batch or Continuous reload)

To evaluate the proliferation resistance of SMRs, the reactor tab was used. Table 2 shows the input data for execution of this tool. By changing the input data, the proliferation resistance of reactor operation stage of nuclear fuel cycles can be compared.

Table 2. Input data of Non-proliferation Assessment Tool (NAT) for reactor operation assessment

	Data	Description
1	Reactor type	PWR, BWR,…
2	Number of cycle	The number of fuel cycles through which the reactor fuel is burned.
3	Storage Time (years)	Duration that spent fuel is stored onsite
4	U235 Enrichment	The enrichment of fuel
5	Steps that Change Material	The number of steps in the process flow that changes the chemical, physical, or radiological properties of the material
6	Average Reactor Thermal Power (MWt)	Average daily reactor thermal power
7	Cycle Length (months)	The average amount of time a particular core loading is burned in the reactor before refueling
8	Core Loading (MT)	Fuel mass in the reactor core
9	Measurement uncertainty (%)	
10	Steps Using Item Accounting (%)	The percentage of steps at this facility that ship or transfer discreet packages of material using item accounting
11	Probability of Unidentified Movement (%)	The probability that nuclear material could leave the facility without detection
12	Fuel Type	U235 enriched UO2
13	Refueling Downtime (days)	The number of days it takes to refuel the reactor
14	Frequency of Measurement	How often nuclear materials at this facility are confirmed to be present
15	Physical Barriers	i.e. inaccessible, canyon, vault, secure, remote, or hands-on
16	Separability	The general content and form of the nuclear material

5. Result and Discussion

To evaluate the proliferation resistance at reactor operation stage, the reactor tab was used. Table 3 provides the basic design information of SMART and large scale PWR

Table 3. Design Information of SMART and PWR

	SMART	PWR
Thermal power (MWt)	330	3000
Fuel type	UO2	UO2
Fuel enrichment	4.95	5
Fuel cycle length (months)	36	18
Refueling downtime (days)	30	30
Fuel mass in the reactor core (MT)	13	1000
Number of fuel assembly	57	220
Uranium mass/fuel assembly (kg)	218	461.5
Spent fuel storage time (yrs)	3	3

According to the results calculated by this tool, the proliferation resistance value of SMART slightly higher than PWR (0.78 in comparison with 0.7). The utility function values are shown in table 4. Both values are much higher than the proliferation resistance values of enrichment, fuel fabrication, spent fuel storage, and reprocessing process of PWR (with the values are 0.59, 0.58, 0.42, and 0.44 respectively) [7].

Table 4. Utility Functions Values calculated by NAT

	Attribute	Weight (w_i)	SMART Value (u_i)	PWR Value (u_i)
1	DOE attractiveness level	0.10	1.00	1.00
2	Heating rate from Pu in material (W)	0.05	0.07	0.00
3	Weight fraction of even Pu isotopes	0.06	0.24	0.04
4	Concentration (SQs/tonne)	0.10	0.85	0.88
5	Radiation dose rates (rem/h at a distance of 1m)	0.08	1.00	1.00
6	Size/weight	0.06	1.00	1.00
7	Probability of unidentified movement of material	0.06	0.97	0.97
8	Frequency of measurement	0.08	0.85	0.85
9	Measurement uncertainty	0.09	0.80	0.00
10	Separability	0.03	0.30	0.30
11	Number of processing steps that change material form	0.04	0.98	0.95
12	% of processing steps that use item accounting	0.05	0.73	0.86
13	Physical barriers	0.10	0.50	0.50
14	Inventory	0.04	1.00	1.00
15	Fuel load type (Batch or Continuous reload)	0.06	1.00	1.00
	PR Value=$\Sigma(u_i*w_i)$		**0.78**	**0.70**

The significant contribution to the difference of proliferation resistance values is caused by the measurement uncertainty attribute that contribute 0.072/0.08 of the total difference value. The bulk throughput of large scale PWR is much bigger than SMART. Consequently, with the same value of the measurement uncertainty, while accounting measures can result in one significant quantity of undeclared nuclear material or more in PWR NPPs, none measure in case of SMART can cause the same consequences.

The observation from this result is reactor operation has the lower level of proliferation risk in comparison with other stages of nuclear fuel cycle. Consequently, in the deployment of SMART, the operation of SMART itself will not provide a significant vulnerability target for proliferators, and there are opportunities to reduce safeguards requirements for SMART while still keeping the proliferation risk at reasonable levels.

When the reactor thermal power of SMART changed from 225MWt to 660MWt, the proliferation resistance remained at the same value is 0.78 as shown in figure 1. The same situation when the cycle length changed from 18 months to 48 months, and when the enrichment changed from 3% to 19% (still low enrichment fuel).

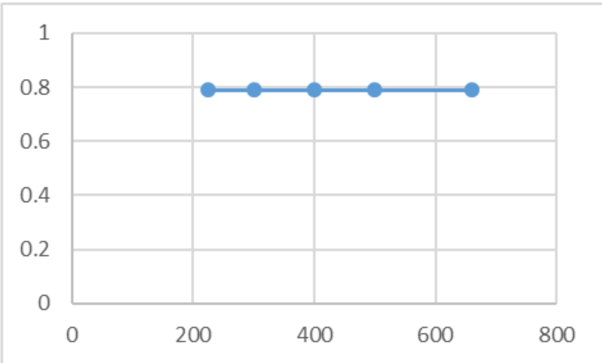

Figure 1. The dependence of the PR value on thermal power

On the other hand, when the data related to the extrinsic attributes including frequency of measurement, physical barriers, measurement uncertainty, the proliferation resistance changed slightly but continuously (as shown in table 5).

Table 5. PR values when changing input data of extrinsic attributes

	Frequency of Measurement			
Input	Continuous	Daily	Weekly	Monthly
PR	0.79	0.78	0.77	0.75
	Physical Barriers			
Input	Inaccessibility	Canyon	Secure	Remove
PR	0.83	0.82	0.78	0.75
	Measurement Uncertainty			
Input	2%	5%	7%	10%
PR	0.79	0.78	0.77	0.76

This result shows that the institutional measures (i.e. safeguards, security, accounting) have significant effect on the proliferation resistance value, and changing these measures could be an effectiveness way to reduce the proliferation risk.

6. Conclusions

Non-proliferation Assessment Tool (NAT) based on multi-attribution utility theory is a useful method in order to assess quantitatively the proliferation resistance of SMART. The operation of SMART itself has a low level of proliferation risk. The proliferation resistance of SMART can be improved by enhancing institution measures i.e. safeguards, security, accounting. The opportunities to reduce safeguards burden when deploying SMART are feasibility, and there should be more research regarding this issue in the future.

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