DEVELOPMENT OF A METHODOLOGY TO ASSESS PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION FOR GENERATION IV SYSTEMS

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ABSTRACT

Enhanced proliferation resistance and physical protection (PR&PP) is one of the technology goals for advanced nuclear concepts, such as Generation IV systems. Under the auspices of the Generation IV International Forum, the Office of Nuclear Energy, Science and Technology of the U.S. DOE, the Office of Nonproliferation Policy of the National Nuclear Security Administration, and participating organizations from six other countries are sponsoring an international working group to develop an evaluation methodology for PR&PP. This methodology will permit an objective PR&PP comparison between alternative nuclear systems (e.g., different reactor types or fuel cycles) and support design optimization to enhance robustness against proliferation, theft and sabotage.

The assessment framework consists of identifying the threats to be considered (e.g., proliferators, terrorists), defining the PR&PP measures (indices) required to evaluate the resistance of a nuclear system to proliferation, theft or sabotage, and establishing quantitative methods to evaluate the proposed measures. The defined PR&PP measures are based on the design of the system (e.g., materials, processes, facilities), and institutional measures (e.g., safeguards, access control).

The assessment methodology uses "analysis of pathways" with respect to specific threats to determine the PR&PP measures. Analysis requires definition of the threats (i.e. objective, capability, strategy), decomposition of the system into its relevant elements (e.g., reactor core, fuel recycle facility, fuel storage), and identification of targets. In the case of proliferation, the targets are nuclear material, or equipment that could be used to make nuclear material suitable for use in a nuclear explosive weapon. In the case of physical protection, the targets may be nuclear or radioactive material (theft), or critical equipment (sabotage). Scenarios for successful proliferation, theft or sabotage are identified. The nuclear system is then analysed to determine what resistance it provides to oppose the successful completion of each pathway by the threat, and the results expressed in terms of the PR&PP measures.

The paper summarizes the proposed assessment methodology including the assessment framework, measures used to express the PR&PP characteristics of the system, threat definition, system element and target identification, pathway identification and analysis, and estimation of the measures.

Keywords: Generation IV nuclear energy systems, proliferation resistance, physical protection, evaluation methodologies.

BACKGROUND

A Technology Roadmap[1] for the development of advanced nuclear energy systems, known as Generation IV, was recently completed under the sponsorship of the U.S. Department of Energy's Office of Nuclear Energy, Science, and Technology (DOE-NE) and nine other countries under the Generation IV International Forum (GIF). The Generation IV Roadmap defines the following goal for proliferation resistance and physical protection (PR&PP) for future nuclear energy systems:

> *Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

DOE-NE and the NNSA Office of Nonproliferation Policy (NA-241) have created an Expert Group to develop an assessment methodology for PR&PP. This Expert Group includes U.S. participants from national laboratories (ANL, BNL, INEEL, LANL, LLNL, PNNL, and SNL), academia, international experts from six GIF member countries (Canada, European Union, France, Japan, Republic of Korea, and the United Kingdom), the International Atomic Energy Agency, and observers from the U.S. State Department and the U.S. Nuclear Regulatory Commission.

The work of the Expert Group builds upon the recommendations of two recent activities (1) Guidance provided in the Generation IV Roadmap regarding future system evaluations[2], and (2) NA-241's Guidelines for the Performance of Nonproliferation Assessments[3].

To focus the development of the methodology it has been necessary to define proliferation resistance and physical protection, since there was no uniformity in the way that previous studies had defined these concepts. The definitions adopted by the group are:

> ***Proliferation resistance*** is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by the host State in order to acquire nuclear weapons or other nuclear explosive devices.
>
> ***Physical protection*** is that characteristic of a nuclear energy system that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices, and the sabotage of facilities and transportation, by sub-national entities and other non-host State adversaries.

FRAMEWORK

A methodological approach has been developed for the assessment of Generation IV nuclear energy systems for proliferation resistance and physical protection robustness. The methodology is applicable to the evaluation of nuclear systems from the early development stages throughout the full lifecycle. A main aim is to establish an iterative process in which the PR&PP

performance of the system is included in the evolution of the design. Proliferation resistance and physical protection are achieved through a combination of intrinsic design choices and engineered features together with extrinsic arrangements or requirements (such as safeguards) that govern deployment, operation and verification. Therefore, the consideration of PR&PP from the early design stage can build upon system characteristics that increase their robustness and features that facilitate the implementation of the external controls and safeguards.

The methodology is organized as a progressive evaluation approach that allows evaluations to become more detailed and more representative as system design progresses. The progressive approach maximizes early, useful feedback to designers and evaluators during the viability and performance phases of Generation IV research and development — from the stage of basic process selection, to the detailed layout of equipment and structures, to facility demonstration testing. The scope and complexity of the assessment of the response can be appropriate to the level of detailed design information available and the level of detail with which the threat space can be specified. Very little specific design information exists for systems in early development stages; thus, in-depth scrutiny of the system flows, physical plant layouts, and interdependencies cannot be probed through analytical evaluation. Rather, the methodology itself will help to guide the design evolution through a successive progression of iterations between design development and design evaluation.

The overall methodological approach is illustrated conceptually in Figure 1. For a given system a set of ***challenges*** is defined, the ***response*** of the system to these challenges is assessed and expressed in terms of ***outcomes***.

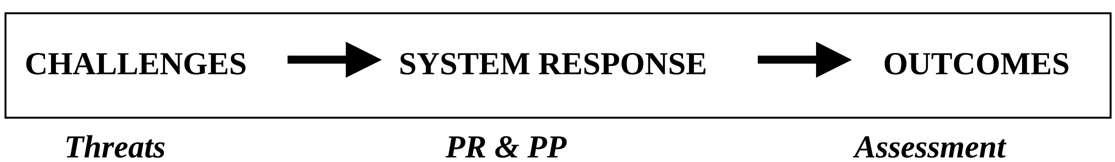

Figure 1. Framework for PR&PP Assessment.

The challenges to the system are given by the threats posed by potential proliferators and other adversaries to the nuclear systems. The characteristics of the Generation IV systems, both technical and institutional, are used to evaluate the system response to the threats and determine their ***resistance*** against the proliferation threats and ***robustness*** against sabotage and theft threats. The analysis of system response includes decomposition of the nuclear system into elements, identification of potential targets within those system elements, and generation of the various pathways, which represent how a threat could meet its objective. The outcomes of the system response are contained in an assessment expressing proliferation resistance and physical protection in terms of ***measures***. These high-level measures are estimated from a set of metrics representing the system characteristics and features. These characteristics include material, facility and process features as well as institutional procedures, such as international safeguards.

METHODOLOGY USERS

During the development of the advanced nuclear energy systems, two basic groups of users of the PR&PP evaluation methodology are expected. The first group is the Generation IV system designers, and the second distinct group is the program managers and policy makers. After deployment of a Generation IV system, other groups of users will include operators and regulators. The system designers need the outcomes of the methodology to provide feedback to the engineering design to enhance the system's performance in PR&PP. Policy makers need the results of the methodology to support decisions about development and deployment of the systems.

The needs of the two principal users are a key consideration in the development of the methodology. To meet the needs of the system designers, the methodology must be capable of providing sufficient information to evaluate the overall performance of the system with respect to PR&PP as well as to assess options for their impact on the system performance. To meet the needs of the system designers, the methodology must be capable of comparing different systems and different design choices with regard to PR&PP in order to support sound policy decisions.

PR&PP EVALUATION METHODOLOGY

The overall PR&PP evaluation approach is illustrated in Figure 2. It evaluates the resistance or robustness of a nuclear energy system to a collection of potential threats. For a given system a set of challenges is identified, the response of the system to these challenges is assessed and expressed in terms of outcomes.

Challenges

To evaluate either proliferation resistance or physical protection robustness, one must first specify "resistance" or "robustness" against whom (e.g., the actor), and against what actions (e.g., the strategy).

The concept of threats and threat definition has been well developed in the field of physical protection, where the characteristics of potential adversaries and their potential strategies have long been defined as a prelude to subsequent studies of physical protection system response.

For PR&PP evaluations, a detailed framework is provided for defining the set of threats that could potentially challenge nuclear energy systems. For both PR and PP, the threat definition includes characteristics of both the actor, and the actor's strategy. For PR, the actor is the host State for the nuclear energy system, and the threat definition includes the proliferation objectives (e.g. number and characteristics of nuclear explosives sought) as well as the capabilities (skills, resources) of the State. For PR the potential threat strategies include diversion, undeclared production, abrogation using declared facilities and materials, and the construction of completely separate, clandestine facilities.

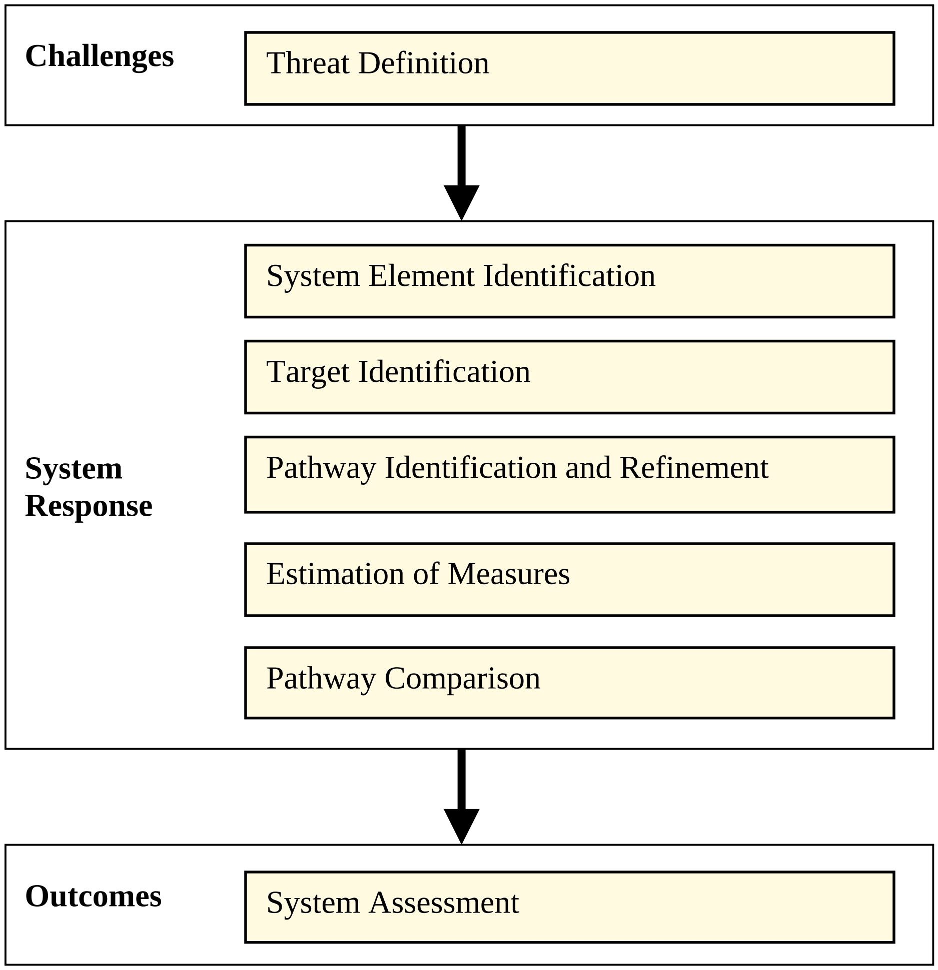

Figure 2. PR&PP Evaluation Methodology.

The detail with which threats can and should be defined depends upon the level of detail of information available about the system design and the locations where the system would be deployed. In the earliest stages of conceptual design, where detailed information about the location of deployment is likely limited, relatively stylized but reasonable threats must be selected. Conversely, when design has progressed to the point of actual deployment, detailed and specific characterization of both the system location and potential threats become possible.

System Response

The characteristics of the Generation IV systems, both technical and institutional, are used to determine their resistance against the proliferation threats and robustness against sabotage and terrorism threats. System response encompasses three elements:

1. System Element Identification. The nuclear energy system is decomposed into smaller elements at a level amenable to further analysis.
2. Target Identification. A systematic process is used to identify targets, within each system element, that actors (proliferators or adversaries) might choose to attack or use.
3. Pathway Identification and Refinement. Individual pathway segments, which are the individual events/actions necessary to complete the challenge, are developed through a systematic process, analyzed at a high level, and screened where possible. Segments are connected into full pathways and analyzed in detail.

The term *System Element* refers to a subsystem of the nuclear energy system; it can comprise a facility (in the systems engineering sense), part of a facility, a collection of facilities, or a transportation system within the identified nuclear energy system where diversion/acquisition and/or processing could take place (PR) or theft/sabotage could take place (PP).

Targets are the interface between the proliferator or adversary and the nuclear system; they form the link between the objectives and the system elements. Physical protection targets are nuclear or radioactive material, facilities, equipment or information to be protected from PP threats of theft and sabotage. Proliferation resistance targets are nuclear material and processes to be protected from PR threats of diversion and undeclared production.

Target identification is conducted by systematically examining the nuclear system for the role that materials, equipment and processes in each system element could have in each of the strategies identified in the threat definition. Typically, this requires iterative identification, review and revision to take different aspects of the strategy into consideration.

A pathway analysis for a set of threats consists of the identification of potential sequences of events that lead to the undesirable outcome (proliferation, sabotage or theft) and the evaluation of the PR&PP measures for each sequence.

Because a pathway analysis is performed by considering multiple pathway segments, measures are first evaluated for segments and then aggregated for complete pathways. Results are aggregated as appropriate to permit pathway comparisons and system assessment. Although aggregation of measures for different pathways may be performed, it is in general more valuable to be able to compare the measures for different pathways and determine the relative importance of different pathways. The objective of the assessment is then the identification of the dominant pathways and the measures associated with them.

Outcomes

The outcomes of the system response are assessments that integrate the sub-elements of the analysis and interpret the results. This includes examination of uncertainty, accuracy, identification of significant paths, weak links, and important findings from sensitivity and uncertainty analysis.

MEASURES

High-level *measures* have been selected for PR and PP to represent the high-level qualities that influence the decision making with respect to the development and deployment of advanced nuclear systems as well as from the point of view of a proliferator or adversary. Six PR measures have been defined for application to the evaluation of Generation IV systems for a spectrum of proliferation threats (noting the importance of the acquisition of the first nuclear explosive):

Proliferation Technical Difficulty – The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation.

This measure does not include the technical difficulty of concealing the diversion or undeclared production; these are reflected in proliferation resources, proliferation time, and detection time (safeguardability).

Proliferation Resources – The economic and manpower investment required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities.

Proliferation Time – The minimum time required to overcome the multiple barriers to proliferation; i.e. the total time planned by the State for the project.

Fissile Material Quality – The degree to which the characteristics of the material affects its utility for use in nuclear explosives.

Detection time (Safeguardability) – The time following the initiation of diversion or undeclared production, for detection resources to detect irregularities and to provide adequate confirmation that diversion or undeclared production has occurred or is occurring.

Detection Resources – Manpower, technology, and funding required to apply international safeguards.

An equivalent set of measures for PP has been defined as follows:

Operational Accessibility – The frequency and duration of access to vital equipment, systems, and zones, required for operations, surveillance, and maintenance activities performed by privileged personnel.

Adversary Delay – The time required to overcome intrinsic barriers to accessing and disabling a vital equipment target set (radiological sabotage) or to removing materials (theft).

Consequences and Mitigation Potential – The consequences of a failure to neutralize a threat, and the potential for mitigation of those consequences.

Detection Time – The time required, after intrusion by outsiders or unauthorized action by insiders, for physical protection system alarms to be received and verified.

Interruption Delay – The additional delay time created by protective force response prior to neutralization.

Physical Protection Resources – The manpower, capabilities, and costs required to provide physical protection (background screening, detection, interruption, and neutralization).

These measures have been selected to characterize the range of major information categories that a threat or policy maker will consider in making their decisions. Each measure characterizes a different aspect of the decision problem. As in most multi-criteria decision-making or design optimization problems, the set of information or solution being evaluated consists of competing and/or synergistic features. The analyst must be mindful of the systems interdependent features and identify them in a clear manner so that the designer can use them to efficiently guide further improvement.

At a coarse level, when very little specific design information exists for systems, measures can be estimated by direct expert elicitation methods. In progressive refinements of an assessment, the measures can be related to physical characteristics of the system or to specific actions and can therefore be estimated with other tools[4].

SUMMARY AND STATUS

Of prime importance in the establishment of the functional requirements for the methodology has been the characterization of the needs of two major sets of users: Generation IV system designers and policy makers. The system designers need the outcomes of the methodology to provide feedback to the engineering design to enhance the system's performance in PR&PP. Policy makers need the results of the methodology to support decisions about development and deployment of the systems.

The basic methodological approach identifies three major segments in the evaluation process:

- Challenges to the nuclear energy system,
- System response to the challenges, and
- Outcomes contained in an assessment.

The methodology for the evaluation of the system response is based on a progressive approach, which can start with qualitative tools and evolve towards more advanced quantitative methods.

The progressive approach maximizes early, useful feedback to designers and evaluators during the viability and performance phases of Generation IV research and development

Implementation of the methodology needs to be completed through its application to example cases. The Expert Group undertook a development case in January 2004 using a hypothetical nuclear energy system. The development case was used to advance the methodology and its implementation and verify that the approach developed by the Expert Group was feasible at a coarse path level. In 2005, the Expert Group will conduct the evlauation of a demonstration case using the methodology to further develop quantitative methods for the methodology and verify its practical implementation for a wide range of fuel cycle elements.

In conclusion, the successful completion of this methodology will facilitate the consideration of PR and PP in early stages of system design. This should result in improvements that make future nuclear energy systems more robust and facilitate the application and implementation of safeguards and physical protection. It should also facilitate sound policy decisions. The evaluation and possible enhancement of the system with respect to resistance to proliferation and robustness against theft and sabotage will not finish with the design of the system, but will extend to the deployment of the systems and throughout their entire life cycle, supported by successive evaluations based on this PR&PP methodology.

ACKNOWLEDGEMENTS

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