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Methodology for categorization of nuclear material in pyroprocessing facility

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1. Introduction

In Korea, advanced nuclear fuel cycles have been developed to manage spent nuclear fuel problems. Pyroprocessing technology is considered as a key part of the advanced nuclear fuel cycles to have proliferation resistance because it doesn't separately recover Pu from spent nuclear fuel. For the pyroprocessing facility to be commercialized in future, current regulations should be evaluated and developed in advance, based on the new types of nuclear materials in the facility. Physical protection system, especially, requires reasonable and reliable categorization of nuclear materials, to prevent from the theft of nuclear materials. In this paper, therefore, current categorization methods of nuclear material are investigated and applied to the pyroprocessing facility. After inconsistencies and gaps are found among methods, they are compared and discussed based on eight considering points (i.e, degrees of attractiveness, levels of category, discount factor, physical barriers, chemical barriers, isotopic barriers, radiological barriers, and capabilities of adversaries), to roughly suggest a new method for categorization.

2. Comparative analysis of categorization methods

2.1 Current categorization methods

Five categorization methods, including IAEA's INFCIRC/225, U.S. Department of Energy (DOE)'s method, newly expected U.S. Nuclear Regulatory Commission (NRC)'s method, figure of merit (FOM), and Bunn's approach, were investigated. INFCIRC/225 is used as an international standard, which is adopted by U.S. NRC and Korea. It recommends that the nuclear materials are regulated by 3 categories. The categories are determined by the quantity of Pu, U-235, or Pu-233 as listed in Table I [1]. In case of U-235 material, its maximum category is limited based on its enrichment, which affects attractiveness to adversaries.

Table I. INFCIRC/225 categorization table

Material	Form	Category I	Category II	Category III
Pu	Unirradiated	≥2kg	>500g, <2kg	>15g, ≤500g
U-235	Unirradiated uranium (≥20% U-235)	≥5kg	>1kg, <5kg	>15g, ≤1kg
	Uranium (≥10 & <20% U-235)	N/A	≥10kg	>1kg, <10kg
	Uranium (<10% U-235)	N/A	N/A	≥10kg
U-233	Unirradiated	≥2kg	>500g, <2kg	>15g, ≤500g

U.S. DOE regulates nuclear material with 4 categories. In addition, 5 attractiveness levels are defined as in Table II, based on physical and chemical properties of material. Maximum category of nuclear material is limited depending on its attractiveness level [2]. Decision tree is used to determine attractiveness level, and discount factor is used to quantify the relevant amount of complex materials having attractiveness levels B and C. U.S. NRC is currently in process of new rulemaking including revision of categorization table. Expected amendment follows similar approach to U.S. DOE, considering 3 attractiveness levels and 3 categories [3]

Table II. U.S. DOE categorization method

Type	Attractiveness level	Category available
Weapons-grade	A	I
Pure products	B[a]	I – IV
High-grade materials	C[a]	I – IV
Low-grade materials	D	II – IV
All other materials	E	IV

a. Discount factor is used to quantify relevant amount.

In 2014, Bunn suggested more detailed approach [4] than the currently used methods. Tables III and IV show proposed category and attractiveness level. Category I is divided into three categories IA, IB, and IC, based on the weapons utility. Physical (size), chemical, isotopic, and radiological barriers are considered to determine attractiveness level. Each category or attractiveness level assigns discount factor, which quantifies reduced probabilities compared to the ideal material.

Table III. Bunn's category, proposed in 2014

Material	Category IA	Category IB	Category IC	Category II	Category III
Pu, U-233	≥15kg (U-233)	≥6kg	≥2kg	≥500g <2kg	≥15g <500g
U-235 (HEU)	≥50eff.kg	≥18eff.kg	≥5eff.kg	≥1eff.kg <5eff.kg	≥15eff.g <1eff.kg
Discount factor	1.0	0.6	0.4	0.2	0.1

Table IV. Bunn's attractiveness level, proposed in 2014

Attractiveness level	Discount factor
A: Weapons and gun-type bomb materials	1.0
B: Implosion-type bomb materials	0.6
C: Compounds and mixes (not requiring chemical separation)	0.8
D: Compounds and mixes (requiring chemical separation)	0.5
E: Reactor-grade plutonium	0.8
F: Lightly irradiated material	0.8
G: Irradiated material (requiring remote handling)	0.2
H: Highly irradiated material imposing disabling doses during theft	0.001

Bathke et al. suggested FOM formula [5] to measure relative attractiveness of nuclear material. When the FOM is used for nuclear weapon states, it is called FOM_1 (1) and critical mass, heat capacity, and radiation dose rate are considered. For nonnuclear weapon states, it is called FOM_2 (2) [6], and spontaneous neutron emission rate is added to consider the preinitiation of neutron.

$$FOM_1 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}}\right) \quad (1)$$

$$FOM_2 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{MS}{6.8(10)^6} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}}\right) \quad (2)$$

2.2 Application to pyroprocessing facility

Investigated methods in Section 2.1 were applied to pyroprocessing facility. For calculation, ORIGEN-ARP and MCNPX codes were used. Burnup history of initial input material to pyroprocessing is assumed as below.
- Advanced Power Reactor (APR) 1400 PWR;
- 16×16 PLUS 7 fuel assemblies with 4.5 wt% U-235;
- 55 GWd/MTU burnup;
- 3-batch cycles (18 months/cycle) with 93% capacity;
- 10 years cooling time.

In addition, 5 target materials were selected as in Fig. 1, based on the attention to the major processes of pyroprocessing. Additional cooling time up to 20 years after processes were considered to identify the effect of decay and secular equilibrium. Unit mass of each target material, which is the amount that can be stolen at once, was assumed as described in Table V. Final categorization results of methods are listed in Tables VI and VII. In case of multiple categorization in the one target, highest level was selected in a conservative way.

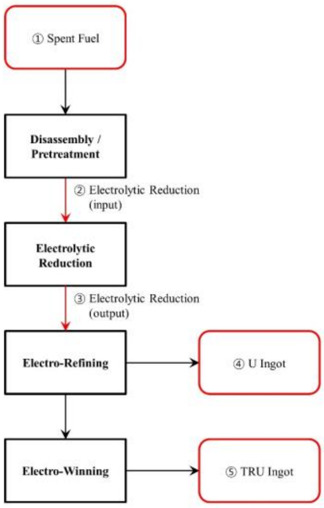

Fig. 1. Target materials in pyroprocessing facility

Table V. Assumed unit mass of target materials

Target	Unit mass (kg)		
	Total	Contained U	Contained Pu
Spent fuel	655	400.60	5.02
ER (input)	50	47.24	0.59
ER (output)	50	48.36	0.61
U ingot	6	6	0
TRU ingot	6	1.12	3.35

Table VI. Final results of attractiveness level

Target	Attractiveness level				
	NRC (new)	DOE	FOM_1	FOM_2	Bunn (2014)
	A-C	A-E	B-E[a]	B-E[a]	A-H
Spent fuel	C	D	E[b]	E[b]	D/E/H
ER (input)	B	D	E[b]	E[b]	D/E/F
ER (output)	B	D	E[b]	E[b]	D/E
U ingot	C	E	E[b]	E[b]	N/A
TRU ingot	A	B	C	E	C/E/F

a. FOM can be applied to U.S. DOE's attractiveness level.
b. FOM can be considered minus infinity having infinite critical mass.

Table VII. Final results of category

Target	Categorization			
	IAEA	NRC (new)	DOE	Bunn (2014)
	I-III	I-III	I-IV	I-III
Spent fuel	II	III	II	IC
ER (input)	III	II	II	II
ER (output)	II	II	II	II
U ingot	N/A	III	IV	N/A
TRU ingot	I	I	I	IC

2.3 Comparison of categorization results

We can easily find that categorization results are inconsistent, while they indicate TRU ingot as the most attractive material to the adversaries. To resolve inconsistencies and to suggest reasonable method, following eight considering points were derived.

- degrees of attractiveness;
- levels of category;
- discount factor;
- physical barriers;
- chemical barriers;
- isotopic barriers;
- radiological barriers;
- capabilities of adversaries

Different degrees of attractiveness and different levels of category affect inconsistencies. Fig. 2 shows the effect of different levels of category. It is important to set various levels to avoid inconsistencies and to make reasonable physical protection systems, while too many levels might create significant regulatory efforts.

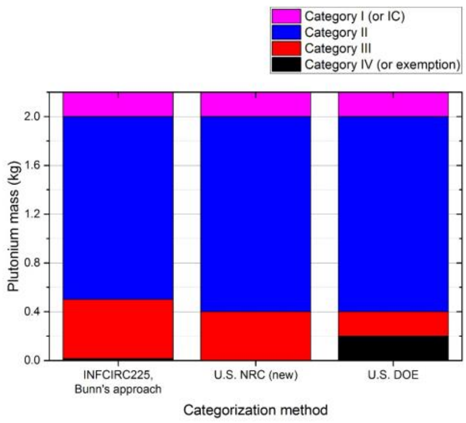

Fig. 2. Categorization among different methods

Effect of physical barriers (i.e., dilution) can be clearly found in Fig. 3. Degradation of attractivness level and category in pyroprocessing is significant, because different materials are mixed in one target. Considering that the threshold quantities of U.S. NRC (new) and U.S. DOE are not technically justified [7], however, relation between physical barriers and level of physical protection in the advanced nuclear fuel cycles should be further discussed. Radiological barriers also bring inconsistencies. In INFCIRC/225, category level suddenly decreases when TRU ingot mass is about 4.75kg, while radiation dose rate of 100 rad/hr at 1m may not be a serious problem to adversaries. It is important to set various and justified thresholds, considering the capabilities of adversaries.

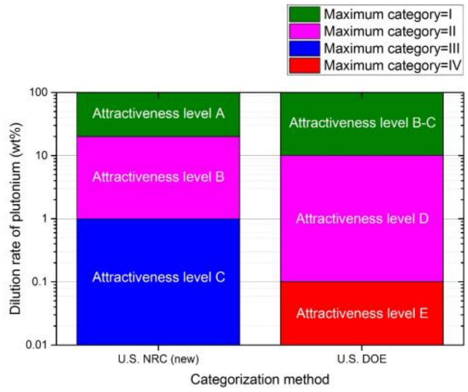

Fig. 3. Effect of physical barriers on categorization

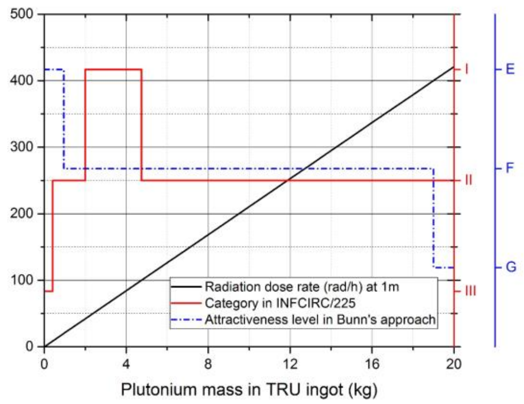

Fig. 4. Effect of radiological barriers on categorization

Isotopic barriers enable exemption of nuclear material as well as degradation of physical protection levels. Bunn's approach, for example, exempt U ingot from the regulation due to low enrichment. Also, sufficient isotopic ratio of Pu-240, which highly emits spontaneous neutron, decreases attractiveness level in Bunn's approach and FOM. In case of chemical barriers, it is hard to determine attractiveness level due to ambiguity of translation. In future, new method should describe definite material to avoid inconsistencies. In addition, discount factor will be a good means to evaluate the relative level of physical protection, providing performance goals.

3. Conclusions

Current categorization methods of nuclear material, including IAEA's INFCIRC/225, U.S. DOE's method, newly expected U.S. NRC's method, FOM, and Bunn's approach, are different and can bring inconsistencies of physical protection requirements. The gap among methods will be significant if advanced fuel cycles are applied to them for the future. For example, the categorization results of 5 target materials in pyroprocessing facility show clear inconsistencies, while TRU ingot is considered the most attractive material. To resolve inconsistencies, it is necessary to determine new method suitable to pyroproessing facility, by considering the effects of eight points (i.e, degrees of attractiveness, levels of category, discount factor, physical barriers, chemical barriers, isotopic barriers, radiological barriers, and capabilities of adversaries). Specifically, coherent and reasonable physical protection systems are possible if various levels of attractiveness and category are set, while too many levels might create significant regulatory efforts. The effects of physical, radiological, and isotopic barriers to the degradation of physical protection level should be further discussed and be technically justified to set reasonable and reliable thresholds, considering the capabilities of adversaries. In case of chemical barriers, definite material from advanced nuclear fuel cycles should be described to avoid the ambiguity of translation. In addition, discount factor will be a good means to evaluate the relative level of physical protection, providing performance goals.

4. Acknowledgments

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