PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION (PR&PP) EVALUATION METHODOLOGY IN SUPPORT OF PR&PP BY DESIGN FOR FAST REACTORS AND ASSOCIATED FUEL CYCLES

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INTRODUCTION: The Generation IV International Forum (GIF) evaluation methodology for proliferation resistance and physical protection (PR&PP) has emerged as a recognized technical platform for supporting PR&PP evaluations of various nuclear energy system (NES) design types. This methodology examines NES response and outcomes to PR&PP threats with the aim of assessing the PR&PP efficacy of the NES. This methodology was developed around a case study of a notional example sodium fast reactor design and has been applied to real fast reactor designs. The paper discusses how the methodology supports PR&PP by design for Generation IV reactor designs, including fast reactors.

1. OVERVIEW: FRAMEWORK OF THE PR&PP EVALUATION METHODOLOGY

The GIF PR&PP evaluation methodology (PRPPEM), formulated by the GIF Proliferation Resistance and Physical Protection Working Group (PRPPWG), provides a means of assessing NESs with respect to PR&PP. The basic framework of the methodology begins by defining a set of challenges, followed by analysing the system response to these challenges, and finally assessing the outcomes. Challenges to NESs include threats from States that are potential proliferators, as well as from sub-national adversaries. The response of each NES will be dependent upon its technical intrinsic features and institutional extrinsic measures. The assessment of the outcomes, expressed in terms of a set of PR&PP measures, sheds light on the resistance of the NES to proliferation threats, as well as robustness against sabotage and nuclear material theft threats [1].

An expanded framework of the GIF PRPPEM is provided in TABLE 1. The first step is the threat definition, which identifies the challenges an NES may face, along with characteristics of both the adversary and the adversary's strategy. This step essentially elaborates on the relevant PR&PP threat space, which is further described in TABLE 2. It should be stressed that this methodology provides evaluation contingent on the challenges occurring, independent of their probabilities. The second step, focused on system response, consists of four components, listed in TABLE 1. The system elements are identified by decomposing the NES into smaller elements or subsystems in a manner convenient for the analysis. The kinds of targets typically identified in the system elements are listed in TABLE 2. Pathways are also identified, which are potential sequences of events and actions followed by the adversary to achieve objectives. The selection of objectives depends upon the chosen scenarios, the extent and quality of relevant design information, as well as preferences of analysts. The results of the system response are expressed in terms of PR&PP measures that characterize high-level features of a pathway that affect decisions and actions of an adversary. These measures are used to evaluate the likely behaviour of the adversary and the associated outcomes. Applicable measures are listed in TABLE 2. More details about the methodology can be found in Ref. [1].

TABLE 1. EXPANDED FRAMEWORK OUTLINE FOR THE PR&PP EVALUATION METHODOLOGY

1. Challenges	Threat Definition
2. System Response	System Element Identification
	Target Identification and Categorization
	Pathway Identification and Refinement
	Estimation of PR&PP Measures
3. Outcomes	Pathway Comparison
	Assessment & Presentation of Results

TABLE 2. PR&PP THREAT SPACE, TARGETS, AND PATHWAY MEASURES

	Proliferation Resistance	**Physical Protection**
Threat Space	• Host State with given capabilities • Acquisition of nuclear weapon(s) • 4 possible strategies (nuclear material (NM) diversion, facility misuse, breakout, and replication of technology in clandestine facilities)	• Sub-National Actor (insider, outsider, mix of both) with given capabilities • Sabotage, theft of NM or information • Various strategies
Targets	• NM to be diverted • Equipment/process to be misused • Equipment/technology to replicate clandestinely	• NM to be protected from theft • Information to be protected from theft • Equipment to be protected from sabotage
PR&PP Measures	• Proliferation Technical Difficulty • Proliferation Cost • Proliferation Time • Fissile Material Type • Detection Probability • Detection Resources Efficiency	• Probability of Adversary Success • Consequence • Physical Protection Resources

2. PR&PP EVALUATION METHODOLOGY APPLIED TO AN EXAMPLE FAST REACTOR

The GIF PRPPWG developed its evaluation methodology with the aid of a sequence of studies, beginning with an initial development study in 2004, followed by a demonstration study in 2005 to 2006. These studies used an Example Sodium Fast Reactor (ESFR), a hypothetical NES consisting of four pool-type sodium-cooled fast reactors (SFRs), co-located with dry fuel storage and a pyrochemical spent-fuel cycle facility (FCF). This type of NES was chosen as SFRs were considered more mature of the six Generation-IV technologies pursued by GIF, with information being available in Refs. [2],[3]. The demonstration study focused on the use of quantitative methods applied to PR aspects of the FCF, with the conclusion that the methodology can be applied to practical cases. This motivated a further 2-year case study applying the methodology to PR&PP aspects of the full ESFR NES, with the aim of showing how NES designers can obtain practical guidance by applying the methodology, and further showing how the PRPPEM can be applied at different levels of design, corresponding to different levels of effort and resources [4].

It has been pointed out [5] that proliferation resistance (PR) studies provide a structured approach to assessing the value of intrinsic features and extrinsic measures to proliferation, including the evaluation of proposed safeguards approaches in such a manner that reveals potential weaknesses and perhaps alternative safeguards approaches that would improve and enhance safeguards effectiveness. This is useful to safeguards authorities and inspectorates who are concerned about the safeguardability of an NES facility, as well as to industrial designers, producers and vendors who are responsible for ensuring that NES facility design conforms to safeguards requirements in a cost-effective manner. Considering safeguards and safeguardability issues in early design stages helps facilitate the achievement of these goals. To this end, PR studies can reveal the benefits of considering design alternatives. The GIF ESFR case study illustrated the consideration of design variations and their effect in a misuse scenario, whereby the methodology was capable of identifying even small differences in measure estimates [4].

Similarly, on the physical protection (PP) side, the GIF ESFR case study also showed how to address strategies for achieving a consistent level of protection for the plant site against local threats, as well as for optimizing the facility design to enhance intrinsic impediments to theft and sabotage, at a reduced cost [4]. As such, the GIF ESFR has illustrated how the GIF methodology supports both PR and PP by design.

There were several noteworthy lessons learned from the GIF ESFR case study [4]. A primary lesson is that the GIF PR&PP methodology allows for systematic treatment of PR and PP threat spaces at all design stages. The qualitative analysis that is part of the methodology offers valuable insights, even at early design stages, when detailed design information is missing or incomplete. In doing so, multi-disciplinary expert elicitation techniques should be utilized to achieve consistency in the analysis, and to provide the required technical expertise on system design and operation [6]. The case study did show that one can readily achieve completeness in identifying targets that would be attractive in PR and PP scenarios, provided that reasonable assumptions are made about the system design and the required safeguards and physical protection approaches. It is less practical, however, to exhaustively identify all possible pathways: while this is possible in principle, in practice one should focus on a subset of representative pathways [4].

3. APPLICATIONS OF THE PR&PP EVALUATION METHODOLOGY

As mentioned in the Introduction section above, the GIF PRPPEM has emerged as a recognized technical platform for supporting PR&PP evaluations of various NES design types. In particular, the methodology has been independently applied in safeguards-by-design studies for some fast reactor designs, such as the MYRRHA reactor [7], a SFR based on the layout of the Japanese Sodium Fast Reactor (JSFR) [8], the European Sodium Fast Reactor [9], and the Molten Salt Fast Reactor (MSFR) [10].

As the designs of other fast reactor designs progress, there is immediate opportunity to apply the GIF PRPPEM as part of safeguards-by-design and proliferation resistance assessments. For instance, Moltex Energy Canada Inc. is proposing in Canada the recycling of spent nuclear fuel followed by the transmutation of actinides in a fast-spectrum waste-burner reactor, in its WAste To Stable Salt (WATSS) recycling facility in association with the Stable Salt Reactor – Wasteburner (SSR-W). In the context of spent nuclear fuel recycling being historically hampered in North America by proliferation concerns, Moltex has carried out a preliminary proliferation resistance assessment of its conceptual design [11] by considering different categories of proliferation resistance relevant intrinsic design features as distinguished in the IAEA's STR-332 document on proliferation resistance fundamentals [12], to make a case that the facility can be suitably placed under safeguards control, alleviating proliferation concerns. The underpinnings of the GIF PRPPEM are closely related to the IAEA's STR-332 proliferation resistance fundamentals; as such, as Moltex continues its safeguards-by-design process, there is real opportunity for relevant parts of the GIF PRPPEM to play a role in this process.

It has also been noted how there are close parallels in GIF goals and methodologies for safety and reliability (S&R) and PR&PP [13]. This presents an opportunity for their integrated consideration in the context of an NES design, to optimize the performance of the NES, and minimize potential conflicts between S&R and PR&PP, while minimizing the cost of implementing the NES. In this regard, work is ongoing in GIF on the systematic consideration of the interfaces of safety, security, and safeguards.

4. CONCLUSION

The paper has discussed the framework of the GIF PRPPEM and its demonstration using a case study of a notional example fast reactor design, as well as in application to real fast reactor designs. As fast reactor designs evolve and new designs come forward, the GIF PRPPEM is a well-known platform for assessing the proliferation resistance and physical protection aspects of the designs.

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