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Proliferation Resistance and Safeguardability Assessment of a SFR Metal Fuel Manufacturing Facility (SFMF) using the INPRO Methodology

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1. Introduction

With the objective of making the assessment of proliferation resistance (PR) of a nuclear energy system easy to understand and perform, an INPRO collaborative project called "Proliferation Resistance and Safeguardability Assessment Tools (PROSA)" was carried out since 2010. PROSA proposes a revised methodology that has been reconfigured as a linear process evaluating the NES against the "Basic Principle" in the area of proliferation resistance. To illustrate the proposed PROSA process, to demonstrate its usefulness, and to provide input to a revision of the INPRO manual in the area of proliferation resistance, a case study has been carried out with a conceptually designed sodium-cooled fast reactor (SFR) metal fuel manufacturing facility (SFMF), representing novel technology still in the conceptual design phase. A coarse acquisition path analysis has been carried out of the SFMF to demonstrate the assessment process with identified different target materials. The case study demonstrates the usefulness of the proposed PROSA PR assessment process and the interrelationship of the PR assessment with the safeguards-by-design process, identifying potential R&D needs.

2. PROSA Process

PROSA is a revised INPRO methodology that has been reconfigured as a linear process evaluating the NES against the Basic Principle that whether the NES is/is not in agreement with the basic principle (BP) in the area of proliferation resistance, as shown in Table 1.

Table 1: PROSA Process

Step	Activities
Step 1	Collection of information on the NES to support PR assessment, such as facilities, nuclear technologies, material quantity, material quality including information in line with the design information questionnaire, obligations on the nuclear material inventories, timeliness goal and frequency of IAEA inspection as a function of nuclear material and technology, and on State's commitments, legal obligations and institutional arrangements.
Step 2	Assessment of UR1 at the State level, based on State's commitment to international non-proliferation regime, legal obligations and institutional arrangements.
Step 3	Identification of plausible diversion paths, diversion and concealment strategies, and assessment of UR3 on the safeguardability of the NES and each facility.
Step 4	Assessment of UR4 of the coverage of each plausible diversion path on the facility/NES and country level by multiple PR intrinsic features and extrinsic measures.
Step 5	Identification of PR strengths, weaknesses/gaps including recommendations for potential R&D needs, resulting from the PR assessment.

The PROSA process which has three simplified User Requirements (UR), along with relevant Criteria (CR), Indicators (IN), Evaluation Parameters (EP), and Acceptance Limits (AL) has been tested to demonstrate its usefulness using the Korean sodium-cooled fast reactor metal fuel fabrication facility (SFMF), representing novel technology that is still in the conceptual design phase.

3. Design Information of the SFMF

The SFMF is a part of the conceptually designed Korean, Innovative, Environment-friendly, and Proliferation Resistant System for the 21st Century (KIEP-21). The SFMF has been defined to consist of the fuel rod fabrication module and fuel assembly module, but exclude the pyroprocessing module for simplicity. The feed material for SFMF is basically U/TRU/RE/Zr ingots produced from spent SFR fuel at the pyro-processing module. The main building with three main modules would include the waste storage, maintenance cells (located above each module), laboratories and utilities, and was designed as a 3-floor building with a basement floor [3]. The metal feedstock is controlled to have a weight composition of 65U-20TRU-5RE-10Zr in the pyroprocessing module before it is transferred to the SFMF, and includes U-TRU-RE-Zr containing process materials recycled from the SFMF (casting heels, fuel slugs end crops, out of specification fuel slugs, etc.). The isotopic composition of the TRU content is commensurate with that of the spent SFR fuel. The design capacity of the SFMF is 38.62 MtHM/yr (1,207 fuel assemblies) of fresh SFR fuel for co-located six SFR units of 1200 MWe each.

The U/TRU/RE/Zr ingot from the pyroprocessing module is induction melted and injection cast into molds, cooled, removed from the mold and sheared to length. The alloy left as a holdup in the crucible is defined as 'heel'. The heel occurs from each batch and recycled to the melter. Residues arising from casting are the oxides generated from melt and molds. Oxide cannot be recycled directly to the melter or caster. They must be converted into metal or dissolved in salt for reuse at the head end pyroprocess module. The casting ends that are sheared off are called the 'scrap', and are also reused as starting materials in the subsequent casting batches. With the injection casting, the casting molds present the most problems. The quartz molds have to be treated as contaminated waste because they are destroyed (not reusable) upon removing the cast metal fuel slugs, increasing the fabrication waste stream volume and cost. After slug removal, the glass shards and residual fuel scrap will be separated - larger pieces by physical separating and fines by electromagnetic separating - in order to minimize amounts of actinide elements transferred to waste.

In the casting process several streams of potential transuranic loss can also be identified. For example, americium (Am) is easily vaporized during melting and casting of Am containing alloy because of its high vapor pressure. It was also experimentally confirmed that about 40% of initially charged Am could be evaporated during melting and casting process [4]. However, the vaporized Am should be solidified at the cold part and recovered to the feed stock unit so that any Am will not be released to environment or waste stream. It is also possible that a leak takes place due to a defect of connection status of pipe or welding status of equipment during the process, but the leaked melt can be easily recovered and recycled because the melt will be immediately solidified. The layout of the SFR fuel rod fabrication module to be used for a coarse acquisition path analysis, including technical specification of equipment and operational conditions of the SFMF, is described in reference 3.

Safeguards by design (SBD) is defined as an approach whereby international safeguards requirements and objectives are fully integrated into the design process of a nuclear facility, from initial planning through design, construction, operation, and decommissioning [5]. In this regard, the process cells are designed to minimize the number of ways that materials can be transferred, process equipment is designed in a modular approach to maximize the simplicity of transfer process between process cell and maintenance cell, as well as to simplify the monitoring of the transfer processes. Maintenance cells are located on the second floor directly above the first floor plot plan which would allow maintenance and refurbishment to be done off-line. The product and waste storage area is located in the basement below the first floor plan. This arrangement would also allow a high modularity and flexibility to the remote handling equipment in the process cells with specifically limited functions. A key issue with separating process and maintenance operations will be the need to reliably remove transuranics-bearing material from equipment modules (except for residual contamination) before they are transferred out of a process cell.

4. Nuclear Material Control and Accountability (NMCA)

The values of plutonium in the metallic U/TRU/RE ingots from the pyroprocessing module would be verified using chemical analysis and by weighing the ingots done by the shipper, as well as non-destructive assay (NDA) at the SFMF by the receiver. This constitutes the plutonium input into the facility. The NMCA system monitors and records all movements within the process by container identification (ID), batch ID, weights, and locations in real time. Nuclear material data are carried forward by the accounting system with the materials in process. The amount of materials out of the product stream, like wastes, will be determined by NDA.

Once the SFR fuel assemblies are fabricated each assembly is verified again using NDA for determination of the active fuel length and weight at the end of the process. Together with the TRU bearing waste materials, this constitutes the facility plutonium "output". The majority of the NDA systems used for verifying plutonium content of TRU materials use neutron and neutron coincidence counting together with high resolution gamma spectroscopy. Gamma spectroscopy is used to determine the presence and relative portion of isotopes of Pu, U, Am, etc., while the coincidence neutron counters are used to determine the effective mass of Pu-240 present in the material assayed. PNAR (Passive Neutron Albedo Reactivity) and ACPF (Advanced spent fuel Conditioning Process Facility) Safeguards Neutron Coincidence Counter (ASNC) with 2-5% measurement uncertainty, under development at KAERI, will be the two main instruments to account for plutonium contents of the fuel material in the process. A preliminary conceptual design of the material balance area (MBA) and key measuring points (KMPs) of the SFMF is shown in Fig. 1.

The MBA for the SFMF is defined to cover the whole SFR fuel rod fabrication module and fuel assembly module. The number of entrance and exit portals into the facility will be minimized in order to simplify the verification that all material additions and removals are consistent with declarations. These transfer ports will require systematic monitoring to ensure no material is diverted at these points in the system. The most important details with respect to safeguards for the fuel manufacturing process are the primary material flow and inventory, the waste streams, and hold up and residual materials that can be released as fines. It is therefore important to have safeguards instrumentation that can assay the residual transuranic material remaining in an equipment module to verify that it is completely removed or it is consistent with declared value. Although most parts generated as waste are not released to waste form fabrication process and recycled to process units, significant amounts of used crucible, breached molds and dross are supposed to be disposed of for waste form fabrication without further recovering TRU. All these materials will be measured using NDA to the extent possible and monitored by NRTA system.

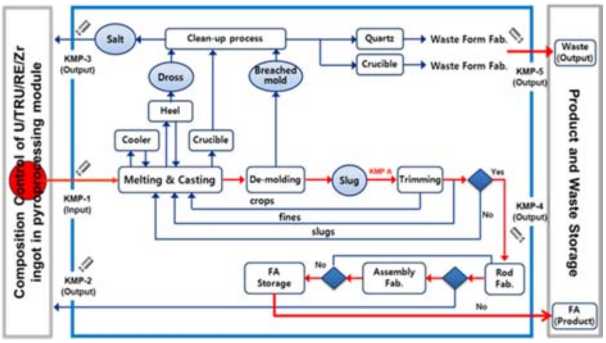

Fig. 1. Metal fuel fabrication flow diagram

Safeguards implementation is in general based on the accountancy system of the operator. Whether for safeguards purpose data from process control will be shared with the IAEA or whether NMCA systems are to be duplicated has to be subject to further analysis and agreement with the IAEA in the course of the safeguards-by-design (SBD) process. Basic principles of NMCA and safeguards implementation will be:

- Facility is designed for remote operation, no human access to process areas except for maintenance due to safety issues (inert gas and high temperatures)
- All SFR fuel materials to be measured and monitored in process,
- Extensive use of unattended weighing and NDA and surveillance systems to verify 100% of the SFR fuel material flows in the process,
- More extensive use of video surveillance to monitor and maintain the continuity of knowledge of SFR fuel materials (amounts and locations), including scrap recovery and product/waste storage areas,
- All NMCA/safeguards systems to accommodate automated facility operation, i.e. no necessity for the operator to shut down the process to accommodate the activities performed for interim verification,
- Additional equipment for each NDA instrument such as video cameras to confirm ID numbers of the object, or independent load cells to confirm the gross weight of the container being assayed,
- All unattended NDA and surveillance systems to be amenable to "remote monitoring."

5. Self-assessment on the Proliferation Resistance and Safeguardability

① Step 1 – Collection of NES information to support PR assessment

- Material Quantity in the SFMF (Capacity: 38.62 Mt HM/yr), information on maximum inventory for each location, main interim storage positions for fuel rod fabrication, and main interim storage positions for fuel assembly module
- Material Quality in the SFMF : feed, intermediate products, final product (Metal Fuel: 65wt% U/20wt% TRU/5wt% RE/10wt% Zr), TRU composition commensurate with that of the spent SFR fuel, Plutonium Fissile (Pu239+Pu241) Isotopic Ratio = 51.05%
- Waste Production : breached quartz from the molds: 10.4 tons/yr with 3.9 kg TRU/yr

② Step 2 – Assessment of UR1 at the State level.

UR1 is assessed using an evaluation questionnaire proposed by PROSA. The host State is assumed to be a party to the Nuclear Nonproliferation Treaty with a Comprehensive Safeguards Agreement (CSA) with the IAEA, and an Additional Protocol to the CSA in force. The host State is also a contracting party to the nuclear export control regime such as Nuclear Suppliers Group, Zangger Committee, and Wassenaar Arrangement. It has several bilateral nuclear cooperation agreements in effect and commercial arrangements with several nuclear supplier countries for imported U ore, conversion and enrichment services. All nuclear materials except minor materials extracted from mineral residues from fertilizer plants and sea water are assumed to be "US obligated".

The self-assessment of UR1 results in the conclusion that the host State's legal commitments, obligations and policies on non-proliferation and its implementation are adequate to fulfil international requirements and good practice to provide a basis for credible assurance of the exclusive peaceful use of the NES, including a legal basis for verification activities implemented by the IAEA.

③ Step 3 – Assessment of UR3 on "Safeguardability"

Potential target materials in the SFMF would be fuel slugs in the fuel slug temporary storage, TRU ingots in a crucible, scrap from the heel/scrap storage, fuel rods in a fuel assembly, etc. Misuse of the facility is not considered because discrete separation of TRU or un-irradiated Pu inside SFMF is not possible. For the assessment of UR3, an exemplified coarse diversion scenario has been developed for each target material with plausible concealment strategies. In some cases target material is replaced with dummy material in order to fake the accountancy report.

Exemplary evaluation results are obtained based on the subsequent screening evaluation questionnaires and findings for Evaluation Parameters from EP3.1.1 to EP3.1.4 and EP3.2.1 and EP3.2.2 [2] for the first exemplified diversion scenario: Diversion of fuel slugs from the fuel slug temporary storage {17} and loading of fuel slugs into a waste container - Removal of fuel slugs in waste container(s) via the waste airlock {34} into the lower waste storage - Removal from the facility; Replacement of diverted fuel slugs in {17} by fuel slug dummies brought in from the upper maintenance floor (ca. 60 fuel slugs are needed for 1 SQ). The number in parenthesis {} denotes the equipment in Reference 3.

④ Step 4 - Assessment of UR4 on “Multiplicity”

Exemplary evaluation results were obtained for the assumed diversion pathways with regard to its coverage by multiple PR features and measures.

In summary it could be shown that all diversion paths of the exemplified coarse diversion scenario can be covered by multiple intrinsic features, which are compatible with other design requirements, and by extrinsic measures on the facility or State level that reduce the attractiveness of an acquisition path for diversion and misuse, and that intrinsic features and extrinsic measures are not in conflict with each other.

⑤ Step 5 – Analysis of Strengths, Weaknesses and Gaps.

The primary value of the assessment is not the top level conclusion, but rather, to gain an appreciation of where gaps exist, at criteria and evaluation parameter level, thereby suggesting directions to pursue to improve long term sustainability of the NES.

o Strengths/Weaknesses/Gaps

The assessment demonstrated that all acceptance limits for “safeguardability”, in principle, can be met although the acceptance limit for the efficiency of the IAEA safeguards can be answered only at the end of the SBD process, including interaction with IAEA operations. However, procedures for destructive assay (DA) for the verification by the IAEA are not defined. Target values for non-destructive assay (NDA) for this type of nuclear material are also not defined. Therefore, there is a need to finish demonstrations of NDA measurements on novel material types and material flows. Nevertheless gross and partial defect will be detectable with the NDA equipment already available.

o Recommendations for improvements / R&D

The acquisition path analysis also shows some concerns that need to be assured in the system design process:

- System design has to assure that the ID No of all storage containers in all storage positions can be read/checked without moving the storage container
- Transfer routes for TRU fuel and heel/scrap (product stream) should be strictly separated from transfer routes for waste, to make the transfer of TRU fuel and heel/scrap into waste containers impossible
- NDA equipment (like ASNC or PNAR) is still to be validated and approved for use by the IAEA
- Safeguards measures and/or surveillance system to make sure that held-up material in the equipment module (i.e., heel) cannot be removed from the process cell without detection by safeguards
- Development of appropriate waste form for graphite
- Discrimination capabilities between waste containers loaded with waste or with TRU fuel and heel/scrap is still to be determined.

6. Conclusions

The PROSA process has been applied to a conceptually designed SFMF, representing novel technology that is still in the conceptual design phase at KAERI. The case study demonstrated that the proposed PROSA process is simpler and easier to perform than the original INPRO methodology and can be applied from the early stage of design showing the relationship of PR assessment to the safeguard-by-design process.

New evaluation questionnaire for UR1 is more logical and comprehensive, and provides the legal basis enabling the IAEA to achieve its safeguards objectives including the detection of undeclared nuclear materials and activities. NES information catalogue replacing UR2 was a useful modification and supports safeguardability assessment at the NES and facility level. Coarse diversion path analysis for the SFMF and safeguardability assessment as proposed by PROSA with UR3, although not complete, showed that assessment could provide reasonable insights regarding safeguardability, and demonstrated the availability of safeguards tools and measures required for the implementation of effective and efficient safeguards, including the coverage of the nuclear energy system by multiple intrinsic features and extrinsic measures. The proposed PROSA process is also capable to identify strengths and weaknesses of a system in the area of proliferation resistance in a generally understandable form, including R&D gaps that need to be filled in order to meet the criteria for proliferation resistance of a nuclear energy system.

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