Risk-informed and Performance-based Nuclear Material Categorization for Advanced Fuel Cycle

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1. INTRODUCTION

Advance nuclear fuel cycle technology has been developed to address spent nuclear fuel (SNF) issues. This new technology will produce new types of nuclear materials that are not considered in the current regulations. In particular, the current regulations on physical protection for nuclear materials cannot reflect the characteristics of dirty nuclear materials and also there is inconsistency in a way to characterize the materials. To fill this gap, the regulation needs to be revised to ensure appropriate level of physical protection before the use of the new technology. This study reviews the current regulations, applies them to new technology, and suggests ways to shape risk-informed and performance-based (RIPB) regulatory framework.

2. COMPARATIVE ANALYSIS ON NUCLEAR MATERIAL CATEGORIZATION REGULATIONS

2.1 Attractiveness and Categorization

The characteristics of nuclear materials decides levels of physical protection. The characteristics include quantity as well as attractiveness for constructing nuclear weapons.

INFCIRC/225, an international standard, is adopted by Nuclear Safety and Security Commission in Korea and U.S. Nuclear Regulatory Commission (NRC). It categorizes nuclear material by types and amount (Table 1) with a more focus on U-235.

Table 1. INFCIRC/225/Rev.5 Standard (2011)

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

U.S. Department of Energy (DOE) uses a graded table for categorizing nuclear materials with 4 categories and 5 attractiveness levels based on physical and chemical properties (Table 2).

Table 2. Attractiveness Level of Nuclear Material, DOE

Type	Attractiveness Level
Weapons-grade	A
Pure products	B
High-grade materials	C
Low-grade materials	D
All other materials	E

Charles G. Bathke developed the Figure of Merit (FOM) formula to evaluate attractiveness of nuclear material using 3 factors, eq. (1), (i.e., critical mass, heat content, and radiation dose rate) with the 4th factor (i.e., spontaneous neutron emission) for non-nuclear weapon states, eq. (2).

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

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

2.2 Historical Investigation of U.S. Cases

Regulations have been updated due to catastrophic events and new technology development. After Special Nuclear Material (SNM) was defined in Atomic Energy Act (AEA) of 1954 and published 10 CFR 70 in 1956, Munich Massacre in 1972 brought extensive revision of 10 CFR 70, developing SNM formula for category I. In 1979, NRC, separated with DOE in 1973, defined categories II and III based on INFCIRC/225 of 1972. This revision was influenced by concerns on proliferation from the 1974 India's nuclear test and decisions not to pursue commercial reprocessing.

After the end of the Cold War, commercial reprocessing was reassumed and U.S. started construction of MOX facilities for nuclear disarmament. Legally, MOX facilities are owned by DOE and NRC regulates them. In 2009, NRC made generic exemption from Category I for MOX fuel with Pu diluted to less than 20%, to solve DOE's financial problems from high categorization of MOX fuel. At present, NRC is in the process of new rulemaking on the historical, legal and technological basis and considers 3 attractiveness levels as well as categorization, similar to DOE approach.

Main driving force for rulemaking is RIPB approach. SECY-98-144 white paper defined that it is a combined principle of 'risk-informed' and 'performance-based' elements to make regulatory decisions. Risk-informed approach considers 5 deterministic principles and Performance-based approach considers probabilistic principles which ensure an adequate safety margin and improve safety level without regulatory intervention.

2.3 Categorization for Advanced Fuel Cycle

Nuclear material categorizations for pyroprocessing facilty were evaluated according to INFCIRC/225, NRC new rulemaking, DOE graded safeguards table, and FOM. 7 target processes (i.e., spent fuel, electrolytic reduction (input), electrolytic reduction (output), U recovery (before salt distillation), U ingot, electro-winning (before RAR), and TRU ingot processes) were selected. Plus 7 fuel assemblies with 4.5wt% U-235 were considered. 55000 MWd/MTU for 3 batch cycles (18 months/cycle) with 93% capacity and 10 years cooling time were assumed as total burnup history. To consider the effect of secular equilibrium, additional decays upto 20 years were considered. All methods were applied in a conservative way. MCNPX and OrigenArp codes were used for calculations (Table 3 and 4).

Table 3. Attractiveness Level for Pyroprocessing facility

Target Process	Attractiveness Level			
	NRC (new)	DOE	FOM1	FOM2
Spent Fuel	B	D	E	E
Electrolytic reduction (input)	B	C	E	E
Electrolytic reduction (output)	B	C	E	E
U recovery (before Salt Distillation)	B	C	E	E
U ingot	C	E	E	E
Electro-winning (before RAR)	B	C	E	E
TRU ingot	A	B	C	E

Table 4. Categorization for Pyroprocessing facility

Target Process	Attractiveness Level		
	INFCIRC /225	NRC (new)	DOE
Spent Fuel	II	II	II
Electrolytic reduction (input)	II	II	I
Electrolytic reduction (output)	I	II	I
U recovery (before salt distillation)	I	II	I
U ingot	III	III	IV
Electro-winning (before RAR)	II	II	I1
TRU ingot	I	I	I

3. CONCLUSIONS

It is inappropriate to apply the current methods of nuclear material categorization for advanced fuel cycle because different nuclear materials are mixed in a single process. To properly treat the complex composition of nuclear materials, a RIPB approach, which considers both deterministic (quantitative) and probabilistic (qualitative) principles, is required.

4. ACKNOWLEDGMENTS

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