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ARTICLE

Development of a passive safety shutdown device to prevent core damage accidents in fast reactors; performance of the device in reactivity control and nuclear material management

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A new subassembly-type passive reactor shutdown device is proposed to expand the diversity and robustness of core disruptive accident prevention measures for sodium-cooled fast reactors (SFRs). The objectives of the present paper are to evaluate the device in reactivity control based on design requirements for selecting candidate materials and specifications in anticipated transient without scram (ATWS) of a 750MWe class SFR, and the ex-core performance evaluation of the device fuel in nuclear material management. As results, based on the examination of the functions and roles of the device fuel during rated power operation, the reference specifications for the alloy-fueled device has been selected as ternary U-Pu-10at%Fe alloy with Pu enrichment of 25% in device fuel zone, and ternary U-Pu-10wt.%Zr alloy with Pu enrichment of 50% in preheating zone. With this reference device, reactivity control effectiveness was confirmed against unprotected loss of flow (ULOF) and unprotected transient overpower (UTOP) accidents. As for the ex-core performance in nuclear material management, the attractiveness of the device was evaluated as the same category of MOX fuel for states and non-state actors, no additional measures would be required in the reactor plant. Non-Destructive Assay (NDA) techniques would be significant for nuclear safeguards verification and for quality assurance.

Keywords: ***sodium cooled fast reactors; passive safety; reactivity control device; nuclear security; non-proliferation***

Nomenclature

ATWS	anticipated transient without scram	SFR	Sodium-cooled Fast Reactor
CDA	core disruptive accident	ULOF	Unprotected Loss of Flow
HSF	hot spot factor	UTOP	Unprotected Transient OverPower
MOX	mixed oxide	BCM	Bare Critical Mass
NED	Nuclear Explosive Device	SFN	Spontaneous Fission Neutron
P/F	Power to coolant Flow ratio	NDA	Non-Destructive Assay
SD	Smear Density		

1. Introduction

Sodium-cooled fast reactors (SFRs) have potential to achieve energy sustainability. Fast reactor is an indispensable option for achieving Carbon Neutral and its long-term sustainability for energy production.

In addition to active reactor shutdown systems, the self-actuated shutdown system and gas expansion module have been developed as passive safety equipment against an anticipated transient without scram (ATWS) to prevent core disruptive accidents (CDAs) in fast reactors [1]. Furthermore, design measures to establish in-vessel retention that mitigates the effects of severe accidents and prevents large-scale mechanical energy release during CDA have been proposed as a practical approach to ensure the containment function of radioactive materials [2]. Since the accident at the Fukushima Nuclear Power Plant, it has become increasingly important to consider measures to prevent and mitigate the consequences of severe accidents in design extension conditions, including severe accidents that exceed the design basis accidents in the defence-in-depth concept [3].

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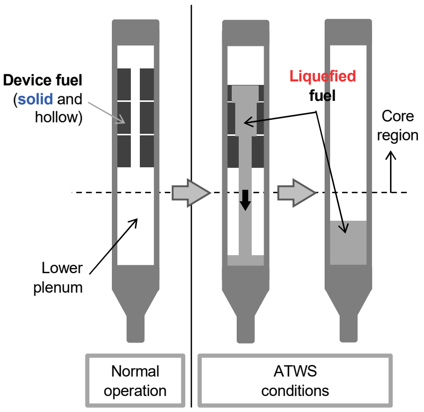

Figure 1. Concept of a passive shutdown device [4].

Novel subassembly-type passive reactor shutdown device (Device) has been developed, aiming to significantly improve the safety of sodium-cooled fast reactors (SFRs) by developing a novel subassembly-type passive reactor shutdown device that provides "diversity" and "robustness" in preventing the occurrence of CDA [4,5]. Our proposing concept of device is an assembly-type passive reactor shutdown device using low melting point fuel as part of a novel safety design measure that can be used in conjunction with existing passive shutdown mechanisms to contribute to accident conditions where core damage due to ATWS should be "practically eliminated" (**Figure 1**). This device, which replaces some of normal fuel subassemblies and is loaded as a passive shutdown mechanism in the fourth layer of the defence-in-depth concept, maintains the subcritical state and prevents core damage by moving (relocating) the liquefied fuel in device pins to a region with low reactivity worth by simple physical phenomena in the event of ATWS. In the previous researches, the requirement for the device has been defined based on the transient analysis of ATWS events [4,5]. In addition, the IAEA recommends "Safety/ Security/Safeguards by Design" which is the process of including the consideration of nuclear safety, security and international safeguards throughout all phases of a nuclear facility project, from the initial conceptual design to facility construction and into operations, including design modifications and decommissioning [6]. Since the proposing device consisting of unprecedented materials, consideration of Safety/Security/Safeguards by Design is significantly important. The objectives of the present paper are the performance evaluation of the device in reactivity control based on design requirements, and the ex-core performance evaluation of the device fuel in nuclear material management.

2. Overview and characteristics of the target large oxide fuel fast reactor]

2.1. Overview of reference large core and fuels

Basic specifications for the reference core was set by citing "a 750 MW-class MOX-fueled SFR core [7]". Outline is a two-zone core with a basic system of 285 core fuel assemblies, core length of 100 cm, axial blankets of 20 cm, coolant Inlet temperature of 395°C, outlet temperature of 550°C, having characteristics such as fuel Pu enrichment of about 19% for inner core and about 23% for outer core, average discharge high burnup 150 GWd/t, 4-batch refueling with 832 days per operation cycle, and sodium void reactivity (in-channel) about 6$. The reference core for this study employed 20%-lower linear heat rating with 311-pin fuel subassembly rather than the original design with 255-pin fuel subassembly, to increase tolerance against ATWS events. The core specification and some characteristics of the core for this study are summarized in **Table 1**.

Table 1. Core specifications [4].

Reactor thermal power	1785	MW
Coolant inlet/outlet temperatures	395/550	°C
Number of fuel assemblies	286	
Number of blanket assemblies	66	
Primary coolant flow rete	9,083	kg/s
Coolant flow rate in fuel subassemblies	8,718	kg/s
Number of pins per subassembly	311	
Pin outer diameter	9.4	mm
Hexagon inside flat-to-flat	191.8	mm
Thickness of wrapper-tube	5	mm
Subassembly pitch	206.8	mm

2.2. Reactivity coefficients of the reference core and asymptotic coolant temperature in an ATWS condition

Prior to making a sizable effort to proceed transient calculations, it is desirable to estimate the device profiles and basic characteristics required in ATWS conditions as initial settings. As in the previous studies [4,5], SFR core characteristics were calculated with 70-group effective cross-sections processed by SLAROM code [8] for JENDL4.0. Power distributions in the core were calculated using a three-dimensional model, and the spatial distributions of the reactivity coefficients were computed for the two-dimensional RZ-model using a diffusion theory code [9] for the end of equilibrium cycle of the 750MWe reference core.

Core-integral reactivity coefficients are tabulated in **Table 2** in the form of averaged temperature coefficients which correspond to the calculated reactivity decrements due to temperature rises of fuel, steel and coolant from zero to the rated power levels in normal operation.

Reactivity coefficients are shown in **Table 3**, with fuel power coefficient (A), the power-to-flow coefficient (B) and the inlet temperature coefficient (C). Using integral reactivity parameters of (A), (B), and (C) for the quasi-static reactivity balance analysis [10], the passive feature of the reference core was estimated against an ULOF situation. In this asymptotic ULOF situation, the coolant temperature was estimated around 860°C, close to bulk boiling temperature of sodium coolant, at P/F-value of 3.2. In order to stabilize core with suppressing fuel pin failures, additional external reactivity insertion is needed to overcome P/F variation back from 3.2 to 1. With this simplified approach, amount of the reactivity required for the device reaches approximately 2.3$ (1.3$ from P/F 3.2

Table 2. Reactivity temperature coefficients for power reactivity decrement (from zero to rated level) in the reference core.

Components considered	Fuel Doppler	Fuel expansion	Steel Doppler	Steel expansion	Sodium expansion	Radial expansion
(d*k*/*kk*')/ °C	-7.1E-06	-3.7E-06	-2.6E-06	-1.2E-06	5.5E-06	-5.8E-06

Table 3. Reactivity Coefficients of Power, Power-to-flow and inlet temperature.

Parameters	A: ¢/(100% Power)	B: ¢/(100%*P*/*F*)	C: ¢/(°C)
Reactivity Coeff.	-103	-30	-0.38

stage to *P*/*F* 1.0 stage, and additional 1$ to cold shutdown stage) and estimated numbers of device subassemblies is around 30 or less.

3. Device concept design study

3.1. Selection of specifications of passive shutdown device

The device specification proposed in the previous study uses a U-Pu-Fe alloy as the device fuel, which has the characteristics of fast reactor fuel and a relatively low melting point [4,5]. Given swelling caused by fuel burnup, the device structure is designed with hollow fuel pellets, which facilitates the movement of liquefied fuel during device operation (Figure 1). During device operation, liquefied fuel flows down along the hollow wall of device fuel pellets. In the present paper, the basic specifications were considered for passive shutdown devices, based on the following points;

(1) Materials and structures that are solid for rated operation and design basis accident events, but are melted during fuel temperature rise transients in ATWS
(2) Characteristics; combination of device fuel pin and preheating fuel pin
(3) Device fuel candidates selected; U-Pu-10 at.% Fe alloy, $(U\text{-}Pu)Cl_3$ salt
(4) Hollow slag metal fuel in the cladding tube, a shape that secures a hollow area even under fuel swelling up to 30% (assuming an initial smear density (SD) of about 25%, and an irradiated slug SD of 33%)
(5) Set the device fuel outlet temperature to the same range as the driver fuel assembly
(6) Limit temperatures considering changes in temperatures and thermal conductivity at rated and transient conditions (consideration of engineering safety margins) [5].

In **Figure 2**, the proposed device subassembly layout is shown with horizontal and axial cross-section, which has combination of device fuel pin and preheating fuel pin. As for the device fuel pin candidates, U-Pu-10mol%Fe alloy, or $(U\text{-}Pu)Cl_3$ compound (Pu: U ratio = 1:3) were considered. As for the preheating fuel pin candidates, U-Pu-10w%Zr alloy (Pu: U ratio = 1:1 to 1:2; Lower preheating fuel with SD 75% in pins). Combination of device fuel and preheating fuel is important and unique to enable coolant temperature to rise up to appropriate level at the bottom of device fuel. For the calculation in the present paper, reactor grade Pu isotopic vector was utilized. The difference in physical properties (density, thermal conductivity, liquidus temperature, solidus temperature, etc.) important for the temperature behavior of the operating device fuel was reflected.

Schematic axial views of the device fuel pin before and after it works are also shown in Figure 2 left and right. The high-density alloy device fuel melts from the top of the thin alloy layer placed on the inner surface of the cladding tube and has a large hollow in the center of the pin, allowing the fuel to fall along the inner surface. In this example, when ATWS occurs, the axial length of 30-40 cm falls in about 0.5 seconds. For the salt fuel, which has a lower fuel substance density, high SD is needed as solid. In particular, salt fuel is mixed with Zr metal powder at a volume ratio of about 24% in order to increase thermal conductivity. In this case length of device fuel section 70 cm in the axial direction for lowering liner heat rate under normal operation. In addition, fuel relocation profile should be different from that of the alloy device case due

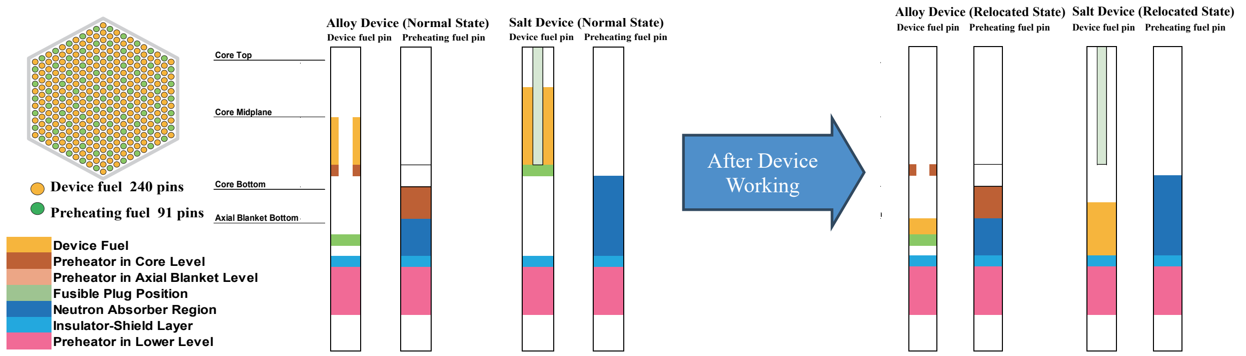

Figure 2. Schematic views of device fuel relocation (Left; device pins under normal operations, Right; after device working triggered by ATWS)

to position of fusible plug. During ATWS, the fuel temperature is raised to the liquidus temperature over the entire axial direction, and as the fusible plug located directly under the device fuel is activated, the liquefied salt fuel drops at once, resulting in negative reactivity insertion.

3.2. Device performance evaluation results

Table 4 exemplifies some of the survey results in relations to the numbers of devices loaded in core. **Figure 3** shows three variants of different device layout in the inner core region, 16, 22 and 28 devices installed.

With a U-Pu-10a%Fe alloy (Pu: U ratio of about 1:3) as an alloy device fuel, a negative reactivity effect of about 2.5$ was obtained in the 28 devices layout. The Pu-enrichment is selected from the viewpoints of linear heat rate, reactivity worth, and avoiding positive reactivity insertion even under hypothetically conservative assumption of device fuel slumping mode [11]. 28-alloy fuel device layout would satisfy the requirement.

The salt fuel device (Pu-U)Cl_3 (Pu: U ratio = about 1:3) has a negative reactivity less than 2$ due to much lower effective fuel density. Reactivity worth for 28-salt fuel devices is short, however, alternative specification of device (397-pin bundle) ensures worth by 1.2 times with 32 fuel device layouts to terminate the event [12].

4. Evaluation of non-proliferation and criticality safety in fuel management

4.1. Nuclear non-proliferation

Since the device subassembly is consisting from abundant U and Pu with as high as ~50% Pu enrichment (**Table 5**), within the range existing in MOX fuel powder in nuclear fuel cycle in Japan [Historical sequence is described in Yoshimoto, (2011)][13], evaluation from nuclear non-proliferation and criticality safety are important for its nuclear material management. As for non-proliferation, the material attractiveness of the device subassembly was evaluated by using the proposed methodology for states and non-state actors. Then nuclear safeguards design in the reactor building is proposed and the impacts after ATWS events are discussed. As for criticality safety, the reactivity evaluation was performed for the device subassembly with hypothetical submerged cask.

4.1.1. Material attractiveness of the device subassembly

The material attractiveness is the relative utility of nuclear material for an adversary in assembling a nuclear explosive device, originally developed for nuclear security purpose against threats of non-state actors [14]. Nuclear material attractiveness is evaluated based on its material properties important to convert it to Nuclear Explosive Devices (NEDs) in acquisition, processing and utilization phases. Each material property was categorized based on the criterion grouping into 4 categories, (I)Preferred, (II) Potentially usable, but not preferred, (III)Impractical, but not impossible, and (IV)Impossible. See the reference for details of the methodology with design basis threats, binning criterion [14,15]. The concept was expanded for state actors by combining "Conversion Time" used in the current international safeguards by IAEA to the processing phase evaluation categorizing to (I) order of days, (II) order of weeks, (III) order of months and (IV) order of years [15]. In the present research, the capability of the

Table 4. Survey results for device of the 331-pin bundle (240 fuel+91 preheating-pin).

	Device total reactivity worth（$）		
	16-device layout	22-device layout	28-device layout
Fe-alloy fuel device (*)	1.63	1.90	2.57
Salt fuel device	0.96	1.13	1.53
(*) The values obtained for the survey case in which had gas plenum region adjacent to the preheater of preheating pins in Fig. 2.			

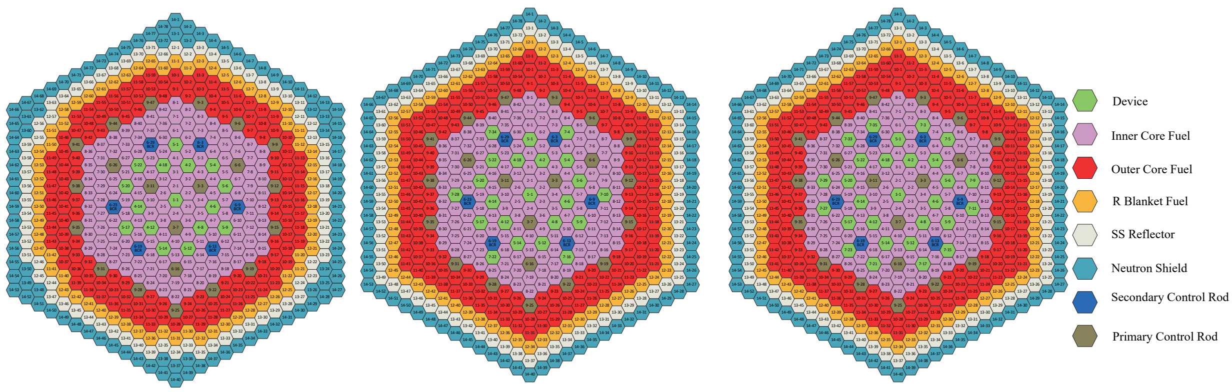

Figure 3. Cross sections for variants of device-loaded cores;
(a) Left; 16 devices in IC (Number of IC fuel 141, OC fuel 128), (b) Middle; 22 devices in IC (Number of IC fuel 135, OC fuel 146)
(c) Right; 28 devices in IC (Number of IC fuel 129, OC fuel 146).

Table 5. Fuel weights per device assembly.

Alloy-fuel device	Weight (Kg)	Salt-fuel device	Weight (Kg)	Reference; MOX fuel assembly for OC	Weight (Kg)
Device fuel (Fe-alloy) Pu	6	Device Fuel (trichloride)Pu	7		
Device fuel (Fe-alloy) U	18	Device Fuel (trichloride)U	20		
Preheater fuel (Zr-alloy) Pu	47	Preheater fuel (Zr-alloy) Pu	40		
Preheater fuel (Zr-alloy) U	51	Preheater fuel (Zr-alloy) U	40		
Total Pu in device Total U in device	53 69	Total Pu in device Total U in device	47 60	Total Pu in fuel assembly Total U in fuel assembly	31 96

Table 6. Material Attractiveness of the device subassembly.

	Acquisition phase			Processing phase	Utilization phase		
Target material	Net weight (kg)	Acquisition time (min)	Radiation Doze @1m (Gy/h)	Processing time and Complexity	BCM (kg)	Heat content (W-BCM)	SFN (†) (n/sec-BCM)
Alloy fuel-device subassembly	~150kg 53kgPu (II)	~20 (*) (II)	<0.1Gy (I)	U-separation +Fe/Z-separation several steps in processing ~ order of weeks (II)	13.7kgPu (I)	176 W (I)	5.25E +06 (III)
Salt-fuel device subassembly	~150kg 47kgPu (II)	~20 (*) (II)	<0.1Gy (I)	U-separation +dechlorization (+Zr powder separation) several steps in processing ~ order of weeks (II)	13.7kgPu (I)	176 W (I)	5.25E +06 (III)
Mixed oxide fuel (OC fuel) subassembly	~150kg 31kgPu (II)	~20 (*) (II)	<0.1Gy (I)	U-separation +deoxidation several steps in processing ~ order of weeks (II)	13.7kgPu (I)	176 W (I)	5.25E +06 (III)

* handling machine time + transportation to the off-site area are taken into account
(†): SFN value is listed just for reference, not used for categorization because of its insensitivity to the design basis threats/states capability

hypothetical state is technically advanced enough to design the NEDs excluding the impact of spontaneous fission neutron (SFN) emissions, only bare critical mass (BCM) and heat content by Pu decay should have importance, in this research.

The evaluation results are shown in **Table 6**. Alloy-fuel device, Salt-fuel device and MOX fuel subassemblies were evaluated and compared. In spite of the high amount of Pu inventory in the device, the single subassembly of all the device and MOX fuel include more than 2 or 8 kg of Pu significant quantities in nuclear security and safeguards, and it did not affect the acquisition phase. Though the difference of the chemical form requires different chemical process to make separated Pu, evaluation results of the processing phase of all types of devices and MOX fuel subassembly were assessed in the same category (II).

As summary, the material attractiveness of the device with alloy or salt form were belonging to the same category of MOX fuel overall, so the same security/ safeguards regulation required may be applied at least at the SFR site. More discussion is needed for whole the fuel cycle including pyro-reprocessing and fuel fabrication of alloy and salt types.

4.1.2. Nuclear safeguards design and impact of the device

As results of the nuclear material attractiveness evaluation, the same treatment of the device may be applicable for nuclear safeguards in SFR plant for the device. An example of fresh fuel handling route and nuclear safeguards installation at SFR plant is shown in **Figure 4**. After the acceptance of the devices and fuels subassemblies, these may be stored in fresh fuel storage, sodium pool fuel storage, and inserted to the reactor vessel by using refueling machine. Due to the invisibility by the sodium inside the sodium tank or reactor vessel, duel independent non-destructive assay (NDA) techniques with passive total neutron and gamma monitors are installed to trace the fuels movement by watching inlet/outlet handling machine. All the key movement from the room to the others, or the fuel handling machines are monitored by surveillance camera and the storage are concealed by containment tools.

The impact of the device for nuclear safeguards could be observed when ATWS events initiated; the passive safety measures including the device works as designed, and no CDA could be expected. Conventional material accounting and verification with item counting can be applied because of the designed fuel relocation inside fuel rods without material leakage, though complicated safeguards would be required for decommissioning damaged fuel, re-establishment of accounting report in case CDA occurs without the device [16,17]. For the

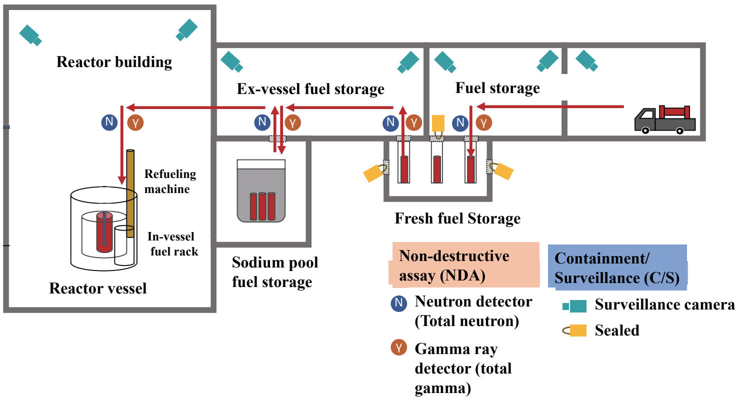

Figure 4. Example of Fresh Fuel Handling Route and Nuclear Safeguards Installation at the SFR plant.

safeguards-verification and quality assurance of the device, NDA with tomography technique may be needed to verify the fuel material location inside the fuel. Currently developing passive X-ray, gamma or neutron tomography would be good candidates for these [18-21].

4.2. Criticality safety for a single device subassembly

As an investigation of basic characteristics of a single device subassembly when submerged in sodium or water, criticality evaluations were performed by modeling the cases where a device in normal state and a device activated state were separately contained in a cask-like steel container. Criticality of the alloy device and the salt device spreads in the rage of 0.51-0.53 in sodium and in the range of around 0.83. Criticality in water is larger than that in sodium, but it is sufficiently subcritical both for normal state and device-fuel-relocated state. The higher Pu-enrichment fuel-10%Zr alloy with 75%SD in the preheating region at the bottom of the device is the dominant factor for criticality safety. The results indicate that conventional cask-design-methodology and device fuel handling ways at a plant can be applicable.

5. Conclusion

Conceptual development of the device has been performed by deciding the material and specifications required for reactivity control in ATWS of a 750MWe class SFR, and the nuclear non-proliferation features and critical safety were evaluated for its nuclear material management. As results, basic specifications were proposed for the device using alloy or chloride fuels with melting points much lower than that of the core fuel. Materials selected for the devices are summarized as follows;

- Device fuel pin material: Alloy fuel U-Pu-10a%Fe or salt fuel $(U\text{-}Pu)Cl_3$, with a U:Pu ratio of approximately 1:3, as a candidate.
- Lower heater fuel candidate: U-Pu-10w%Zr alloy (Pu: U ratio about 1:1 to 1:2).

Nuclear non-proliferation feature was analyzed based on material attractiveness for fissionable materials of the devices. The analysis clarified that device with alloy or salt form were categorized in the same of MOX fuel. It implies that same security/safeguards regulation could be applied to new devices. NDA such as passive gamma or neutron tomography would be needed for nuclear safeguards verification or for quality assurance. For future works, additional demonstration by cold and hot examinations are expected.

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