NENS Nuclear Energy Environment and Nuclear Security Laboratory

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

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Contents

Motivation and Objectives

- Why Proliferation Resistance (PR)?
  - Deterrence measures in case of new countries when pursuing nuclear energy development
  - The public global concern about the misuse of nuclear material for nuclear weapon
  - Safeguards burden of the IAEA (approximately 37% of regular budget of the IAEA in 2016)
- **Goals** of the research:
  1. Choosing design options for SMRs by comparing the PR values of SMART to other reactors:
     - To reduce proliferation risk
     - To minimize the public concern about the misuse of nuclear material for nuclear weapon
  2. Identifying opportunities to develop the safeguards approach in order to minimize safeguards burden of the IAEA by:
     - Reducing the safeguards requirements
     - Minimizing the frequency of inspection

Motivation and Objectives

Work that need to be done in order to achieve these goals:

- To examine the Proliferation Resistance (PR) value of SMR (specifically SMART) by using Non-proliferation Assessment Tool (NAT) that developed the University of Texas in Austin and the Oak Ridge National Laboratory.
    - To compare the PR value of SMART to a large scale PWR.
    - To compare the PR value of SMART to other SMRs concepts: NuScale, KLT-40S.
- To make recommendations regarding SMRs design in order to get low level of proliferation risk.
- From PR assessment results, make suggestions regarding safeguards approach for SMRs in order to reduce safeguards burden of the IAEA.

Background

- **What is Small Modular Reactor (SMR)? [1]**
  - Small: power rating from approximately 10 to 300 MWe.
  - Modular: refers to modularity characteristic: the unit assembly of the nuclear steam supply system (NSSS) which can be assembled from one or several sub-modules.

- **Why Nuclear Energy? Why SMR?**
  - Energy demand, global warming issue: nuclear energy is almost no greenhouse gasses and is a stable/sustainable energy.
  - Providing electricity for isolated areas (islands), or no access/ difficult to access the main electrical grids.
    - Vs. wind or solar energy: has advantages when compared (wind and solar energy critically dependent on local weather conditions and time).

Background

- **What is Proliferation Resistance (PR)?**
  - **Proliferation resistance**: the characteristic of a nuclear energy system (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 [2].
  - Proliferation resistance vs. safeguards?
    - **Safeguards:** a set of measures implemented by the IAEA for timely detection and deterrence of diversion of significant quantities (SQ) of nuclear material [3] → can be covered by PR.

- **Proliferation resistance implications:** high PR values result in:
  - Low level of proliferation risk.
  - Higher level of public acceptance.
  - Opportunities to enhance the effectiveness of safeguards measures, and to reduce safeguards burden.

Literature Review

- **INFCE and NASAP**: identify the opportunities to enhance PR by implementing institutional, safeguards, and other technical measures
- **TOPS** (Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems): **define** a set of **intrinsic and extrinsic barriers** which impede proliferators [4]: Hassberger applied this framework to evaluate qualitatively the PR of various nuclear fuel cycles [5]
- **MAUT** (Multi Attribute Utility Theory):
  - Papazoglou research (1978): most early PR analysis using MAUT
  - An electrical circuit model proposed by Won I. Ko (2000)
  - William S. Charlton research: **define** a set of **attribute** (similar to intrinsic and extrinsic barriers), then **assign** the **utility function** and **weighting factor** for each attribute [6], can quantitatively assess PR
- **Fuzzy Logic:** using TOPS barrier framework, quantitative assessment of PR: **assign fuzzy number**, membership **function** and **weighting** factor **for each barrier**, and the combine:
  - Jun Li: first research using fuzzy logic for PR assessment
  - Steven Skutnik: used figures of merit (FOM - developed by Charles G. Bathke) for isotopic barrier
- **Proliferation pathway analysis:**
  - **PR&PP** (Proliferation Resistance and Physical Protection methodology – under Generation IV International Forum): **identify** potential **threats, targets**, possible diversion **pathways**, and the using measures (difficulty, cost, time, detectability,… - similar to intrinsic and extrinsic barriers) to evaluate each pathway [7].
  - **PRADA** (Proliferation Resistance: Acquisition/Diversion Pathway Analysis, under INPRO - The International Project on Innovative Nuclear Reactors and Fuel Cycles project): develop diversion scenario, and evaluate by intrinsic and extrinsic barriers [8].
  - Hyeongpil Ham research, MinSu Kim research

Literature Review

Proliferation Resistance Evaluation Methodology

- **Attribute approach:** TOPS barrier framework, Multi Attribute Utility Theory, barrier-based fuzzy logic method
- **Scenario approach:** GIF PR&PP (Proliferation Resistance and Physical Protection methodology), INPRO PRADA (Proliferation Resistance: Acquisition/Diversion Pathway Analysis)

Approach	Advantages	Disadvantages
Attribute	- Less design information requirements (**conceptual analysis**) - Ranking assessment - Shorter time is required - Qualitative or quantitative results	- May include subjective results - No example of diversion pathways or scenarios
Scenario	- Quantitative results - Ranking assessment - Identifying the potential targets diversion pathways or scenarios	- Time consuming - May include subjective results - Require more detail information

In case of conceptual design stage of SMRs → using **Attribute Approach**

Methodology

- This research used Non-proliferation Assessment Tool (NAT) Tool that was developed based on Multi Attribute Utility Theory. 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.

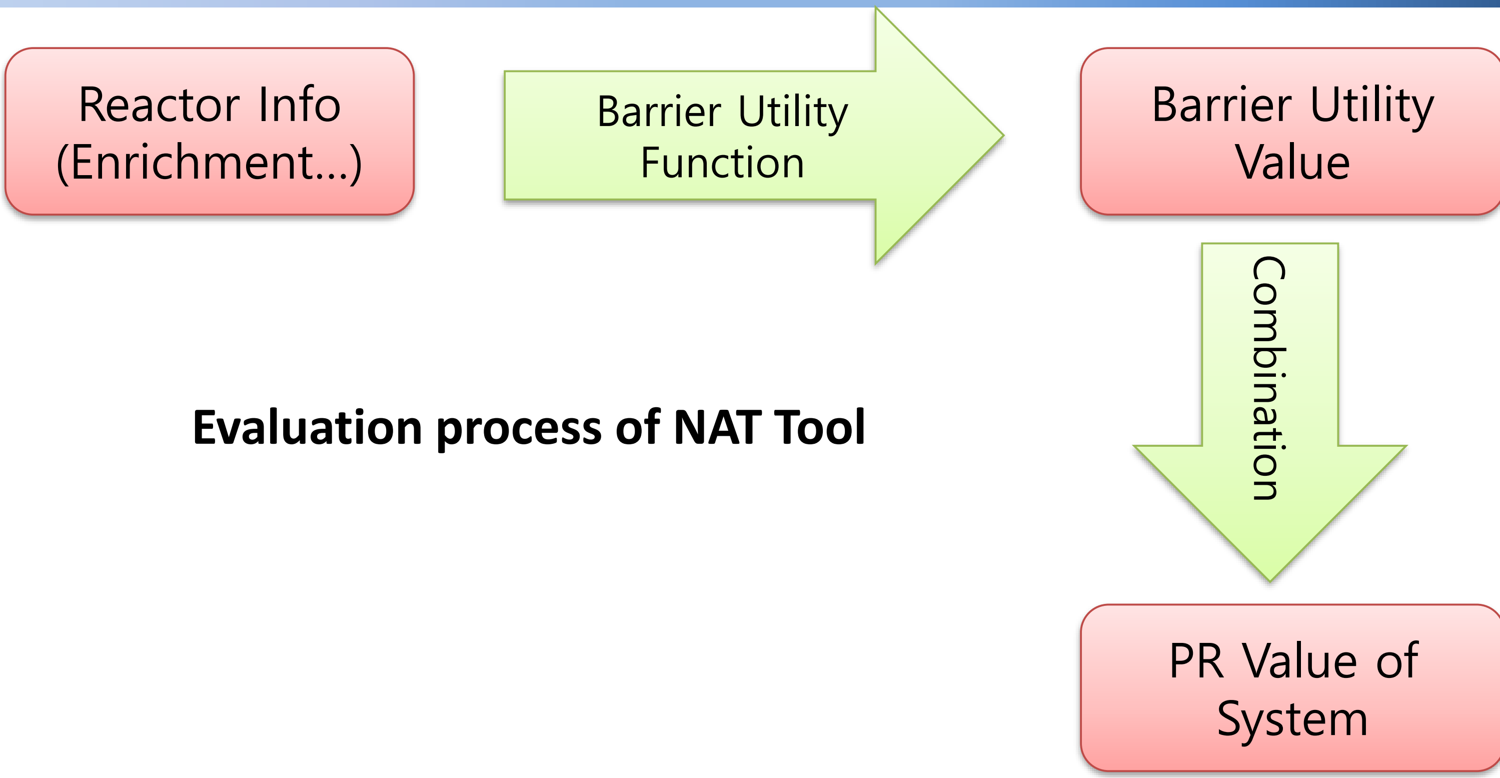
- PR equation of process i:

  $PR(i) = \sum_{j=1}^{15} w_j * u_j(x_{ij})$ Where:

  - wj: the weighting factor of attribute j (got by expert judgement)
  - uj: the utility function of attribute j
  - xij: input value for the utility function for attribute j of process i

Group	j	Attribute
1.Attractiveness level	1	DOE attractiveness level
	2	Heating rate from Pu in material (W)
	3	Weight fraction of even Pu isotopes
2.Concentration	4	Concentration (SQs/tonne)
3.Handling requirements	5	Radiation dose rates (rem/h at a distance of 1m)
	6	Size/weight
4.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
5.Accessibility	13	Physical barriers
	14	Inventory
	15	Fuel load type (Batch or Continuous reload)

Methodology



Evaluation process of NAT Tool

- A nuclear fuel cycle can be divided to many stages:
  - Beginning of cycle: mining, milling, conversion, enrichment, fabrication…
  - **Reactor operation**: fuel storage, irradiation, spent fuel handling and storage…
  - Back-end: storage spent fuel, reprocessing, disposal..
- For SMRs, the fuel assembly will be transported to nuclear power plant from fuel supplier. The spent fuel, after years storage at plant site, will be sent back to the fuel supplier or be transported to final disposal facility. Consequently, this research will focus on reactor operation process only.

Methodology

- Input data of NAT for reactor operation assessment [6]:

	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 stor ed 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 radiologi cal 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 burne d in the reactor before refueling
8	Core Loading (MT)	Fuel mass in the reactor core

	Data	Description
9	Measurement uncertaint y (%)	
10	Steps Using Item Accounting (%)	The percentage of steps at this facility that ship or transfer discre et packages of material using item accounting
11	Probability of Unidentifie d Movement (%)	The probability that nuclear mate rial could leave the facility withou t detection
12	Fuel Type	U235 enriched UO2
13	Refueling Downtime (da ys)	The number of days it takes to ref uel the reactor
14	Frequency of Measurement	How often nuclear materials at th is facility are confirmed to be prese nt
15	Physical Barriers	i.e. inaccessible, canyon, vault, secure, remote, or hands-on
16	Separability	The general content and form of t he nuclear material

Methodology

- This PR calculation process will be applied for PWR and SMRs (including SMART, NuScale, and KLT-40S that may have 1 unit, 2 units, 4 units, 8 units, or 12 units).
- From PR values of these reactors, the follow-up processes are as follows:
  - Comparing the PR value of SMART with PWR
  - Comparing the PR value of SMART with other designs of SMRs (NuScale and KLT-40S)

→ Expected results:

- PR(SMART)>PR(PWR); and
- SMART, NuScale, KLT-40S have similar PR values.

Result and Discussion

- SMART vs. PWR large scale

- PR value of SMART (one unit) is higher than PWR (0.78 and 0.7), and much higher than the PR values of enrichment, fuel fabrication, spent fuel storage, and reprocessing process of PWR (with PR values are 0.59, 0.58, 0.42 and 0.44 respectively)

→ Reactor operation itself has the lower level risk of proliferation

- The significant contribution to the difference of PR values is caused by **measurement uncertainty attribute** that contribute 0.072/0.08 of the total difference value. Because the bulk throughput of large scale PWR is much bigger than SMART, the same value of the measurement uncertainty can result in big different consequences.

	Attribute	Weight (w_i)	SMART u_i	PWR 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/ton)	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**

Result and Discussion

PR Examination of SMART

– The PR remained at the same value (= 0.78) when changing the material barriers:
  - The reactor **thermal power** from 225MWt to 660MWt,
  - The **cycle length** from 18 months to 48 months, and
  - The **enrichment** from 3% to 19% (still low enrichment fuel).

• When changing technical input data:

	Frequency of Measurement			
Input	Continuous	Daily	Weekly	Monthly
PR	0.79	0.78	0.77	0.75
	Measurement Uncertainty			
Input	2%	5%	7%	10%
PR	0.79	0.78	0.77	0.76

→ Changing the material barriers data does not have a significant effect on PR value

→ PR of SMART can be improved by enhancing **technical and institution measures** (i.e. safeguards, security, accounting systems)

Result and Discussion

SMART vs. NuScale, KLT-40S

- PR values of SMART, KLT-40S, and NuScale with 01 unit, 02 units, 04 units, 08 units, and 12 units

Reactor (01 unit)	Thermal power (MWt)	Fuel enrichment (%)	Cycle length (yrs)	Refueling time (days)	Burnup rate (MWd/kg)	Spent fuel storage time (yrs)
SMART	330	4.95	3	30	36.1	3
NuScale	160	5	2	30	50	3
KLT-40S	150	19	2.3	30	45.4	3

→ Similar PR value of SMART, KLT-40S, NuScale (even floating, underground deployment)

→ Floating, underground designs and deployments do not have effects on PR evaluation

	PR Value				
Reactor	01 unit	2 units	4 units	8 units	12 units
SMART	0.78	0.75	0.72	0.70	0.70
NuScale	0.80	0.79	0.78	0.76	0.74
KLT-40S	0.80	0.79	0.77	0.74	0.72

→ Safeguards requirements is clearly important, further research regarding safeguards approach for SMRs is obviously important in order to reduce the safeguards burden

Result and Discussion

- Observations from NAT calculations:
  - The operation of SMRs themselves have low levels of proliferation risk.
  - Changing the intrinsic attributes data does not have significant effect on the proliferation resistance value.
  - The proliferation resistance of SMRs can be improved by enhancing institution measures i.e. safeguards, security, accounting.
  - The opportunities to reduce safeguards burden when deploying SMRs are feasibility (reduce the frequency of onsite safeguards inspection by using remote safeguards inspection).
  - This tool is not applicable for identifying the most vulnerable stage of reactor operation (including fuel storage, irradiation, spent fuel handling and storage stages) → can be done by quantitative review, fuzzy logic method, or hand calculation by using the methodology that was used to develop NAT tool.

SMRs Design Opportunities and Safeguards Concerns

Opportunities	Advantages	Safeguards Concerns
No onsite refueling, entire core will be removed	Reducing onsite handling of core fuel, MC&A requirements	Continuity of knowledge (CoK) during the long period of irradiation
Increasing the cycle length	Reducing the accessibility of fresh fuel and spent fuel	CoK has to be provided
Increasing the burnup	Reducing the amount of fresh fuel, economic reason, higher radiation barrier	Increasing the amount of Plutonium. Higher important of SF manage ment
Spent fuel pool is inside the containment building	Saving the space if spent fuels are stacked, ensure the continuous of surveill ance (no need to transfer to an other building)	CoK, difficulties with verif ication measurements (new technologies for surveillance are needed)
Deploying in isolated area (underground, floating, etc.)	Security, safety benefits (may be autonomous operation)	Difficulties for inspection access, increasing the cost.

Safeguards Aspect for SMRs

- Current safeguards measures may be applied for SMR:
  - Nuclear material accountancy (implemented by operator, state, and will declare/ report to the IAEA)
  - Verifying the state reports
  - Containment, surveillance, and monitoring systems: seal, lock, camera to detect the movement of nuclear material with the time of movement (complement to accountancy systems - for CoK)
  - Onsite inspection: comprehensive safeguards agreement or additional protocol (complementary access): by verifying measurements, onsite environmental sampling
- Remote monitoring, remote safeguards inspection:
  - Reducing the IAEA onsite inspection activities (support integrated safeguards)
  - Strengthening virtual presence of the IAEA
  - Strengthening the deterrence towards possible proliferators
  - Supported by SSAC inspection that was performed by host states (need enhanced cooperation)

Conclusions

- Non-proliferation Assessment Tool (NAT) could be an effective tool in order to quantitatively and quickly evaluate the proliferation resistance of SMRs.
  - Quantitative value.
  - No need design information of reactor in detail (at conceptual design stage).
- The expected results is low level risk of proliferation when deploying SMART that will result in benefits for global nuclear proliferation issue and the IAEA safeguards measures.
- Further analysis is needed to address SMR specific safeguards concerns.
- New technological developments are important for SMR safeguards.

Future Work

- **Work need to be done:**

- Identifying the most vulnerable stage for reactor operation of SMRs by using other methods: apply Multi Attribute Utility Theory for each stage of reactor operation process, Barrier-Based Fuzzy Logic Method.
- Further analysis is needed to address SMR specific safeguards concerns.
- New technological developments are important for SMR safeguards.

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Thank you for your attention!