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ARTICLE

Proliferation resistance analysis of Offshore Floating Nuclear Power Plant

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An offshore floating nuclear power plant (OFNP) drastically reduces the impacts of earthquakes and tsunamis, enhances heat removal functions based on the massive amount of surrounding sea water, and fundamentally eliminates the need for resident evacuation. However, owing to the differences in the site location and fuel management (including fuel transportation and storage), stakeholders desire a nuclear proliferation risk analysis of OFNPs based on non-traditional threat assumptions. As such, this study aims to clarify the proliferation resistance (PR) of OFNPs against host nations. For the PR analysis, we improve the evaluation methodology proposed by the Proliferation Resistance and Physical Protection Working Group of the Generation IV International Forum. Specifically, we modify the "fissile material type" measure to capture the sensitivity in variable nuclear fuel types with High-Assay Low-Enriched Uranium and U-Pu mixed-oxide (MOX) fuels for high burnup. We also add a new evaluation index, termed the "proliferation occasion", as a sensitive parameter concerning the frequency of nuclear fuel transfers and transportation. As a result, we conclude that there are no significant PR differences between onshore and offshore plant locations. Nevertheless, the proliferation opportunity increases for scenarios involving transport from an OFNP to a shore-based fuel storage facility, which may increase the proliferation risk. As a target, MOX fresh fuel (MOX-FF) has a more vulnerable PR. To further enhance the PR, this study suggests a higher burnup of fuel to increase the content ratio of ^{238}Pu for a high decay heat. In addition, this study suggests extending the operation period per batch during fuel transfer within the OFNP and increasing the number of fuel assemblies to be transported outside the OFNP at one time (including providing collective fuel transport with the maximum possible number of units and increasing the capacity of the casks for storing fuel). However, for the collective transport of MOX-FF, decision makers should carefully consider that the long-term storage of MOX-FF before use reduces the reactivity in the initial stage of irradiation.

Keywords: Offshore Floating Nuclear Power Plant (OFNP); proliferation resistance (PR); safeguards

Nomenclature

OFNP	Offshore Floating Nuclear Power Plant	JAERI	Japan Atomic Energy Research Institute
NPP	Nuclear Power Plant	U-f	Fissile Uranium
PR	Proliferation Resistance	Pu-f	Fissile Plutonium
GIF/PRPP	Proliferation Resistance and Physical Protection Evaluation Methodology Working Group of the Generation IV International Forum	MT	Fissile Material Type
		SFN	Spontaneous Fissile Neutron Emission Rate
		BCM	Bare Critical Mass
HALEU	High-Assay Low-Enriched Uranium	PO	Proliferation Occasion
MOX	U-Pu Mixed-Oxide	IAEA	International Atomic Energy Agency
ABWR	Advanced Boiling Water Reactor	TD	Proliferation Technical Difficulty
SFP	Spent Fuel Pool	PC	Proliferation Cost
FF	Fresh Fuel	PT	Proliferation Time
SF	Spent Fuel	DP	Detection Probability
UO_2	Uranium Dioxide	DE	Detection Resource Efficiency

1. Introduction

Nuclear power has been one of important energy sources to ensure a stable energy supply, increase energy security and achieve sustainable clean energy society. An OFNP comprises a cylindrical floating structure combined with a reactor and floats approximately 30 km offshore [1,2], as shown in **Figure 1**. OFNPs are expected to improve nuclear safety according to the lessons from the Fukushima Daiichi NPP accident and also improve economic efficiency and business predictability. Examples

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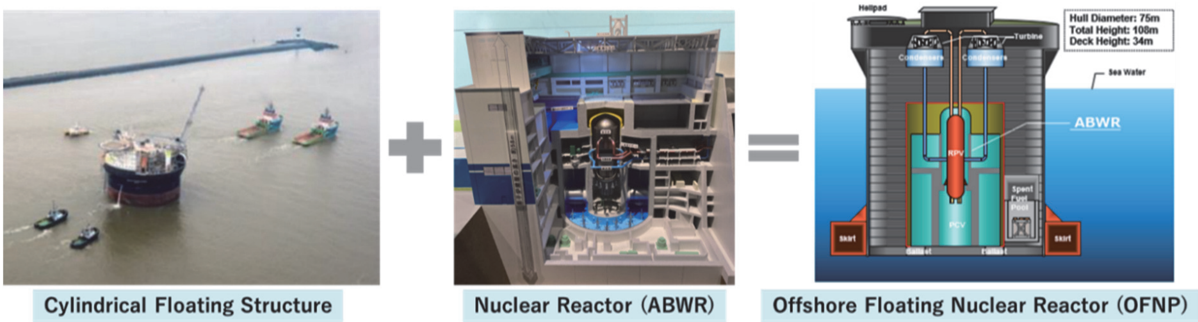


Figure 1. OFNP concept [1,2].

of the advantages of OFNP are as follows:

- Reducing the impacts of earthquakes and tsunamis;
- Enhancing cooling and heat removal functions using the massive amount of surrounding sea water;
- Eliminating risks of the massive spreading of radioactive materials requiring large-scale evacuations;
- Providing a concept of the "fusion of proven technologies" from the NPP and oil industry with great feasibility;
- Avoiding unexpected decommissioning risks owing to the discovery of active faults (in view of offshore location);
- Allowing various types of nuclear reactors to operate and expanding the location/position options on both land and sea, thereby enhancing the potential for peaceful uses of nuclear energy;
- Enhancing industrial competitiveness by construction at the production base and deployment at the berth.

However, owing to the differences in the site location and corresponding nuclear fuel management (including its transportation and storage), decision-makers require a nuclear proliferation risk analysis of OFNPs. As such, this study aims to clarify the PR of OFNPs against host nations. We refer to and improve the GIF/PRPP evaluation method [3,4], to ensure differences in the proliferation pathways, including fuel transport practices unique to offshore locations and the various HALEU and MOX fuels for achieving high burnup.

This study develops comprehensive nuclear fuel management scenarios for offshore-specific nuclear fuel transport and storage and prepares safeguards for the layouts of OFNPs and onshore fuel storage facilities. In addition, we establish possible strategies for fuel diversion. Finally, we evaluate the PR of OFNPs through a route analysis.

2. Methods

2.1. Management scenarios and types of nuclear fuels

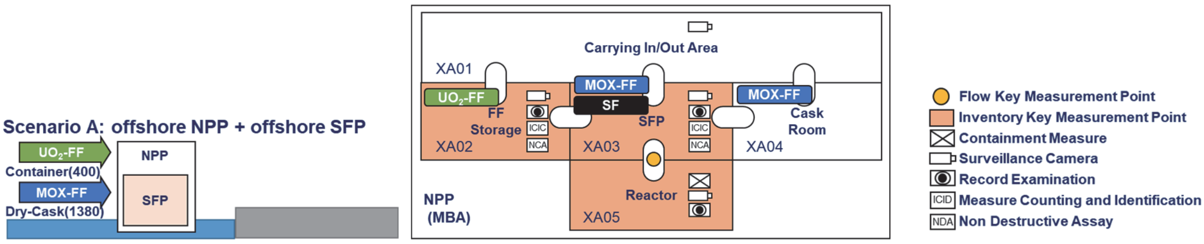
We established several "management scenarios" and "types" of nuclear fuels for an ABWR to clarify the characteristics of the offshore location and evaluate the PR of an OFNP.

Figure 2 shows representative nuclear fuel management scenarios for OFNPs [4]. We prepared them in consideration of fuel transportation and storage between onshore and offshore because OFNPs are generally accompanied by onshore fuel storage facilities. As the system elements, we used a FF storage container, SFP, reactor, carrying in/out area, cask room, and cask storage. In addition, we defined both the onshore and offshore facilities as independent material balance areas and added safeguard measures into the corresponding elements. As the targets aimed for by the threat actor, we selected UO_2-FF, MOX-FF, and SF. In Scenario A shown in Figure 2(a), the nuclear fuels were irradiated and stored only in the OFNP. In Scenario B shown in Figure 2(b), nuclear fuels irradiated and cooled for more than three years in the OFNP were loaded in a wet cask and transported collectively to the onshore SFP storage facility, with a total of 440 assemblies per transportation. In Scenario C shown in Figure 2(c), fuels burned and tentatively restored for more than 18 years in the OFNP were loaded in a dry cask and transported collectively to an onshore cask storage facility, with a total of 1380 assemblies per transportation. To represent the maximum capacity for scenarios A/B/C, we collectively transported 400 UO_2-FF assemblies in a container and 1380 MOX-FF assemblies in a dry cask per transport to the OFNP. The "Ref." scenario reflects a typical scenario of onshore NPPs, in which UO_2-FF, MOX-FF, and SF are transported at each reactor refueling (batch process).

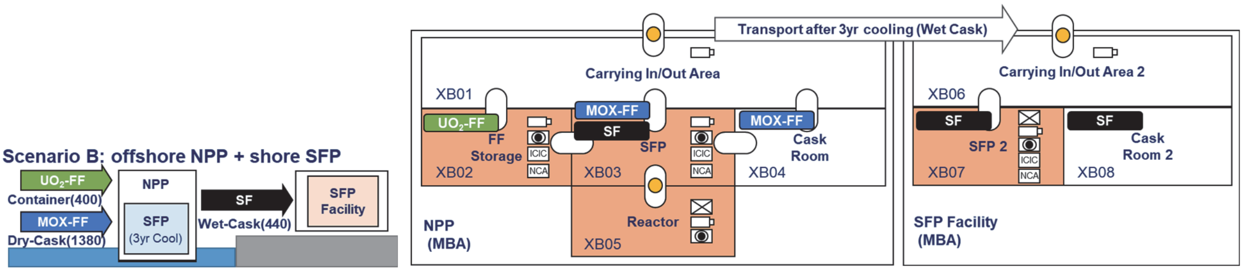
Table 1 shows the multiple fuel types simulated in this study. As we focused on the PR especially for offshore-specific fuel transportation, we prepared several operation periods for the UO_2 and MOX fuels of the ABWR. We also selected fuels with a higher burnup (72.0 GWd/ton) based on the benchmark problem proposed by JAERI [5] for an improved PR. Therefore, the selected fuels for this study were HALEU 9 × 9 fuel with 5.5% U-f enrichment and MOX 10 × 10 fuel with 7.0% Pu-f enrichment. They were irradiated for 12 mon (eight batches) or 24 mon (four batches) with 3-mon refueling during one cycle. For comparison, we prepared typical UO_2 and MOX reference fuels, which were burned for 12 mon (five batches) with a burnup of 45.0 GWd/ton. Therefore, the initial fuel compositions were based on JAERI benchmark [5], and burnup calculation was performed with SCALE 6.2.4/TRITON code and ENDF/B-VII library [6].

2.2. Measures of PR analysis

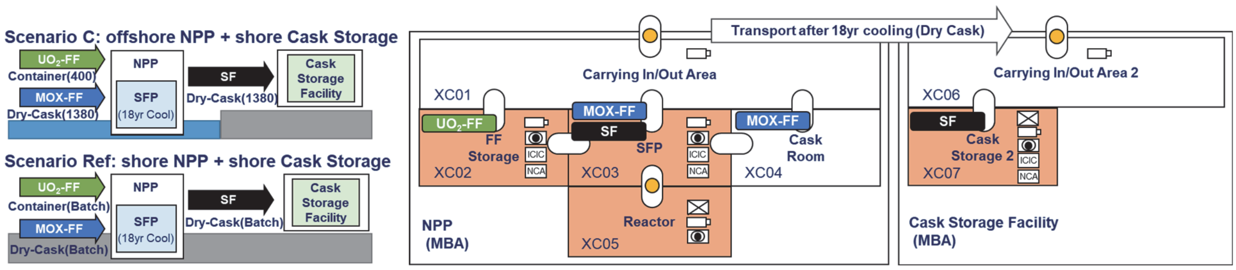
Table 2 shows the measures of the PR analysis for this study. We referred to and improved the GIF/PRPP evaluation method to assess OFNP several nuclear fuel diversion pathways for multiple fuel management scenarios, including



(a) Nuclear Fuel Management Scenario "A".



(b) Nuclear Fuel Management Scenario "B".



(c) Nuclear Fuel Management Scenario "C" and "Ref".

Figure 2. Nuclear fuel management scenario, its system element and target.

Table 1. Nuclear fuel types.

No.	Fuel type	Operation period	Burnup (GWd/ton)
1)	UO_2 Fuel (5.5%U-f; 9 × 9)	12-mon burn - 3-mon decay; eight batches	72.0
2)		24-mon burn - 3-mon decay; four batches	72.0
3)	MOX Fuel (7.0%Pu-f; 10 × 10)	12-mon burn - 3-mon decay; eight batches	72.0
4)		24-mon burn - 3-mon decay; four batches	72.0
Ref 1: UO_2 Fuel		12-mon burn - 3-mon decay; five batches	45.0
Ref 2: MOX Fuel		12-mon burn - 3-mon decay; five batches	45.0

fuel transport and transfer, while acquisition, processing, and utilization phases. Although the GIF/PRPP methodology evaluated the PR through six indexes on a five-point scale (Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH)), we modified the measure of MT and added a measure for PO applicable to not only OFNPs but also to other nuclear facilities. The highest resistance measure represented the PR of the nuclear system.

This MT indicator was modified because the MT in the GIF/PRPP method is defined as the fissile isotope ratio of U and Pu; it does not consider the differences between various fuel types such as the higher-burnup HALEU and MOX fuels. Aoki et al [7], modified "Material Attractiveness," an indicator of a material-specific usefulness developed by Bathke et al [8], for non-state actors, to one for state actors. Among the four indicators of Material Attractiveness for state actors proposed by Aoki, we deleted "Conversion Time" because other measures indicated it and ignored the SFN because the assumed state actor had a higher production technology for a nuclear explosive device. Therefore, we applied the BCM and "Heat Content" as the components of the MT. The BCM reflected the bare critical mass of the reprocessed metal in the alpha phase, and its thresholds corresponded to those for uranium enrichment (70/20/10%). Heat Content showed the total decay heat of reprocessed metal per BCM and its

Table 2. Measures of PR analysis.

Measure & Description		VL	L	M	H	VH
TD	Proliferation Technical Difficulty	0–5%	5–25%	25–75%	75–95%	95–100%
PC	Proliferation Cost	0–5%	5–25%	25–75%	75–100%	>100%
PT	Proliferation Time	0–3 mon	3 mon–1 yr	1–10 yr	10–30 yr	>30 yr
DP	Detection Probability	<L	50%/yr	20%/3mon,50%/yr	50%/mon, 0%/yr	>H
DE	Detection Resource Efficiency	0.00–0.01	0.01–0.04	0.04–0.10	0.10–0.30	>0.30
MT (GIF)	Fissile Material Type[a]	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
MT	BCM [kg-BCM]	-	<80	80–800	800–4000	>4000
	Heat Content [W-BCM]	-	<450	450–4500	>4500	-
	Ref 3: SFN [n/s-BCM]	-	$<6.77\times10^5$	6.77×10^5–3.51×10^6	$>3.51\times10^6$	-
PO	Proliferation Occasion [times/yr]	>12	4–12	1–4	0.1–1	0.0–0.1

[a] HEU = High-enriched U, normally 95% U_f; WG-Pu = Weapons-grade Pu, normally 94% Pu_f; RG-Pu = Reactor-grade Pu, normally 70% Pu_f; DB-Pu = Deep burn Pu, normally 43% Pu_f; LEU = Low-enriched U, normally 5% U_f.

threshold was set based on the ^{238}Pu content (8/80%). Thus, the higher resistance indicator between the BCM and Heat Content was used for the MT PR of the nuclear materials. We calculated the nuclide compositions of nuclear fuels after irradiation or decay based on the SCALE 6.2.4/TRITON code and ENDF/B-VII library [6] for the Heat Content, and the MCNP4C code and ENDL92 library [9] for the BCM. For reference, if in a low-technology-level state, we used the SFN, which represented that of the reprocessed metal per BCM and corresponded to the ^{240}Pu content (7/30%).

This study established the PO for indicating the average annual frequency of external transports and internal transfers of OFNP nuclear fuels to clarify the impacts of offshore-specific fuel movement on the PR. We adopted 1mon/3mon/1yr of the IAEA timeline detection goal [10] and 10 yrs as thresholds for the PO; consequently, the PO measures (times/yr) were 12/4–12/1–4/0.1–1/0.0–0.1 for VL/L/M/H/VH, respectively.

Based on past GIF/PRPP studies [3,4], we estimated the TD based on three types of needs for special equipment: during clandestine fuel export, for construction of processing facilities, and according to the technology level of the state actor. The PC was evaluated as the fraction of national military budget required to execute the proliferation pathway (threshold: 5/25/75/100%). The PT was estimated as the total time to complete the pathway starting with the first action taken to initiate the pathway (threshold: 3 mon/1 yr/10 yr/30 yr). We defined the DP based on the IAEA detection probability of one significant quantity and conversion time target [10]. The DE was proposed as the GWe years of capacity supported per Person-Days of Inspection (PDI) criterion (threshold: 0.01/0.04/0.10/0.30 GWe/PDI).

2.3. Threat definition and export strategies

The threat actor was assumed to be an advanced, industrialized, non-nuclear weapons state with commercial reactors for power generation and demonstration-stage enrichment/reprocessing technology. The assumed state aimed to confidentially divert nuclear materials from declared facilities. Furthermore, the state ratified not only the "Comprehensive Safeguards Agreement" and "Additional Protocol," but also integrated safeguards for the MOX no-use facility.

We envisioned the following export strategies of the targeted nuclear fuels as clandestine diversions:

(1) Export fuels without a cask;
(2) Export fuels within a cask disguised as empty; and
(3) Export fuels intentionally left in a cask disguised as empty.

3. Results

Table 3 shows results from the improved MT measure composed of the BCM and Heat Content. As a reference, it also shows the results from the MT in the GIF/PRPP study and SFN. In addition, we show the mass ratio of the Pu metal as reprocessed through the Fluoride Volatility or Plutonium Uranium Recovery by Extraction on the right.

As the result for the MT, UO_2-FF indicates "VH" owing to the subcritical nature of the BCM. MOX-FF and SF result in "L" and "M," respectively, mainly owing to the ^{238}Pu mass ratio of reprocessed Pu metal (^{238}Pu contains a higher decay heat of 560 W/kg). SF with 5.3 to 5.4 wt% ^{238}Pu shows a 508–545 W-BCM Heat Content corresponding to "M"; however, MOX-FF with 2.1 wt% ^{238}Pu reveals a 254 W-BCM for "L." As a reference, if SFN is considered owing to a lower technical capability of host states, the MT for MOX-FF and SF increase from "L" and "M" to "H," respectively.

Table 4 shows PR results for the newly established PO measure for each target through various scenarios and fuel types. The PO is composed of the three components shown on the right: the frequency fuel movements of front-end transport to the OFNP (=X), internal transfer within the OFNP (=Y), and back-end transport from the OFNP to an onshore fuel storage facility (=Z).

As the results for the PO measure, for targets within NPPs, the Ref. scenario shows "M," whereas scenarios A, B, and C result in "H," i.e., a one-step higher PR (with

Table 3. Results of fissile material type (MT) measure.

Fuel type	Burnup [GWd/ton]	Result: BCM [kg-BCM]	Heat Content [W-BCM]	MT	MT (GIF)	Ref 3: SFN [n/s-BCM]	Mass fraction of reprocessed Pu metal [wt%]: ^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
UO_2-FF		Subcritical	—	VH	VH	—	—	—	—	—	—
MOX-FF		13.9	254	L	M	5.4E+06	2.1	54.5	25.0	9.3	6.4
UO_2-SF	72.0	15.0	508	M	M~H	8.8E+06	5.4	41.7	27.2	14.1	11.6
MOX-SF	72.0	16.2	545	M	H	1.1E+07	5.3	34.5	33.3	14.1	12.8
Ref 1: UO_2-SF	45.0	13.3	217	L	M	4.9E+06	2.3	54.9	24.1	13.4	5.3
Ref 2: MOX-SF	45.0	15.3	390	L	M~H	8.5E+06	3.9	41.8	31.6	13.0	9.8

Table 4. Results for proliferation occasion (PO) measure.

	Fuel type	Operation period	PO [times/yr]: UO_2 NPP Fuel Storage X+Y	MOX NPP SFP X+Y	MOX NPP Cask Room X+X	SF NPP SFP Y+Z	SF Onshore SFP 2 Z	SF Onshore Cask Room2 Z+Z	SF Onshore Cask Storage2 Z	Frequency [times/yr]: Front-end transport X	Internal transfer Y	Back-end transport Z
A	1) UO_2	12mon (8batches)	1.02:M	—	—	0.80:H	—	—	—	0.22	0.80	—
	2) UO_2	24mon (4batches)	0.69:H	—	—	0.44:H	—	—	—	0.24	0.44	—
	3) MOX	12mon (8batches)	—	0.86:H	0.13:H	0.80:H	—	—	—	0.06	0.80	—
	4) MOX	24mon (4batches)	—	0.51:H	0.14:H	0.44:H	—	—	—	0.07	0.44	—
B	1) UO_2	12mon (8batches)	1.02:M	—	—	1.00:M	0.20:H	0.40:H	—	0.22	0.80	0.20
	2) UO_2	24mon (4batches)	0.69:H	—	—	0.66:H	0.22:H	0.44:H	—	0.24	0.44	0.22
	3) MOX	12mon (8batches)	—	0.86:H	0.13:H	1.00:M	0.20:H	0.40:H	—	0.06	0.80	0.20
	4) MOX	24mon (4batches)	—	0.51:H	0.14:H	0.66:H	0.22:H	0.44:H	—	0.07	0.44	0.22
C	1) UO_2	12mon (8batches)	1.02:M	—	—	0.86:H	—	—	0.06:VH	0.22	0.80	0.06
	2) UO_2	24mon (4batches)	0.69:H	—	—	0.51:H	—	—	0.07:VH	0.24	0.44	0.07
	3) MOX	12mon (8batches)	—	0.86:H	0.13:H	0.86:H	—	—	0.06:VH	0.06	0.80	0.06
	4) MOX	24mon (4batches)	—	0.51:H	0.14:H	0.51:H	—	—	0.07:VH	0.07	0.44	0.07
Ref 1: UO_2		12mon (5batches)	1.60:M	—	—	1.60:M	—	—	0.80:H	0.80	0.80	0.80
Ref 2: MOX		12mon (5batches)	—	1.60:M	1.60:M	1.60:M	—	—	0.80:H	0.80	0.80	0.80

some exceptions). This is because the fuel transportation (=X, =Z) method changes from at each refueling to collectively refueling for maximum capacity, resulting in less transportation (X, Z: 0.06–0.24 to 0.80). However, the UO_2-FF in 12-mon operation shows "M," i.e., a one-step lower PR, as the shorter operation period (12 mon rather than 24 mon) increases the frequency of internal transfers (=Y) (Y: 0.44 to 0.80).

In Scenario B when considering 12-mon operation, the SF within the OFNP indicates "M," whereas in Scenario C, the SF within the onshore cask storage facility shows "H." This is because in addition to the frequency of the internal transfer (=Y) varying depending on the operation period, the frequency of back-end transport (=Z) changes depending on the cask capacity (Z: 0.06–0.07 to 0.20–0.22).

The overall PR results were scored as "H" or "VH" in all scenarios. Therefore, it was evaluated that the OFNPs do not have significant differences in PR compared to land-based power plants.

Table 5 shows the PR scores for different target materials, diversion points, and export strategies in Scenario C. The overall score shown as PR results was determined by the highest score at each column. It was found that the DE, MT, and PO scores are sensitive to fuel management scenarios and fuel types, but other measures do not differ according to them. Comparing by the target type, MOX fuel showed the lowest scores for TD, PT, and MT measures. The strategy (3) (i.e., export fuels intentionally left in a cask, disguised as empty) showed a lower score than the other strategies for DP (VL), but its overall score becomes "H" due to the PO score caused by its specific fuel type.

Table 5. PR in Scenario C.

Scenario C	Target	UO_2-FF	MOX-FF	MOX-FF	MOX-FF	SF	SF	SF	SF
	Point	NPP FF Storage	NPP SFP	NPP SFP	NPP Cask Room	NPP SFP	NPP SFP	Onshore Cask Storage 2	Onshore Cask Storage 2
	Strategy	(1)	(1)	(2)	(3)	(1)	(2)	(1)	(2)
TD: Technical Difficulty		M	VL	VL	VL	H	M	H	M
PC: Proliferation Cost		VL	VL	VL	VL	VL	VL	VL	VL
PT: Proliferation Time		M	VL	VL	VL	M	M	M	M
DP: Detection Probability		L	H	H	VL	M	M	M	M
DE: Detection Efficiency		H	H	H	H	H	H	H	H
MT: Fissile Material Type		VH	L	L	L	M	M	M	M
PO: Proliferation Occasion		M~H	H	H	H	H	H	VH	VH
PR Result		VH	H	H	H	H	H	VH	VH

4. Discussion

Although the comprehensive PR analysis results in no significant differences between OFNPs and onshore NPPs, we should aim to further enhance PR through safeguards by design. This study discusses key countermeasures for improving the PR for the PO and MT, which differ depending on the nuclear fuel management scenario and fuel type.

Regarding the MT, we clarified that the higher burnup of nuclear fuels enhances the PR of the SF because it increases the ^{238}Pu mass ratio of the Pu metal reprocessed from the SF, and ^{238}Pu possesses high heat decay. Consequently, we propose a "high burnup of nuclear fuel" as an effective means for improving the PR of the SF. In terms of the improvement of analysis methods, this approach enables us to evaluate the effects of the decay heat, which can be a barrier to nuclear explosive device production. For instance, the IAEA decides whether safeguards are necessary by a threshold of 80% of ^{238}Pu content [11]. Accordingly, we believe this methodology can assess the material attractiveness for host states for MTs more appropriately than past studies.

Regarding the PO, we confirmed three key consequences. First, the operation period affected the frequency of internal fuel transfers (0.44 to 0.80 times/yr). Therefore, we propose extending the operation period per batch. Second, the frequency of back-end fuel transport varied depending on the cask capacity (0.06–0.07 to 0.20–0.22 times/yr). Accordingly, to reduce proliferation risks during transport from the OFNP to an onshore storage facility, we suggest increasing the number of fuel assemblies (such as large-capacity casks) transported at one time. Third, the external fuel transport method should be modified from being conducted at each refueling time to collectively for maximum capacity and decreased transport frequency (0.06–0.24 to 0.80 times/yr). Thus, we consider collective transportation as an effective countermeasure to the proliferation risk.

However, MOX-FF is likely to decrease nuclear reactivity at the early phase of burning owing to the nuclide

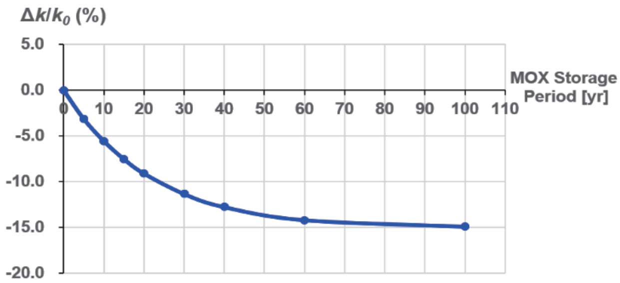


Figure 3. Nuclear Reactivity in bulk transport of MOX fresh fuel.

decay in the time from reprocessing to use. **Figure 3** shows "$\Delta k/k_0$: difference in initial infinite multiplication factor between 0yr storage and a given period storage MOX-FF – initial infinite multiplication factor of 0yr storage MOX-FF(%)" when storing MOX-FF before irradiation for long-term use (from 0 to 100yr). The initial fuel compositions were based on JAERI benchmark [5], and decay/burnup calculation was performed with SCALE 6.2.4/TRITON code and ENDF/B-VII library [6]. The results show that it decreases by 5.5% for the 10yr storage FF and by 14.9% for 100yr storage FF owing to the accumulation of ^{241}Am (neutron poison) over time. Therefore, we should carefully consider the long-term storage of MOX-FF before use, as it significantly lowers the reactivity.

Lastly, when considering the proposed measures, we should discuss the interfaces and synergy of safety, security, and safeguards, because the design and management of fuels affect the safeguards as well as nuclear safety and security.

5. Conclusions

To take advantage of OFNPs, we must first assess their nuclear proliferation risks. As we clarify the non-proliferation characteristics of nuclear fuel management for offshore-specific fuel transportation and storage, we analyze the PR of OFNPs through developed nuclear fuel management scenarios and nuclear safeguard systems.

This study refers GIF/PRPP method to clarify nuclear fuel diversion pathway, and improves MT and PO measures for various nuclear fuel management scenarios and fuel types. As a result, the following conclusions are drawn:

- No significant PR differences exist between OFNPs and onshore NPPs.
- However, the PO increases for scenarios involving transportation from OFNPs to onshore fuel storage facilities, which may increase the proliferation risk.
- As a target, MOX-FF has a more vulnerable PR than UO_2-FF and SF; this is not unique to OFNPs and also applies to conventional NPPs.
- A higher burnup of nuclear fuel increases the content ratio of ^{238}Pu for a high decay heat, thereby reducing material attractiveness.
- Extending the operation period per batch decreases the POs for host states during fuel transfers within OFNPs.
- Increasing the number of fuel assemblies to be transported outside the OFNP at one time (including collective fuel transportation by maximum possible number and increasing the capacity of casks for storing fuel) is effective for improving PR.
- However, the collective transport measures for MOX-FF should consider that the long-term storage of MOX-FF before use significantly reduces the nuclear reactivity in the initial stage of irradiation.

In the future, based on the results from this study, we expect to design and manage nuclear fuels considering not only nuclear safeguards, but also nuclear safety and security.

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