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Categorization methods of nuclear materials used in advanced nuclear fuel cycles for physical protection systems

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HIGHLIGHTS

- Protection of nuclear materials needs categorization based on characteristics.
- Current categorizations are inconsistent for new types of materials.
- Influencing factors to material categorization methods are identified.
- Nuclear materials in pyroprocessing are tested for the current regulations.

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ABSTRACT

The physical protection of nuclear materials is a significant regulatory requirement to prevent and impede the theft of materials suitable for nuclear explosives. These materials need to be systematically categorized based on their characteristics and risk. The categorization methods are evolving to reflect new issues. One of which is new types of materials from new technologies. We first reviews existing categorization methods for degrees of attractiveness, category levels, discount factor, physical barriers, chemical barriers, isotopic barriers, and radiological barriers. This paper tests the categorization methods for nuclear materials from pyroprocessing which converts spent oxide fuels to metallic forms and separates transuranic elements from fission products. TRU ingots from pyroprocessing are classified into Category I by all methods. However, several inconsistencies of categorization methods were found. The attractiveness level of TRU ingots can be differently interpreted as two different levels for some methods. For some materials, the application of radiological barriers results in different categories. Some approaches adopt multiple levels of radiological barriers for different capabilities of terrorists. Many methods evaluate materials as the current forms without considering the difficulty of separation, but a few methods consider chemical separation. Some methods exempt U ingots, but the others do not.

1. Introduction

Nuclear materials might be used for malicious, criminal, or terrorist actions if they fall into the wrong hands. The threat of nuclear terrorism is real. Terrorists have reportedly attempted to secure nuclear materials (Allison, 2010; Jaspal, 2012), and some of these attempts have involved kilogram quantities. Aum Shinrikyo, in the early 1990s, sought to purchase U and develop enrichment technology (Nehorayoff et al., 2016). Al Qaeda also tried to purchase nuclear materials (Albright, 2002). North Caucasus terrorists attempted to steal nuclear weapons (Saradzhyan, 2006). In 2016, ISIS was reportedly seeking to steal nuclear materials from Belgian nuclear facilities (Johnston, 2016). They could possibly design and make a crude nuclear explosive device (NED) if they secured the nuclear materials.

The physical protection of nuclear materials is necessary to ensure that nuclear energy systems impede the theft of materials suitable for NED and radiation dispersal devices (RDD), as well as the sabotage of facilities by terrorists. To limit the misuse of high-risk nuclear materials, this physical protection requires the systematic and reliable categorization of nuclear materials. The levels and approaches of physical protection during production, storage, and transportation differ based on the characteristics, both quantity and quality, of the nuclear materials.

National regulatory bodies in both nuclear weapon states (NWS) and non-nuclear weapon states (NNWS) are responsible for adopting these categorization methods for physical protection. In addition, international organizations and conventions suggest potential guidelines for member states (IAEA, 2016). Some

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researchers have suggested different approaches for categorizing nuclear materials including the figure of merit (FOM) of Bathke et al. (2008) at Los Alamos National Laboratory (LANL); the risk-informed and graded approaches of Bunn (2007, 2014) at Harvard University; ATTR (i.e., attractiveness) of Saito (2008) at Tokyo Institute of Technology (TIT); multi-attribute utility analysis of Charlton et al. (2007) at Texas A&M University; and the categorization of reactor-grade Pu of Pellaud (2002), Mark (1993), and Kessler et al. (2008). The categorization methods are still evolving to reflect new issues. In particular, the development of new fuel cycle technology can produce new types of nuclear materials (NRC, 2015).

We test the current categorization methods for new types of materials from pyroprocessing which converts oxide spent nuclear fuels to metallic forms and separates transuranic elements (TRU) from fission products. We first review and compare the current categorization of nuclear materials for physical protection. Comparative analysis reveals the varying effects of different factors that influence the categorization. The factors include degrees of attractiveness, category levels, discount factors, physical barriers, chemical barriers, isotopic barriers, and radiological barriers.

2. Current regulations and suggestions for nuclear material categorization

2.1. CPPNM principles

The Convention on the Physical Protection of Nuclear Material (CPPNM) is the only legally binding convention on the international physical protection of nuclear material. It also promotes cooperation among member states against nuclear theft, smuggling, and radiological sabotage. In 2005, the convention was amended to strengthen its provisions for the first time since it was signed in 1980. The amendment to the CPPNM entered into force on May 8, 2016 (IAEA, 2016).

In implementing the obligations, each state party shall accept the following "Fundamental Principles of Physical Protection of Nuclear Material and Nuclear Facilities" (Table 1) (IAEA, 2016). Fundamental principles H, I, and J (graded approach, defense in depth, and quality assurance) are guidelines of national regulatory bodies for categorizing nuclear materials (DOE, 2013; NRC, 2015).

2.2. INFCIRC/225 categorization

INFCIRC/225 is an international standard for the physical protection of nuclear material or facilities against theft and sabotage (IAEA, 2011). It has been adopted by many national regulatory bodies including the U.S. Nuclear Regulatory Commission (NRC) and Korea's Nuclear Safety and Security Commission (NSSC). The CPPNM also acknowledges the latest revision of INFCIRC/225.

Table 1
CPPNM fundamental principles (IAEA, 2016).

Fundamental principle A	Responsibility of the state
Fundamental principle B	Responsibilities during international transport
Fundamental principle C	Legislative and regulatory framework
Fundamental principle D	Competent authority
Fundamental principle E	Responsibility of the license holders
Fundamental principle F	Security culture
Fundamental principle G	Threat
Fundamental principle H	Graded approach
Fundamental principle I	Defense in depth
Fundamental principle J	Quality assurance
Fundamental principle K	Contingency plans
Fundamental principle L	Confidentiality

Currently, INFCIRC/225 characterizes nuclear materials by the amount of materials present, including Pu, U-235, and U-233. Table 2 shows how they are classified into three categories. The amount of nuclear materials for each isotope is related to their potential risk in constructing NEDs. For Pu and U-233, the threshold amounts for Category I are set at a quarter of the significant quantity (SQ) (IAEA, 2002, 2011). In the case of U-235 enriched to 20% or more, the threshold amount for Category I is one fifth of the SQ. Note that natural and depleted U are exempt from the regulation.

Considering radiological barriers besides isotopic composition, nuclear material with an unshielded radiation dose rate above 100 rad/h at 1 m is considered as irradiated, and its category could be reduced by one level. The reduction of the category in light of the radiation dose rate is optional rather than essential. Physical protection for facilities are decided by the categories of nuclear material they contain. Category I requires physical protection against Design Basis Threat (DBT), while Category II and III do not. Category III requires no armed response force (IAEA, 2011).

2.3. U.S. NRC categorization

The U.S. NRC currently uses the method of INFCIRC/225 for the categorization of nuclear materials. By this method, Category I nuclear material is defined as strategic special nuclear material (SNM) in 10 CFR Part 74. An important exemption from the categorization table is diluted Pu. Facilities using mixed oxide (MOX) fuel assemblies are not required to apply Category I, until they contain up to 20 wt% PuO_2.

The NRC is in the process of making new rules in order to consider a risk-informed and graded approach for future nuclear fuel cycles, including the use of MOX fuel. An initial suggestion in the NRC report considered not only the quantity of materials but their quality, including chemical composition, physical form, isotopic content, concentration, and level of irradiation (NRC, 2015; Vietti-Cook, 2009). Because this suggestion is inconsistent with INFCIRC/225, a modified method was proposed, shown in Tables 3 and 4 (Harris, 2014). This new proposal, which will be referred to in this paper as "U.S. NRC (proposed)", considers the dilution of nuclear materials, causing concerns about degradation of regulation, if the nuclear material is sufficiently diluted.

2.4. U.S. DOE categorization

The U.S. Department of Energy (DOE) uses the graded approach for categorizing nuclear materials, called a graded safeguards table (GST). This table is only valid for DOE facilities and it is not applicable to civilian facilities in NNWSs. It classifies nuclear materials by both quantitative (i.e., category) and qualitative (i.e., attractiveness) methods, as shown in Tables 5 and 6. Each attractiveness level shows how much attractive a nuclear material is to terrorists for theft. In addition to Table 5, the concentration of nuclear material shall be considered in the DOE's decision tree that determines the attractiveness level B through E (DOE, 2013). For example, nuclear material with a concentration <10 wt% and >1 wt% is considered level D.

Effective factors are assigned to arrange compound materials with different attractiveness levels (B and C) into a single level. For example, the limit of Pu-containing materials in level C is three times larger than that of materials in level B because the Pu/U-233 factor of level B is one third of that in level C. Once the attractiveness level is decided, the DOE classifies nuclear materials into Categories I–IV (DOE, 2013). Each category indicates different potential consequences and requires a certain level of physical protection (DOE, 2016).