Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

A Preliminary Study on Applicability of the High Reliability Safeguards Approach to the Nuclides Management Process Reducing Environmental Burden

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1. Introduction

As the use of nuclear energy has been expanded, and nuclear fuel cycle technologies become diverse, nuclear proliferation issues increase. In order to enhance safeguardability of a developed technology or a facility, an advanced safeguards approach is required.

Since a traditional safeguards technology is based on mass balance, it takes time and cost in conducting a procedure of nuclear material accountancy, which requires sampling and destructive assay. This approach may not be appropriate for the new facility depending on its feature.

The safeguards approach needs to consider a feature of the facility. Depending on the feature, it may require inspector's visits frequently, which increase safeguarding cost. Moreover, this could severely disrupt process robustness or operation efficiency by requiring process shut-down or breaking operational environment. To reduce safeguards costs and enhance the integrity of the process operation, an appropriate safeguards approach is needed by reducing demanding procedures.

As an option for managing used fuels, nuclides management process (NMP), a novel technology, is under development to reduce environmental burden. It can decrease radiotoxicity and volume of high level waste (HLW) by separating used fuel components (nuclides) to a few groups according to their features in disposal. A high-reliability safeguards (HRS) approach is suggested to improve safeguardability of advanced nuclear fuel cycles, such as pyroprocessing.

In this study, we investigate applicability of HRS approach to NMP by focusing on features of NMP. As conclusion remarks, the applicability and a direction of future research are suggested.

2. Nuclides management process

To manage used fuels, several technologies have been developed as back-end fuel cycle options.

For the purpose of reusing used fuels, hydrometallurgy-based technologies, such as PUREX have been used. However, since these technologies have inherent proliferation issues, resulted from pure plutonium separation, the use of the technologies are very limited. To enhance proliferation resistance of a recycling technology, pyroprocessing has been developed as an alternative technology. Pyroprocessing is an electrochemical process using electricity as a driving force to separate elements.

Another type of technology is also under development not for reusing fissile and fissionable materials but for reducing the volume of HLW. NMP separates elements consisting a used fuel as two or three groups according to features of nuclides as follows:

1) A group containing highly mobile nuclides (ex. iodine, krypton),
2) A group containing high thermal emission nuclides (ex. strontium, barium), and
3) Uranium (optional).

The third group (uranium) separation is optional and it requires further processes after separating group 1 and 2 [1].

While pyroprocessing separates elements using differences in electrochemical properties, NMP utilizes differences in physical properties (vapor pressure, density) and chemical reactivity of chemical compounds such as metal chloride (MCl_x) and metal oxide (M_xO_y).

NMP consists of a few steps as follows:

- Step 1. Pretreatment:
  - A used fuel is mechanically disassembled through chopping and decladding processes and prepared as feed material.
- Step 2. Thermal treatment:
  - Highly mobile nuclides are released as off-gas due to differences in boiling points. Nobel gas, and chemicals having low boiling points are captured and stored for disposal.
- Step 3. Oxide-chloride conversion:
  - High thermal emission nuclides existing as metal oxides are converted to metal chlorides according to differences in each reactivity by a chlorinating reagent.
- Step 4. Oxide-chloride separation:
  - Metal oxides and metal chlorides are separated due to differences in boiling points. The separated metal chlorides are converted to metal oxides. Both the converted and the separated metal oxides are fabricated as blocks for disposal by sintering.

To separate uranium, Step 3 and 4 are repeated using the separated metal oxide from Step 4. In the process, transuranics and rare earth elements are converted to metal chlorides and separated from the metal oxides (uranium oxide). This further processes can reduce more than 90% volume of HLW since uranium oxide, the most part of a used fuel, is classified as intermediate level waste according to its heat generating rate and radioactivity.

Currently, the overall concept of NMP is proposed and each unit process is tested by lab-scale experiments. Detail process designs would be flexibly changed to improve efficiency and optimize the process.

3. High-reliability safeguards approach

As an effort to compensate the traditional safeguards methods for a novel fuel cycle technology, several advanced safeguards approaches have been developed. The HRS approach is a method satisfying the concept of safeguards by design (SBD), recommended by the international energy agency (IAEA). The HRS approach aims to achieve safeguardability of a facility by integrating safety, security, and safeguards [2]. It consists of proliferation resistance, physical protection, security, and safety. The proliferation resistance takes account of both intrinsic measures and extrinsic controls as equally important factors. While the extrinsic controls need international regulations such as Comprehensive Safeguards Agreement (CSA), the intrinsic measure requires comprehensive engineering design.

Borrelli et al. suggest the HRS approach and provide its application method by using a pyroprocessing facility as a study case [2-3]. There are two elements in applying HRS to a facility. One is functional components to facility design and the other is risk-informed approaches to assess safeguardability. The functional components are a design-perspective strategy. It provides various considerations to restrict diversion pathways. Extended containment and surveillance is used as a major method and other components are designed according to the facility's features. The risk-informed approach is analogous to a reactor safety assessment method. Due to a lack of available data, this approach has a limitation in quantitative research. However, a modeling-based research has been conducted [4] and its result is expected to be used in a conceptual facility design for assessing safeguardability.

The research team suggests that the HRS approach is applicable to other types of fuel cycle facilities.

4. Applicability of HRS approach to NMP

As introduced, U separation is optional in NMP. If the U separation process is included in NMP, the increased number of unit processes reduces inherent safeguardsability of the process since complicity of the process increases. In addition, self-protection of waste (uranium) is weaken due to decreased radiological toxicity. However, if NMP do not have the U separation process, the main purpose of NMP, to reduce environmental burden by decreasing the volume of HLW, is hardly achievable. Therefore, this study assumes NMP includes the U separation process.

In the HRS approach, the intrinsic features of safeguardability take account of process properties. Accordingly, it is necessary to understand each unit process and the overall facility.

NMP and pyroprocessing have common features. Both processes need to be conducted in hot cells, requiring remote-control, due to the harsh operational environment, resulted from high operating temperature and highly radioactive process materials. Also both use a series of batch-type reactors (unit processes).

On the other hand, there are clear differences. NMP separates elements by using physical and chemical differences without a use of electrochemical force (ex. electric potential and current). Since the U separation process is a key unit process in the safeguards perspective, the differences of NMP and pyroprocessing in U separation are compared on Table I.

Table I: Comparison of nuclides management process (NMP) and pyroprocessing in U separation process

	NMP	Pyroprocessing (electrode refining)
U separation principle	Difference in vapor pressure (boiling point)	Difference in standard reduction potential
U separation method	Gas-solid phase separation	Electrolysis (electrode deposition)
Process material state	Metal chloride (gas: other elements) vs. Metal oxide (solid: uranium oxide)	Metal ion (M^{x+}) vs. Metal (M)
Driving force	Temperature and pressure	Electrode potential and current density
Power source	Electric power (power for reactor operation)	Electric power (power for reactor operation), and electric current or potential (applied to the electrochemical cell)
Media	(none)	Molten salt
Atmosphere	(no need to control)	Inert (no oxygen and humidity)
Pretreatment (previous process)	Chlorination (to convert metal oxide to metal chloride using a chlorination agent)	Electro-reduction (to convert metal oxide to metal using a reducing agent and electricity)

Using a distinguished process area (a hot cell) has a benefit in terms of physical protection due to the limited number of accessible doors. This common feature would allow NMP to have a similar design with the one for pyroprocessing, suggested by Borrelli et al.[2-4]. However, it is necessary to consider the discrepancy in required atmosphere of the hot cell. This approach, comparing commonality and discrepancy, will provide information regarding functional components to facility design, the first factor in the intrinsic features. While the second factor, risk-informed approaches to assess safeguardability, needs process data, which is expected to be collected through on-going and further research.

There is an additional element to be considered for SBD. As a compensatory safeguards technology, process monitoring (PM) approach and technologies have been suggested [5]. PM tracks a flow of process materials, without direct interaction with a process, which may occur interruption in the process. PM is specially expected to be useful in a commercial-scale of pyroprocessing.

As NMP utilizes inherent properties of process materials (physical and chemical), there are available/detectable signals for monitoring such as pressure and temperature of reactor vessels, flow of off-gas (ex. velocity, radiation). A well-defined relation between signals and process materials can provide useful information in a facility design for SBD.

5. Conclusion remarks

As nuclear fuel cycle technologies are diverse, advanced safeguards approaches are required to improve proliferation resistance of the facility and to maintain robustness of the facility. This goal can be achievable by considering features of the facility and reflecting them in an initial facility design stage. This allows to conduct a concept of SBD, recommended by IAEA. The HRS approach has been suggested as a method to satisfy the needs by using a pyroprocessing facility as an example.

In this study, the applicability of the HRS approach to NMP is discussed. NMP is a novel technology for managing used fuels. It has commonality with pyroprocessing and also discrepancy. Since NMP is under development, the process design is flexible. By considering the features of NMP comprehensively, further research will be conducted to develop an appropriate safeguards approach.

ACKNOWLEDGEMENT

This work was partly supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (NRF-2021M2E3A3040093).

REFERENCES

[1] J.M. Hur, H.O. Nam, C.H. Lee, and Y.Z. Cho, “Analysis on Options of Nuclides Management Process”, Technical report, 2021(KAERI/TR-8743/2021)

[2] R. A. Borrelli, J.H. Ahn, and Y.S. Hwang, “Approaches to a Practical Systems Assessment for Safeguardability of Advanced Nuclear Fuel Cycles”, Nuclear Technology, 197(3), pp. 248-264, 2017.

[3] R. A. Borrelli, "The High-Reliability Safeguards Approach for Safeguardability of Remotely Handled Nuclear Facilities: 2. A Risk-Informed Approach for Safeguardability", Journal of Nuclear Material Management, 42(3), pp. 27-39, 2014.

[4] J. Lee, M. Tolman, R.A. Borrelli, “High Reliability Safeguards approach to remotely handled nuclear processing facilities: Use of discrete event simulation for material throughput in fuel fabrication”, Nuclear Engineering and Design, 324, pp. 54–66, 2017.

[5] Y.E Jung, S.K. Ahn. M.S. Yim, "Investigation of neural network-based cathode potential monitoring to support nuclear safeguards of electrorefining in pyroprocessing", Nuclear Engineering and Technology, 54, pp. 644-652, 2022.