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Review of GIF PR&PP Evaluation Case Study for Application to Pyroprocessing

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1. Introduction

The Generation IV International Forum (GIF) emphasizes proliferation resistance and physical protection (PR&PP) as one of the main aspects to be considered regarding future nuclear energy systems (NESs). As such, the PR&PP Working Group developed an evaluation methodology [1] and applied it to the Example Sodium Fast Reactor (ESFR) as a case study [2]. This paper has summarized and reviewed the ESFR case study, as it relates to the application of the evaluation methods to pyroprocessing facilities as well as the sodium fast reactor fuel cycle in the future as a self-assessment study. The GIF PR&PP evaluation methodology and the case study both addressed physical protection, but this paper focuses only on proliferation resistance. It does not consider physical protection.

2. Case Study and ESFR Description

2.1 ESFR Case Study

The ESFR case study had three objectives. The first was the application exercise of the GIF PR&PP methodology to a complete Generation IV reactor and nuclear fuel cycle system. The second was to demonstrate that the methodology can generate meaningful results for designers and decision makers. Finally, the case study set out to provide examples of PR&PP evaluations for future users of the methodology. Thus, the working group demonstrated the possibility of the PR&PP methodology being applicable to practical cases. Additionally, while developing this methodology, the group came to an international consensus on concepts, an evaluation framework, and a common vocabulary. Fig. 1 shows the framework of the PR&PP methodology.

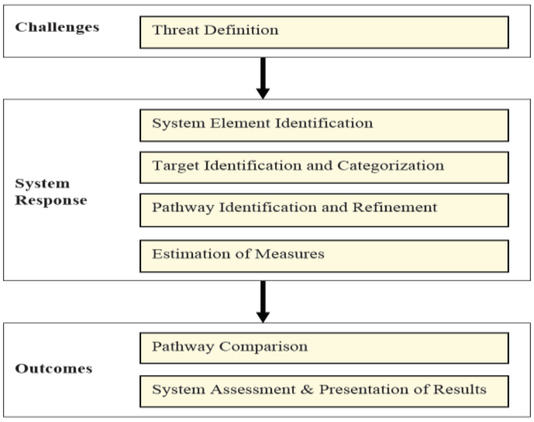

Fig. 1. Framework of PR&PP methodology

In general terms, the methodology involves identifying the challenges a given nuclear fuel cycle faces, examining the system's responses to those challenges, and delineating the outcomes.

2.2 Example Sodium Fast Reactor

The conceptual design of Generation IV NESs and the technology for a nuclear fuel cycle (NFC) had not yet been developed. Therefore, the working group developed a hypothetical ESFR. This concept incorporates the following system elements:

1. Light water reactor (LWR) spent-fuel storage
2. A co-located fuel cycle facility (FCF)
3. ESFR spent-fuel and fresh-fuel storage cells
4. A fuel services building (containing a single fuel assembly staging/washing area and transfer tunnels to each reactor)
5. Four identical SFRs (each having an in-vessel storage basket)
6. Waste storage
7. An LWR spent-fuel cask receiving and parking area
8. Excess uranium storage
9. A uranium container parking area

Fig. 2 shows the ESFR nuclear system, including all of the system elements listed above.

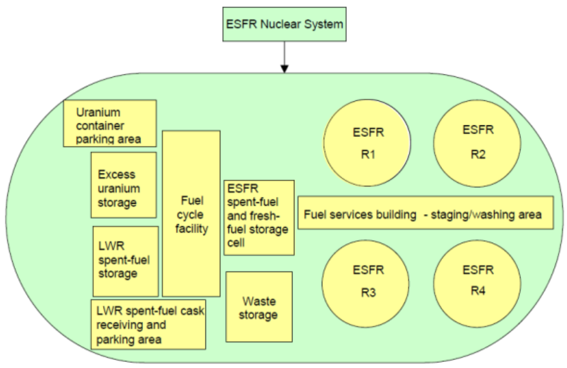

Fig. 2. ESFR nuclear system elements

3. Overview of ESFR Safeguards Approach

Fig. 3 shows the material balance areas (MBAs), the key measurement points (KMPs), and the various measures used to implement safeguards. The FCF in the red circle incorporates a pyroprocessing and metal fuel fabrication process, and so can be used as a reference for future analyses of pyroprocessing. Table I lists the FCF strategic points as they related to a safeguards approach.

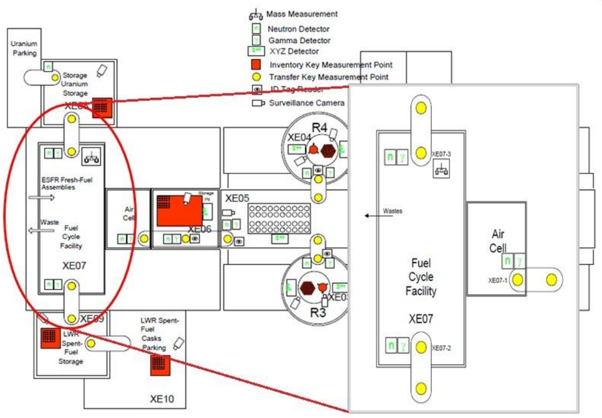

Fig. 3. Overview of ESFR safeguards approach

4. Representative Pathway and Analysis

The case study threat space was divided into four major categories:

1. Concealed diversion of material
2. Concealed misuse of the facility
3. Breakout and overt diversion or misuse
4. Theft of weapons-usable material or sabotage of facility system elements

This study focuses on reviewing the concealed diversion and misuse threat only, and the details are summarized below.

4.1 Concealed Diversion

The diversion analysis in the case study proceeded along the following steps:

1. Examine every potential target
2. Characterize the target material
3. Identify the possible physical mechanisms that could be used to remove the material
4. Identify the physical and design barriers to removal
5. Identify the safeguards instruments and approaches that detect each physical mechanism that could be used to remove the material
6. Hypothesize means of defeating implemented safeguards
7. Lay out qualitative pathways for the removing each target
8. Perform a coarse qualitative estimation of the PR measures applied to each diversion pathway

Table I: Strategic points and safeguards measures at FCF (from Ref [1])

Strategic point label	Description	Scope	Actions taken	Technique adopted
XE07-1	Located at the transfer tunnel connecting the storage pit to the fuel cycle facility	a) To track ESFR fuel element movements b) To discriminate (dummy, fresh, or irradiated) and perform attribute verification on fuel elements in transit	a) Assemblies are counted and their ID tags checked b) NDA techniques are used to identify/perform attribute verification on assemblies	High resolution gamma-ray spectroscopy (HRGS) coupled with passive neutron measurement
XE07-2	Located at the transfer tunnel connecting the SF LWR storage to the fuel cycle facility Physically coincides with XE09-1	a) To track SF LWR fuel element movements b) To perform attribute verification on fuel elements in transit	a) Assemblies are counted and their ID tags checked b) NDA techniques are used to identify/perform attribute verification on assemblies	HRGS coupled with passive neutron measurement
XE07-3	Located at the transfer tunnel connecting the fuel cycle facility to the exceeding recovered U storage Physically coincides with XE08-1	a) To track exceeded U movements b) To characterize the material in transit(enrichment, ...)	a) U mass is measured. U enrichment is measured	Gamma/x/weighing (GXW) may be a viable option A neutron detector is used to detect the illicit diversion of Pu

The target identification in this case study considers the different types of nuclear material in each system element, its location, and its configuration, resulting seven distinct target materials. In the diversion pathway analysis, each target was estimated by applying PR measures to the pathway. Six PR measures were identified in the evaluation methodology. These were proliferation technical difficulty (TD), proliferation cost (PC), proliferation time (PT), fissile material type (MT), detection probability (DP), and detection resource efficiency (DE).

Although the proliferation of nuclear weapons occurs in three stages, which are acquisition, conversion processing, and fabrication, the first and second stages, namely acquisition and processing, were mapped in the evaluation step. The case study involved a qualitative evaluation of 10 different diversion pathways. Table II lists an example evaluation result for the concealed diversion of TRU materials from the FCF (T4-XE-07-1).

Table II: Example evaluation result for one of the pathway to divert TRU via waste container from the FCF

Mea-sures	Value	Evaluation Rationale
TD	Low	[Acquisition Basis] No material accountability on waste once it leaves the facility [Processing Basis] Low concentration of TRU means that processing must be efficient to extract the content. Misuse scenario could have higher concentration.
PC	Low	[Acquisition Basis] Little cost since plans are for waste to be removed to the disposal site [Processing Basis] Hot cell and chemical processing of metal
PT	Medium	[Acquisition Basis] Dependent on the amount of TRU in the waste [Processing Basis] Construction of chemical processing facilities is not difficult under the given availability
DP	Very Low	[Acquisition Basis] Once the waste is removed, no safeguards are applied. Some TRU is expected in the waste. If misuse is involved, more TRU may be put into waste so may be more easily detected [Processing Basis] Detection probability of processing facility not considered
MT	Medium	[Acquisition Basis] TRU is desirable but waste needs to be cleaned up [Processing Basis] Usable for weapons but not optimum
DE	High	[Acquisition Basis] This is part of a multi-reactor facility, which would have extensive safeguards. [Processing Basis] This would be a function of the cost of the international intelligence community and would be difficult to determine.

4.2 Concealed Misuse of the Facility

The misuse analysis in the case study considered a plutonium production scenario which included the irradiation pathway of uranium targets in the ESFR reactor cores. This pathway involves the following steps.

1. Acquire U feed
2. Fabricate U pins
3. Assemble final target assemblies
4. Irradiate U targets in ESFR reactor cores
5. Disassemble target assemblies
6. Separate Pu

For the host state, several assumptions were made to apply the PR&PP methodology. As a result the representative pathway became:

1. Host state acquires natural uranium (or depleted uranium [DU] if available) from an external source.
2. Host state prepares target uranium pins outside the ESFR site.
3. Host state brings target pins to the ESFR site and then into the FCF.
4. Host state assembles ESFR final-target-fresh fuel assemblies, made up of uranium target pins and standard ESFR fresh-fuel pins using the FCF.
5. Host state transfers target assemblies from the FCF to in-vessel storage baskets.
6. Host state loads target assemblies into the outer ring of the four reactors during refueling.
7. Host state irradiates target assemblies for 12 months in the outer ring of the core.
8. Host state unloads target assemblies from reactor cores into in-vessel storage baskets during subsequent refueling process and leaves them there for cooling.
9. Host state transfers target assemblies from in-vessel storage baskets to FCF.
10. Host state disassembles target assemblies and recovers target pins in the FCF, and then transfers target pins from the ESFR FCF to a clandestine facility.
11. Host state separates plutonium at the clandestine facility.

The working group developed questions supporting the measures estimation for each of the pathway segments, and estimated the PR measures for each segment according to the metrics proposed in the methodology. Then PR qualifiers for each segment (either qualitatively or by entering the measures estimates in the corresponding bins proposed in the methodology) were obtained and aggregated over the whole pathway using judgment, rather than a mechanistic aggregation of the segment estimates. A result of misuse analysis had similar form of the result from diversion analysis.

The case study tried to demonstrate if the methodology was able to give useful outcomes for different design (operation) configuration of the system. Two design variations of reactor operation were considered for misuse. The first variation was a burner configuration and the second one was a deep burner configuration. The results of design variation were identical or similar with the result of the baseline design.

5. Discussion of Evaluation Method in Case Study for Application to Pyroprocessing

KAERI is planning to assess high-level PR features for pyroprocessing-SFR system based on the GIF PR&PP evaluation methodology. The main objectives are to identify vulnerable points, recommend possible PR enhancement features, and evaluate their effectiveness. The initially identified diversion targets for the pyroprocessing facility are listed in Table III.

Table III: Target materials of pyroprocessing facility

ID	Target	Target Material Character	Possibility of Misuse
TM1	SF cask	Irradiated U-235, TRU (Pu), oxide Cask = 12 assemblies = 8.4 SQ	No
TM2	SF Assembly	Irradiated U-235, TRU (Pu), oxide assembly = 0.688 SQ	No
TM3	SF Rod	Irradiated U-235, TRU (Pu), oxide assembly = 236 rods 1 SQ = 343 rods	No
TM4	SF chopped Rod	Irradiated U-235, TRU (Pu), oxide 1 SQ = 900-kg-chopped rod	No
TM5	SF Powder	Irradiated U-235, TRU (Pu), oxide	No
TM6	Reduction metal	Irradiated U-235, TRU (Pu), metal	No
TM7	Recycled U/TRU metal	TRU metal (85% Pu)	Yes
TM8	Recycled U metal	Irradiated U-235	Yes (high-purity U)
TM9	UCl_3	U-235 in UCl_3	No
TM10	Salt waste	TRU metal (85% Pu)	Yes (higher TRU concentration)

This study will be followed by the self-assessment of the PR aspects of pyroprocessing based on the procedures described in the previous section, applying several modification based on the reviewing the case study results as below.

In the concealed diversion analysis, each PR measure was evaluated for each of the acquisition and processing stages. Many of the assessment basis of DP and DE for the processing stages were “not meaningful,” “not considered,” or “difficult to determine,” as described in Table II. Because the processing stages assume clandestine facility, which is independent to the system subject to PR evaluation, it is not appropriate (and also not possible) to evaluate most PR measures, except MT measure. MT measure should reflect aspects based on both the acquisition and processing stages. Instead of considering two different stages, segmentation of the acquisition stage and then evaluating PR measures for each segment would make any assessment more meaningful.

The rationale for the TD measures considered the difficulty in overcoming detection by the implemented safeguards, which had already been considered in the DP measures. The evaluation of TD, PC, and PT should therefore focus on those difficulties caused by technical barriers, rather than by the application of the safeguards.

The analysis of the concealed misuse in the case study included several segments in a clandestine facility. The assessment results for a clandestine facility can vary considerably depending on any identified threat (host state). As discussed in the previous paragraph, the assessment of the processing stage in the clandestine facility produces little variance or usefulness for most measures (TD, PT, PC, DT, and DE).

A concealed misuse analysis attempted to develop questions for each measure in each pathway segment. The resulting questions for each segment were not very different, however. It will be worth developing definite questions for the concealed diversion analysis, also, but not for each segment.

No design variation evaluation was performed for the concealed diversion because the working group estimated that there would be no impact due to there being little difference except for the TRU ratio. In evaluation of design variation, the assessment of two different SFR core design variations was demonstrated to determine whether the qualitative application of the methodology to a misuse scenario is capable of identifying small differences. The first design variation was similar to the baseline design. Because the baseline design and this design variation are so similar, the pathway analysis for the baseline design is applicable. Assumptions made for the baseline design still hold, with the exception of the different number of target assemblies needed for producing 1 SQ of plutonium. Although small differences could be pinpointed by the replies to the questions, the final PR qualifiers for all segments were identical to those of the baseline design. The small differences are not important enough to alter the overall PR judgments of the segments. The second variation was a deep burner configuration. This difference implies a substantial variation in the overall fuel cycle strategy, leading to a shorter cycle length and a different fuel composition. The same procedure was used as for the other analyses, and similar replies were produced to the supporting questions for most segments. Due to the binning process, however, the PR judgment for the two pathways was essentially the same.

Through the GIF ESFR case study, it became possible to identify the weaknesses to be addressed:

- The practical use of some measures needs further investigation (it is still unclear how to make the best use of MT and DE).
- The example metrics illustrated in the GIF PR&PP evaluation methodology [2] may need some additional investigation (especially those for PC and DE).

Considering the above weaknesses and findings of the case study, the PR measures and evaluation steps will be modified slightly. It should be noted that this modification will also reflect the purpose of the self-assessment, which is to enhance the PR of pyroprocessing, without comparing it with other fuel cycle technologies. We expect that the results will be shared with and reviewed by GIF expert groups, generating positive feedback to enhance the proliferation-resistant aspect of pyroprocessing technology.

ACKNOWLEDGEMENTS

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