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ARTICLE

Evaluation for proliferation resistance of small and medium modular LWRs with U_3Si_2 fuel

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Small modular reactors (SMRs) are expected to be stable and distributed energy sources. If the grade regulations for large power reactors and SMRs are similar, safety and security would be considerably affected. Therefore, introducing a graded approach is important to establish a reasonable and feasible regulation for SMRs. Uranium silicide (U_3Si_2) fuel is one of the accident tolerant fuel (ATF) candidates. During the reprocessing process of U_3Si_2 fuel, Si residue remains in the nitric acid solution due to the chemical stability of U_3Si_2 fuel. The Si residue is expected to make the U_3Si_2 fuel difficult to divert. The evaluation methodology for the Proliferation Resistance and Physical Protection of Generation IV nuclear energy system (GIF/PRPP) defines a set of challenges, analyzes system response to these challenges, and assesses outcomes for a proposed nuclear energy system design. In this study, proliferation resistance of small and medium modular LWR with U_3Si_2 fuel was analyzed by GIF/PRPP. The evaluation was conducted for on-site refueling reactor systems and transportable reactor systems. This study aims to evaluate the proliferation resistance of small and medium LWRs loaded with U_3Si_2 fuel on the on-site refueling reactor system and the transportable reactor system without on-site refueling for 10 years and to reveal the safeguards issues. Based on the designed safeguard system of each reactor system, the vulnerable diversion pathways unique to small and medium reactors were identified for irradiated fuel assembly and nuclear reactor itself as targets. For the on-site refueling reactor system, the diversion pathways were the same as the large scale LWR and the required safeguard efforts were more than that of the large LWR. On the contrary, the derived diversion pathways on the transportable reactor system were limited, verifications of multiple reactors could be performed simultaneously, and the frequency of inspections is less than that of the large LWR. Further, the conversion time of silicide fuel could be increased such that it was higher than that of oxide fuel, and the inspection frequency could be reduced. On the contrary, since the safeguard system of the transportable reactor system would be heavily dependent on the containment and surveillance (C/S) for a long period, verification methods, such as NDAs, should be developed to directly obtain information on nuclear materials and the inside of the reactor.

Keywords: proliferation resistance; proliferation; safeguards; SMR; ATF; Uranium silicide fuel

1. Introduction

Small and medium reactors are expected to be distributed as stable energy sources, which actively introduce inherent safety features. On the contrary, if the same regulations as those for conventional large reactors are applied to small and medium reactors, it can be an excessive burden on operators and regulators. Therefore, it is important to implement a graded approach to the regulation of small and medium reactors based on their inherent safety and nuclear non-proliferation features.

Uranium silicide (U_3Si_2) fuel is one of the candidate materials of accident tolerant fuel (ATF), which has higher uranium density and higher thermal conductivity than uranium oxide (UO_2) fuel. These properties are expected to extend the burnable period, reduce the enrichment process, and improve heat removal performance in small and medium PWRs [1]. In addition, U_3Si_2 fuel is chemically stable, making Pu separation more difficult.

Proliferation resistance is defined as a property of a nuclear energy system 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]. Various methods have been studied to evaluate the proliferation resistance based on material, technological, and institutional characteristics. The Generation IV Proliferation Resistance and Physical Protection (GIF PR/PP) evaluation method by GIF/PRPP WG [3] is a methodology for evaluating the system response of a hypothetical nuclear system to proliferation threats and for revealing its proliferation resistance and robustness against sabotage and terrorism threats.

In this study, the proliferation resistance of small and medium LWRs loaded with U_3Si_2 fuel is evaluated and safeguard issues for small and medium reactor systems are revealed.

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2. Proliferation resistance evaluation methodology

2.1. Threat definition and identification of system

The following nuclear systems to be evaluated are the two types of small and medium PWR systems and the large PWR system.

- On-site refueling reactor systems
- Transportable reactor systems without refueling
- Large PWR systems (reference)

Refueling on the on-site refueling reactor systems is done once every two years [4]. In this study, the transportable reactor system is assumed to be assembled in the factory, transported to/from the operation site, and realized long-life onsite operation for 10 years without refueling. Refueling on the large PWR system is done once every 13 months.

The hypothetical host state is assumed as non-nuclear weapon states and industrialized states without enrichment and reprocessing facilities declared to the International Atomic Energy Agency (**Table 1**). In this study, concealed acquisition of nuclear materials from declared reactors was considered. Note that the hypothetical state is assumed to have a safeguard agreement with IAEA and the integrated safeguards in force.

The system layout of on-site refueling reactor systems and transportable reactor systems is shown and their safeguard design proposal presented in **Figure 1**. These layout were designed referring the safeguards system design of the conventional large LWR [5] which is refueled once in 13 months . Small and medium PWR systems with 12 units at a site were considered to support the site capacity equivalent to a large-scale PWR. A reactor is transferred from reactor pool to refueling pool when exchanging fuel on the on-site refueling reactor system. The reactor is opened, and then, fuel is exchanged between the core and the fuel pool (**Figure 1(a)**). On the contrary, the system component of the transportable

Table 1. Assumed host state capabilities and objectives for transportable reactor system

Characteristic	Description
Capabilities	
Technical skills	General know-how in scientific and technological fields
Resource	High to pose no limitations
Uranium and Thorium Resource	Not present
Industrial capabilities	Industrial state
Nuclear capabilities	Electricity production via the operation of LWR, without enrichment and reprocessing facility
Objectives	
No. of nuclear weapon devices	1
Technical Performance (yield and reliability) of nuclear weapon devices	Any yield; >50% reliability
Ability to stockpile	Sufficient for short-term stocking (around 10 years)
Deliverability	Compatible with modern multi-role fighter jets
Production rate	Not applicable. Only one device is planned

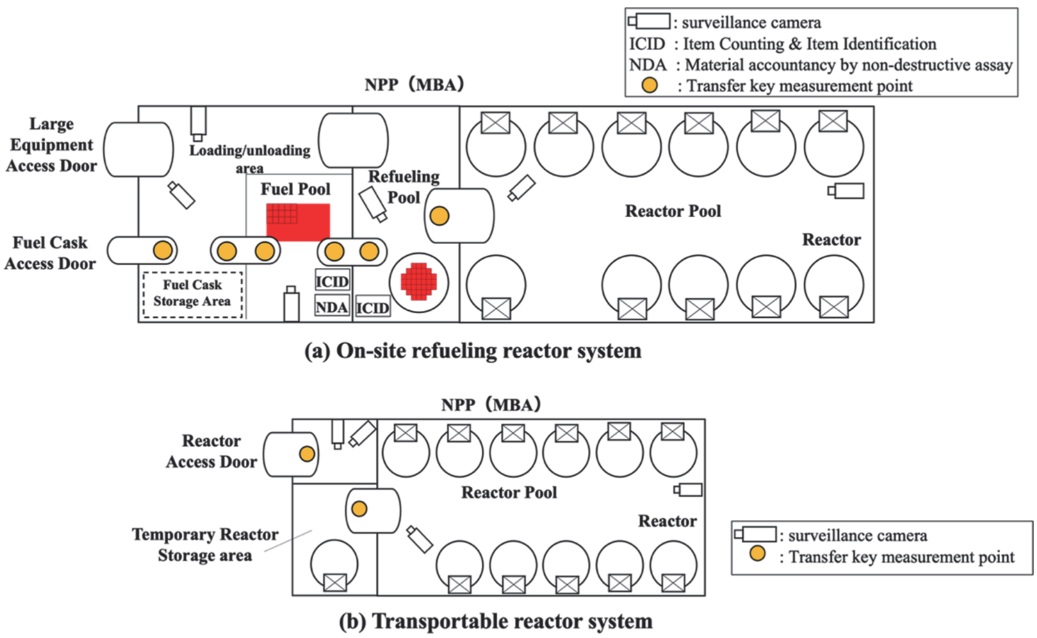

Figure 1. Safeguards system design for SMRs

Table 2. Target material for each nuclear system (Cooling time for spent fuel is 10 years).

Type of Fuel assembly		^{235}U enrichment	Total mass [kg]	U mass [kg]	Pu mass [kg]
Large PWR					
Fresh	UO_2	^{235}U 4.11 wt%	308	247	-
Spent 48 GWd/t			308	232	2.58
On-site refueling reactor system					
Fresh	U_3Si_2	^{235}U 3.5 wt%	355	297	-
	U_3Si_2+MA 0.5 wt%		355	295	-
	U_3Si_2+^{241}Am 0.5 wt%		355	295	-
Spent 32 GWd/t	U_3Si_2		355	284	2.55
	U_3Si_2+MA 0.5 wt%		355	283	3.48
	U_3Si_2+^{241}Am 0.5 wt%		355	283	3.73
Transportable reactor system					
Fresh	U_3Si_2	^{235}U 6.5 wt%	355	297	-
	U_3Si_2+MA 0.5 wt%		355	295	-
	U_3Si_2+^{241}Am 0.5 wt%		355	295	-
Spent 53 GWd/t	U_3Si_2		355	279	3.35
	U_3Si_2+MA 0.5 wt%		355	275	4.32
	U_3Si_2+^{241}Am 0.5 wt%		355	275	4.51

reactor system is simple because there is no refueling (**Figure 1(b)**). After ten years of operation, the reactor is moved to the temporary reactor storage area; then, it is transported to the refueling facilities outside. As for safeguard systems, containment and surveillance (C/S) with camera, item counting and ID check, and nondestructive assay (NDA) techniques for spent fuel verification are assumed.

The target material for diversion on systems are listed in **Table 2**. As for the on-site refueling reactor, 3.5wt% enriched uranium is used in silicide fuel whose enrichment is much less than that of oxide fuel 4.17 wt% in the reference reactor [4]. As for transportable reactor, 6.5 wt% enriched uranium silicide fuel is needed to support more than 10 years of reactor operation without onsite refueling. As a technical option, minor actinide (MA) doping to fuel was also considered because it works as burnable poison and increases the non-proliferation by increasing the decay heat of Pu, making the irradiated fuel difficult to be diverted.

2.2. Metrics for proliferation resistance measures

The proliferation resistance of the systems was evaluated based on six evaluation measures (technical difficulty, proliferation cost, proliferation time, fissile material type, detection probability, and detection resource efficiency) employed in the GIF/PRPP by GIF/PRPP WG GIF/PRPP WG [3,6]. In the "Fissile Material Type", instead of grade of uranium and plutonium suggested by GIF/PRPP, metrics of bare critical mass (BCM), heat content (HC), and spontaneous fission neutron rate (SFN)* are used to evaluate the impact of uranium/plutonium isotopic vector on nuclear explosive devices more quantitatively based on nuclear material attractiveness [7] (**Table 3**). "Proliferation Technical Difficulty" is evaluated based on how technically difficult to achieve the diversion pathway

Table 3. Measures values for proliferation resistance analysis.

Qualitative Descriptor		VeryLow[VL]	Low[L]	Medium[M]	High[H]	VeryHigh[VH]
Proliferation Technical Difficulty		Probability of segment/pathway failure from inherent technical difficulty considering threat capabilities				
Proliferation Cost		~5 %	5~25 %	25~75 %	75~95 %	95 %~
Proliferation Time		~1 month	1~3 months	3month ~1 year	1~10 years	10 years
Fissile Material Type	BCM [kg]	-	<80	80~800	800~4000	4000<
	HC [W/BCM]	-	<1292	1292~6274	6274<	-
	SFN* [n/s/BCM]	-	<1.56E+6	1.56E+6~5.62E+6	5.62E+6<	-
Detection Probability		Probability that safeguards will detect the execution of a diversion or misuse segment/pathway				
Detection Resource Efficiency [GWy/PDI]		~0.01	0.01~0.04	0.04~0.10	0.10~0.30	0.30~

*SFN is evaluated just for reference, not used for any judgement.

such as high skills, special equipment or vehicle to divert nuclear materials. This metric depends on how technically developed the country is. "Proliferation Cost", "Proliferation Time", and "Fissile Material Type" are evaluated using the target nuclear material. "Detection Probability" and "Detection Resource Efficiency" are evaluated via safeguard inspection applied for the systems. If visual inspection of reactor core is applied to the reactor system, "Detection Probability" will be higher than the reactor system without the visual inspection.

3. Result and discussion

3.1. Evaluation result of the number of inspections

IAEA reduces the increased number of inspections onsite under the additional protocol by implementing integrated safeguards, such as random inspections. The safeguard inspections are classified into physical inventory verification (PIV), design information verification (DIV), and interim inspection verification (IIV). In PIV, inspectors are present before and after refueling to measure the presence of spent fuel that has been moved from the reactor core into the spent fuel storage pool. For large LWRs, PIV is conducted twice a year, since a fuel change is performed every 13 months and PIV is performed before and after the fuel change. DIV helps better verification of the actual facility design compared with the design information submitted by the state; further, DIV helps verify the C/S. DIV is performed during the construction phase, operation, and decommissioning of the facility, with a frequency of once a year at a probability of 20%. IIV is performed once a year with a probability of 20% and verifies and evaluates the nuclear material accountancy of the facility based on indirect information, such as the operating history. In power reactors, a fuel assembly is regarded as one item, and nuclear material accountancy is carried out mainly by checking the item ID and not by measuring the amount of nuclear material contained in the fuel assembly. In Japan, inspections were conducted more than four times/year for one large LWR, but the number was reduced to 2.4 times/year with the transition to integrated safeguards [8], which is written in 2.4 PDI/year. "Person Day per Inspection (PDI)" represents the amount of inspection. The detection resource efficiency of the large PWR system was evaluated as follows:

$$(0.87\ \text{GW}\times 1\ \text{year})/16.8\ \text{PDI}=0.36\ \text{GWy/PDI}. \qquad (1)$$

Therefore, the detection resource efficiency of the large PWR system was "Very High".

On the contrary, for transportable reactors, material accountancy based on counting fuel assemblies as items is impossible because there is no chance without onsite refueling. Owing to the continuity of knowledge by C/S of fuel assemblies loaded into the reactor at the factory, one reactor is regarded as one item by re-batching, and PIV can be performed only by the ID check and counting the reactors. Since only visual inspections (PIV, DIV, IIV) are assumed to be required, they can be simultaneously performed for all reactors at a site. In the transportable reactor system, PIV was once in a year as large PWR system, and DIV and IIV were 0.2 time/year. The inspection in transportable reactor system was 1.4 times/year in total, which was less than large PWR system. In the unit of PDI, the amount of inspection is 1.4 PDI/year. The detection probability was "Low" because the direct information of core cannot be obtained and compromising C/S measure would lead difficult to detect the diversion activity. The detection resource efficiency was evaluated as the follows:

$$(0.54\ \text{GW}\times 1\ \text{year})/1.4\ \text{PDI}=0.39\ \text{GWy/PDI}. \qquad (2)$$

Therefore, the detection resource efficiency of the transportable reactor system was "Very High".

At La Hague Reprocessing Plant, reprocessing of low burnup U_3Si_2 fuel for research reactors was approved by the CEA (The French Alternative Energies and Atomic Energy Commission) in May 2017, the first industrial-scale fuel reprocessing with silicon separation by adding a multi-stage centrifuge to the PUREX process to make a physical separation Si residue [9]. Regardless of the use of Pu or MA and irradiation on U_3Si_2 fuel, silicon separation is required for U/Pu/MA isolation, which complicates the treatment process. The conversion time for the finished Pu or U metal component from spent U_3Si_2 fuel was evaluated as 3 months as of spent UO_2 fuel or even much longer [10]. On the contrary, the conversion time of fresh $(U,Pu)_3Si_2$ fuel was evaluated as 1–3 months as of spent UO_2 fuel, while the conversion time of fresh $(U,Pu)O_2$ fuel is 1–3 weeks. Therefore, the grade of fresh U_3Si_2 fuel on safeguards will be downgraded and decrease the amounts of inspection.

3.2. Proliferation resistance analysis

The image of diversion pathways on the transportable reactor system is shown in **Figure 2**, and the derived diversion pathway is summarized in **Table 4**. "Proliferation Technical Difficulty" of large PWR was evaluated as "Very Low" because there is equipment such as crane for refueling and canister for transporting. Therefore, there is no need to prepare any equipment for diversion. "Detection Probability" of large PWR was evaluated as "Medium" because there is visual inspection of reactor core. The

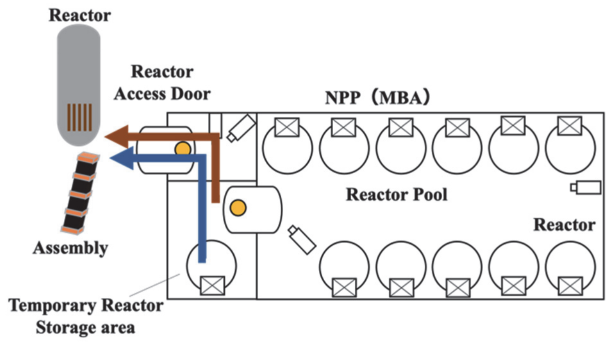

Figure 2. Diversion pathways on transportable reactor system.

Table 4. Measures estimation for representative diversion pathway.

System	Large PWR system	Transportable reactor system	
Target Description	Spent UO_2 fuel assembly	• U_3Si_2 fuel • MA/^{241}Am doped U_3Si_2 fuel Spent fuel assembly	• U_3Si_2 fuel • MA/^{241}Am doped U_3Si_2 fuel Reactor loaded with spent fuel assembly
Strategy	Fuel cask	Shielded container	Shielded reactor
Diversion Points	Fuel pool Reactor	Reactor	Temporary reactor storage pool Reactor pool
Proliferation Technical Difficulty	**VL**	**M**	**H**
Proliferation Cost	**VL**	**VL**	**VL**
Proliferation Time	**L**	**L** / **M**	**L** / **M**
Fissile Material Type	**L**	**L(non-MA)** ~ **M(MA doped)**	**L(non-MA)** ~ **M(MA doped)**
Detection Probability	**M**	**L**	**L**
Detection Resource Efficiency	**VH**	**VH**	**VH**

derived pathways were limited owing to the simplicity of the system on the transportable reactor. The pathway with the lowest proliferation resistance was "opening the containment and pressure vessel by compromising the C/S measures, removing the irradiated fuel assembly from the reactor vessel on the reactor pool/temporary reactor storage area, and using a special container to carry it out." The technical difficulty was evaluated as "Middle" with a much higher resistance than that of the large PWR because of no fuel handling equipment to remove the fuel assembly from the reactor vessel and special container to carry it out. The proliferation time was evaluated to be between "Low" and "Middle" because the conversion time of spent U_3Si_2 fuel is 3 months or longer. Fissile material type of the MA-added fuel was evaluated as "Medium", while fuel without MA was evaluated as "Low". This is because the addition of MA increases the amount of decay heat from ^{238}Pu, making the use of nuclear weapon devices more difficult. The detection probability was evaluated as "low" because the direct verification of the fuel inside the transportable reactor is impossible, which was lower than that of Large PWR. It was not evaluated as "Very Low" because there is a possibility that indirect verification is applicable. As mentioned in 3.1, the detection resource efficiency of the transportable reactor system was "Very High" because the inspection was simultaneously performed for all reactors at a site. Although the pathway of carrying out reactor itself was also identified, the technical difficulty was evaluated as "High" owing to the needs of special marine vessels to transport a reactor; it was not evaluated as vulnerable as the fuel assembly diversion pathways. This is because preparing special marine vessels is larger in scale than any other equipment.

4. Conclusion

Proliferation resistance of small and medium LWRs loaded with U_3Si_2 fuel was evaluated for the on-site refueling reactor system and the transportable reactor system without onsite refueling for 10 years, and safeguard issues were revealed by analyzing the misuse of the facilities and diversion pathways of nuclear materials on each system. The GIF/PRPP methodology coupled with material attractiveness was used for measuring "fissile material type" of states. Threats to nuclear reactor systems were defined as the industrial state, each of which is assumed to covertly divert nuclear materials from declared facilities. Small and medium PWR system with 12 units at a site were considered to support the site capacity equivalent to a large-scale PWR.

The vulnerable diversion pathways unique to small and medium reactors were identified for irradiated fuel assembly and nuclear reactor as targets. For the transportable reactor system, the derived diversion pathways were limited, multiple reactors were simultaneously verified, and the frequency of inspections was less than that for large LWR 2.4 PDIs.

Further, the conversion time of silicide fuel could be higher than that of the oxide fuel. Moreover, the inspection frequency could be reduced regardless of irradiation or the presence of direct-use materials, such as Pu. The addition of MA to the fuel is a technical option for initial reactivity reduction and enhances proliferation resistance. On the contrary, since the safeguard system of the transportable reactor system would be heavily dependent on C/S for a long period, verification methods, such as NDAs, to directly obtain information on nuclear materials and the inside of the reactor might be important technical issues for future research.

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