SYSTEMATIC PROLIFERATION RESISTANCE ANALYSIS OF SMALL MODULAR REACTOR DESIGNS

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Abstract

Small Modular Reactors (SMRs) are defined by the IAEA as nuclear reactors with a power capacity up to 300 MW(e). More than 80 SMRs designs have been proposed by different vendors and the IAEA Advanced Reactors Information System (ARIS) database contains information about 49 SMRs designs.

Starting from the ARIS database, we conducted a systematic proliferation resistance analysis of a set of SMRs designs using the Proliferation Resistance and Physical Protection (PR&PP) methodology. Only SMRs with a detailed design were considered for the analysis to ensure that enough safeguards-relevant information is available.

Each selected SMR design was evaluated with the PR&PP methodology in terms of proliferation technical difficulty, cost, time, material type, and detection resource efficiency. In addition, a comparison between SMR designs and current light water power reactors was made in term of safeguards inspection effort. The PR&PP analysis showed that some of the SMR designs achieve a proliferation resistance similar to current light water power reactors, although some points of attention emerge for some technologies.

1. INTRODUCTION

One of the United Nations Sustainable Development Goals is to take urgent action to combat climate change and its impacts [1]. Nuclear energy is considered one of major low-carbon energy sources and was recognized by the COP28 conference as a way to reduce the effects of climate change [2].

The renewed interest in nuclear energy is also seen by the development of innovative nuclear energy systems and with the introduction of Small Modular Reactors (SMRs).

SMRs are defined as advanced nuclear reactors with a nominal electric power up to 300 MW_e. Due to their specific designs, SMRs aim to be factory-built and transported to the end-user site. SMRs can be deployed either as single- or multi-units depending on the user needs [3].

More than 80 SMR designs are being developed globally and are in different design stages ranging from early conceptual design to advanced detailed design. Five SMRs are under construction or operational in Argentina [4], China [5], [6], India [7], and Russia [8].

In the context of the rapid SMRs development, research is being conducted to assess the proliferation resistance of the different SMR designs. Several proliferation resistance methodologies have been developed, such as the Proliferation Resistance and Physical Protection (PR&PP) [9] and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [10] methodologies.

This paper covers the proliferation resistance analysis of several SMR designs and makes a comparison with a large-size power reactor. After this introduction, the reactors information used for the analysis is summarized in Section 2 and the PR&PP methodology is described in Section 3. The results from the proliferation resistance assessment are discussed in Section 4 and the conclusions are drawn in Section 5.

2. REACTORS INFORMATION

The Advanced Reactors Information System (ARIS) is a database that contains technical information on advanced reactor designs [11]. The information included in the database is given by the design organization of each reactor and the database is maintained by the International Atomic Energy Agency (IAEA).

The ARIS database collects general information about the reactor (e.g. type of neutron spectrum, thermal output) but also specific information on nuclear steam supply system, reactor coolant system, reactor core, core materials, and reactor pressure vessel. Table 1 shows an extract of the information in the ARIS database for the SMRs chosen for the proliferation resistance analysis.

The SMRs evaluated in this paper were selected in order to consider all reactor technologies included in the ARIS database (i.e. water-cooled, gas-cooled, molten-metal-cooled, molten-salt-cooled), and reached a design level advanced enough to provide all information needed for the proliferation resistance analysis.

In addition to the SMR designs, Table 1 also shows technical information for the Belgian Tihange-2 pressurized water reactor (PWR) [12]. The reactor started operation in June 1983 and was placed in permanent shutdown in February 2023. The proliferation resistance of the Tihange-2 PWR was also assessed in this paper and served as a comparison between SMR designs and a large-size PWR.

3. PR&PP METHODOLOGY

In the frame of the General IV International Forum (GIF) an evaluation methodology has been developed for assessing the proliferation resistance and physical protection (PR&PP) of nuclear energy systems (NES). [9]

Although the PR&PP methodology was developed to assess both proliferation resistance (PR) and physical protection (PP) of NES, this article will focus only on the PR analysis. The PR&PP methodology defines proliferation resistance as the *"characteristic of an 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."* [9]

The basic approach for the PR&PP analysis is as follows. The PR&PP analyst first identifies the challenges to the NES, then estimates the system response, and finally assesses the outcomes on the NES. Detailed information on the PR&PP methodology is available in literature. [13]

For this analysis the focus was on the estimation of the system response to the diversion of fresh fuel, in-core fuel, and spent fuel.

The system response was evaluated according to the metrics of:

- Proliferation technical difficulty (TD): technical difficulty associated to the completion of the proliferation pathway.
- Proliferation cost (PC): total cost needed to complete the proliferation pathway, considering the development and use of existing and new facilities.
- Proliferation time (PT): total time needed to complete the proliferation pathway.
- Fissile material type (MT): categorization of nuclear material depending on its possibility for direct use in nuclear weapons.
- Detection probability (DP): probability to detect the proliferation pathway.

- Detection resource efficiency (RE): foreseen inspection effort compared to generated electricity by the NES.

For all metrics apart from RE, a proliferation resistance score from very low to very high was attributed for each identified target according to the threshold values shown in Table 2.

The proliferation resistance score for the RE metric has been estimated from the foreseen inspection effort for each reactor design and for each identified target. The estimated days of inspections during the lifetime of each reactor design are summarized in Table 3. For this analysis it was assumed for the fresh fuel to have 1 day of inspection during each reactor refuelling, for the in-core fuel to have 1 day of inspection yearly except for the first and last year of operation, and for the spent fuel to have 1 day of inspection yearly starting from the first refuelling. For SMRs where on-load refuelling is possible, monthly inspections for each target were assumed due to the presence of direct use material. The RE metric was then calculated using the nominal electric power (P), the plant lifetime (T), and the inspection days (D) according to Formula 1.

$$RE = \frac{P \cdot T}{D} \qquad (1)$$

Table 1: Reactor information used for the proliferation resistance analysis. Where not otherwise indicated, data come from the ARIS database [11] for the SMRs, and from [12] for the Tihange-2 PWR.

Reactor	Power (MW_{th} ------- MW_e)	Coolant --------- Moderator	Fuel type (enrichment)	Plant lifetime --------- Refuelling cycle	Number of fuel elements	Total initial fissile loading	Core discharge burnup (GWd/t_{HM})
4S (SFR)	30 ------- 10	Sodium --------- None	U-10Zr (avg. 17% max. 19%)	60 years --------- 30 years	18	6700 kg ^{235}U	34
ALFRED (LFR)	300 ------- 125	Lead --------- None	MOX (avg. 25.77%)	40 years --------- 12 months	171	228 t Pu [14]	100 (peak) [15]
HTR-PM (GCR)	500 ------- 200	Helium --------- Graphite	TRISO (8.5%)	40 years --------- On-load	420000	250 kg ^{235}U	90
IMSR-400 (MSR)	400 ------- 185	Fluoride salts --------- Graphite	UF_4 in diluent fluorides (2-3% startup, 5-19% makeup)	60 years --------- 7 years	Not applicable	769 kg ^{235}U	26-29
IPHWR-220 (HWR)	754.5 ------- 210	Heavy water	UO_2 (0.7%)	40 years --------- On-load	3672	572 kg ^{235}U	63
NuScale (iPWR)	200 ------- 57	Light water	UO_2 (<4.95%)	60 years --------- 2 years	37	460 kg ^{235}U	36
SMART (iPWR)	330 ------- 90	Light water	UO_2 (4.8%)	60 years --------- 3 years	57	686 kg ^{235}U	36.1
ThorCon (MSR)	557 ------- 250	Molten salt --------- Graphite	UF_4, ThF_4 (avg. 5% max. 19.7%)	80 years --------- 4 years	Not applicable	630 kg ^{235}U	509
Tihange-2 (PWR)	3064 ------- 1008 [16]	Light water	UO_2 (4.5%)	40 years --------- 18 months	157	~3600 kg ^{235}U	40 - 55

Table 2: Estimated measure value bins for proliferation resistance analysis. For the material type (MT) metric the acronyms are high-enriched uranium (HEU), high-assay low-enriched uranium (HALEU), low-enriched uranium (LEU), weapons-grade Pu (WG-Pu), reactor-grade Pu (RG-Pu), deep-burn Pu (DB-Pu).

Qualitative descriptor	TD	PC	PT	MT	DP
Very low (VL)	0-5%	0-5%	0 – 3 months	HEU ($^{235}U > 20\%$)	0-5%
Low (L)	5-25%	5-25%	3 months – 1 year	WG-Pu ($Pu_{fissile} > 90\%$)	5-25%
Medium (M)	25-75%	25-75%	1 – 10 years	RG-Pu ($Pu_{fissile} > 70\%$) HALEU ($^{235}U \sim 20\%$)	25-75%
High (H)	75-95%	75-95%	10 – 30 years	DB-Pu ($Pu_{fissile} < 40\%$)	75-95%
Very high (VH)	95-100%	95-100%	> 30 years	LEU ($^{235}U < 5\%$)	95-100%

Table 3: Estimated inspection days during the lifetime of each reactor design.

Reactor	Fresh fuel	In-core fuel	Spent fuel	Cumulative
4S	2	58	30	90
ALFRED	39	38	39	116
HTR-PM	479	478	479	1436
IMSR-400	8	58	53	119
IPHWR-220	479	478	479	1436
NuScale	29	58	58	145
SMART	19	58	57	134
ThorCon	19	79	76	174
Tihange-2	26	38	39	103

4. RESULTS

The results from the system response according to the PR&PP metrics are summarized in Table 4. The colour coding used in Table 2 for the qualitative descriptors was also used in Table 4 to facilitate the comparison of the reactor designs. At first glance it is evident that no reactor design reaches very high proliferation resistance for all targets and all metrics. Without considering the RE metric, the water-based SMR designs appear to reach a similar proliferation resistance of the large-size PWR. The next sections discuss in details the comparison for the different targets.

4.1. Fresh fuel

Technical difficulty ranges from medium to very high for the considered reactors. Medium difficulty was attributed to the large-size PWR, as well as to water-based SMRs, considering the similarities in plant design and fuel type. High technical difficulty was attributed to SMRs with liquid metals or molten salts due to the foreseen technological challenges related to e.g. material compatibility, fuel type [14]. Very high technical difficulty was attributed only to the HTR-PM reactor due to the additional challenges to reprocess the TRISO fuel [17].

Proliferation cost was evaluated as medium for reactors where fuel ^{235}U enrichment is around 20%, and evaluated as high in all other cases. It is assumed that enriching U starting from 20% would have a lower cost compared to starting from lower enrichment or compared to the construction of a reprocessing plant.

Proliferation time was evaluated as low for the majority of reactor designs since one fuel assembly for most of the reactor designs contains a large amount of fissile material. Only for HTR-PM and IPHWR-220 was evaluated as medium due to the large number of assemblies that needs to be diverted to acquire a significant quantity.

Material type was evaluated comparing the information in Table 1 with the thresholds in Table 2. For reactors where more than one material type is present, the category with lowest proliferation resistance was retained.

Detection probability ranges from low to very high depending on the reactor design. On-load reactors such as HTR-PM and IPHWR-220 were rated as low due to the continuous refuelling. ALFRED was rated with medium detection probability due to the opaqueness of the coolant, whereas water-based reactors were rated with high detection probability. Very high detection probability was given to the 4S and IMSR-400 designs due to their sealed core operations.

Detection resource efficiency was calculated according to the information in Table 1 and Formula 1. Reactors with large power output perform in general better than smaller size reactors. Only molten salt SMRs (i.e. IMSR-400 and ThorCon) reach a RE metric comparable to the Tihange-2 PWR due to the long refuelling cycle and relatively large power. On the contrary, on-load refuelling reactors such as HTR-PM and IPHWR-220 are penalized due to the large number of foreseen inspections during the reactor lifetime.

4.2. In-core fuel

Technical difficulty was evaluated as high for all reactor types apart from the HTR-PM due to the need for reprocessing of the irradiated fuel. The metric was ranked as very high for the HTR-PM reactor because of the additional challenges in reprocessing TRISO fuel.

Proliferation cost was evaluated as high due to the need for reprocessing facility to obtain the material used in a nuclear explosive device.

Material type was evaluated as low for HTR-PM and for IPHWR-220 since on-load refuelling allows short irradiations and therefore production of weapons-grade Pu. For all other reactors the material type was ranked as medium since it is assumed that in-core fuel would have characteristics similar to reactor-grade Pu.

Detection resource efficiency was particularly low for on-load reactors and for reactors with low power output. It is worth noting that the value obtained for the Tihange-2 PWR is significantly larger than any of the SMR designs considered in the analysis.

Proliferation time and detection probability obtained the same results as in the case of fresh fuel.

4.3. Spent fuel

The analysis for spent fuel resulted in values largely identical to the one of in-core fuel, due to the similarities of facilities and processes needed to obtain the material for a nuclear explosive device. Differences were observed only for the material type and detection resource efficiency metrics.

The material type was evaluated considering a full irradiation cycle until the discharge burnup provided in Table 1. Therefore, for the majority of reactor designs a reactor-grade Pu was assumed as spent fuel while only for ALFRED, HTR-PM, and ThorCon reactors the spent fuel was assumed to be deep-burn Pu due to the high discharge burnup.

Similar to the target of in-core fuel, the detection resource efficiency was significantly lower for SMRs compared to the large-size PWR. As for the other targets, on-load reactors and small size SMRs are particularly penalized in this metric.

Table 4: results from the proliferation resistance analysis of the selected SMRs. The metrics are proliferation technical difficulty (TD), proliferation cost (PC), proliferation time (PT), fissile material type (MT), detection probability (DP), and detection resource efficiency (RE). RE metric is expressed in $MW_e y/d$.

Target	Metric	4S	ALFRED	HTR-PM	IMSR-400	IPHWR-220	NuScale	SMART	ThorCon	Tihange-2
Fresh fuel	TD	H	H	VH	H	M	M	M	H	M
	PC	M	H	H	M	H	H	H	M	H
	PT	L	L	M	L	M	L	L	L	L
	MT	M	M	H	M	VH	VH	VH	M	VH
	DP	VH	M	L	VH	L	H	H	L	H
	RE	300	128	17	1388	18	118	284	1053	1551
Fuel in core	TD	H	H	VH	H	H	H	H	H	H
	PC	H	H	H	H	H	H	H	H	H
	PT	L	L	M	L	M	L	L	L	L
	MT	M	M	L	M	L	M	M	M	M
	DP	VH	M	L	VH	L	H	H	L	H
	RE	10	132	17	191	18	59	93	253	1061
Spent fuel	TD	H	H	VH	H	H	H	H	H	H
	PC	H	H	H	H	H	H	H	H	H
	PT	L	L	M	L	M	L	L	L	L
	MT	M	H	H	M	M	M	M	H	M
	DP	VH	M	L	VH	L	H	H	L	H
	RE	20	128	17	209	18	59	95	263	1047

5. CONCLUSION

The proliferation resistance of several SMR designs was assessed in this paper according to the PR&PP methodology.

The considered SMRs covered all major reactor types and included reactors where the design status is advanced enough to provide sufficient information to complete the PR&PP analysis. The diversion of fresh fuel, in-core fuel, and spent fuel was considered as target in the study.

The PR&PP analysis showed that no SMR design excels in all evaluation metrics for any of the considered targets. The evaluation showed that the use of TRISO fuel increases the proliferation technical difficulty due to the challenges of reprocessing such material. SMRs with a sealed core led to very high proliferation resistance in terms of detection probability. On the contrary, SMRs with on-load refuelling and small power output showed significant drawbacks in terms of material type and detection resource efficiency.

When comparing the proliferation resistance of SMRs with a large-size PWR, water-based SMRs are mostly similar in terms of proliferation resistance. However, the detection resource efficiency for large-size PWR is significantly larger than any SMR design considered in this study.

Future work will refine the proliferation resistance analysis by considering other factors such as presence of nuclear fuel cycle facilities (e.g. enrichment, reprocessing) and co-location of several SMR units. The estimation of the inspection effort to safeguards the SMR designs will also be refined considering the possibilities for e.g. remote data transmission and inspection of multi-unit sites.

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