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Evaluation Methodology for Proliferation Resistance & Physical Protection of Generation IV Nuclear Energy Systems: An Overview

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EVALUATION METHODOLOGY FOR PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION OF GENERATION IV NUCLEAR ENERGY SYSTEMS: AN OVERVIEW

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SUMMARY/ABSTRACT

This paper provides an overview of the methodology approach developed by the Generation IV International Forum Expert Group on Proliferation Resistance & Physical Protection for evaluation of Proliferation Resistance and Physical Protection robustness of Generation IV nuclear energy systems options.

The methodology considers a set of alternative systems and evaluates their resistance or robustness to a collection of potential threats. For the challenges considered, the response of the system to these challenges is assessed and expressed in terms of outcomes. The challenges to the system are given by the threats posed by potential proliferant States and sub-national adversaries on the nuclear systems.

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

1. System Element Identification. The nuclear energy system is decomposed into smaller elements (subsystems) at a level amenable to further analysis.
2. Target Identification and Categorization. A systematic process is used to identify and select representative targets for different categories of pathways, within each system element, that actors (proliferant States or adversaries) might choose to use or attack.
3. Pathway Identification and Refinement. Pathways are defined as potential sequences of events and actions followed by the proliferant State or adversary to achieve its objectives (proliferation, theft or sabotage). For each target, individual pathway segments 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 outcomes of the system response are expressed in terms of PR&PP measures. Measures are high-level characteristics of a pathway that include information important to the evaluation methodology users and to the decisions of a proliferant State or adversary. They are first evaluated for segments and then aggregated for complete pathways. Results are aggregated as appropriate to permit pathway comparisons and system assessment.

The paper highlights the current achievements in the development of the Proliferation Resistance and Physical Protection Evaluation Methodology. The way forward is also briefly presented together with some conclusions.

INTRODUCTION

The Generation IV International Forum (GIF) was initiated in 2000 and formally chartered in mid 2001. It is an international collective effort representing the governments of ten Countries (Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland, UK and the USA) strongly involved in the deployment and development of nuclear technology for energy production. The European Atomic Energy Community (EURATOM), represented by the European Commission, signed, on July 30, 2003, the GIF agreement, becoming thus the eleventh participating "Country".

Generation IV nuclear energy systems will have to exhibit highly innovative solutions and technologies requiring extensive research and development effort, hence the new concepts will be ready for deployment in the 2030 timeframe (Figure 1) [1].

The Technology Goals for Generation IV nuclear energy systems, developed during the Roadmap project [2], highlight Proliferation Resistance and Physical Protection (PR&PP) Robustness as one of the four goal areas in which these technologies will have to excel, along with Sustainability, Safety & Reliability, and Economics.

On the basis of these four goal areas an evaluation methodology was developed during the roadmap project [2] which contributed to identify the nuclear energy systems options to be considered for further development. At the end of the roadmap phase, six candidate Generation IV reactor concepts were selected by GIF for development together with the associated fuel cycles options. The selected reactor concepts are, in alphabetic order, Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Super Critical-Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR).

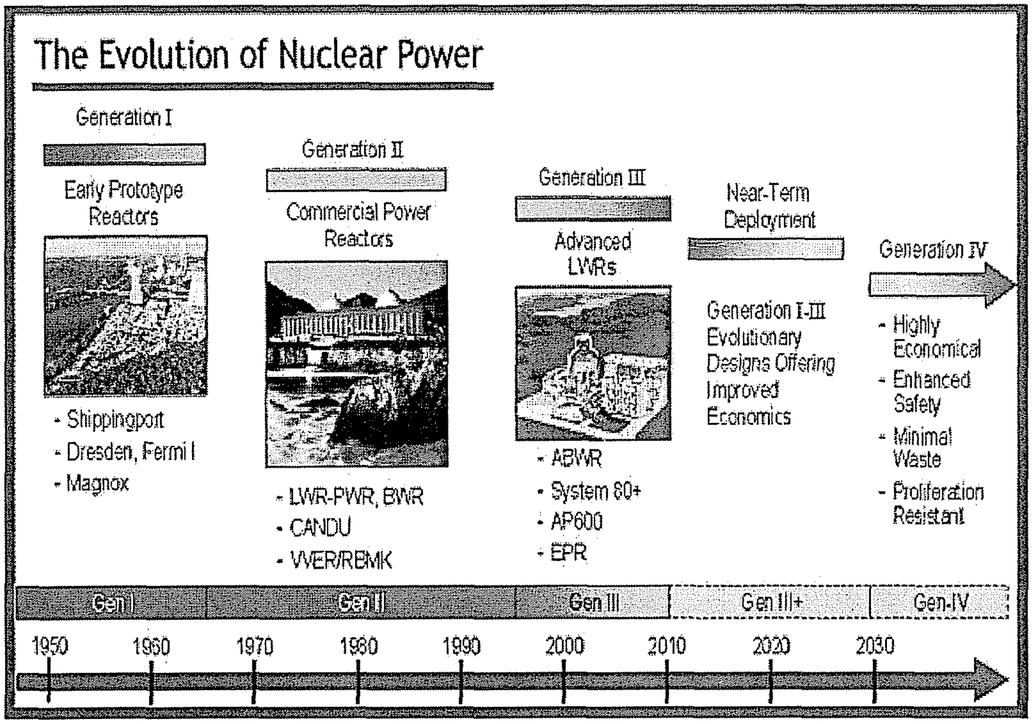

Figure 1. The evolution of nuclear power: the 4 Generations of Nuclear Reactors. [1].

The proliferation resistance of the candidate options were roughly evaluated on the basis of spent fuel characteristics and presence or absence of separated plutonium in the associated fuel cycle.

The physical protection robustness was evaluated on the basis of the degree of passive safety features.

The Generation IV Roadmap [2] recommended however the development of a comprehensive evaluation methodology to assess PR&PP of Generation IV nuclear energy systems. Accordingly, an Expert Group was formed and tasked by the GIF in December 2002 to develop an improved evaluation methodology on the basis of the recommendation in [2]. The expert group includes members of the GIF Participants and representatives from the IAEA.

The methodology, builds innovatively on previous efforts and methods (see [3-5] for a review of PR methods). Some of the features of the evaluation method being developed have been already reported in previous meetings and in international conferences [e.g. 6-12].

The methodology is organized as a progressive approach applying alternative methods at different levels of thoroughness as more design information becomes available and research improves the depth of technical knowledge. After a number of iterations and internal reviews within the expert group members, the Revision 2 Draft Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems methodology report has undergone to a process of internal peer review resulting, on September 2004, in the internal release of the revision 2 methodology report, representing a major milestone of the project [13].

In the year 2004, an example case study, named the Development Study has been carried out with reference to a hypothetical medium size, metal fueled Sodium Fast Reactor (L2 type, in the classification scheme developed during the roadmap project [1] i.e. cooled with Liquid metal), with on site re-fabrication of fuel elements on a dedicated Fuel Cycle Facility (FCF) operated by means of pyro-processing techniques. The aim of the development study is basically to advance with the methodology development rather to arrive at an evaluation of the nuclear energy system, named ESFR (Example Sodium Fast Reactor).

In addition, the evaluation methodology has been presented and discussed together with Generation IV systems designers in a workshop held in Crystal City in Arlington Virginia on November 2004. Overviews of the method have been published in 2005 [10-12]. In parallel the PR&PP expert group has initiated the development of an implementation guide. In 2006, a Demonstration Study will be carried out by focusing on the Fuel Cycle Facility. This paper, largely based on [12] will provide an updated overview of the methodology approach developed by the PR&PP Expert Group according to revision 3 Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems internal project report of the PR&PP Expert Group [14]. The paper highlights the achievements already reached in the Proliferation Resistance and Physical Protection evaluation methodology, and the direction taken to tackle the issues still open.

APPROACH TO THE EVALUATION

PR&PP evaluation can be applied across the entire fuel cycle of each Generation IV nuclear energy system, namely the front end (from the mine, to the conversion, the enrichment and fuel fabrication), the reactor and the back end (storage, conditioning and repository) taking into account also the needed transportation of material. The approach facilitates the use of information resulting from the application of the methodology to aid in decisions among alternative policy choices regarding the development of Generation IV systems. The approach also permits comparisons of designs or comparison of options that can provide information to designers on how a system can be improved. It can also permit comparison with a reference system, if one is defined.

The methodology is organized as a progressive approach under a single integrated structure, applying alternative evaluation methods at different levels of thoroughness, as more detailed design information is developed, and as research improves the depth of technical knowledge. The overall methodological framework is outlined in Figure 2. A progressive approach permits broad application of the PR&PP evaluation to Generation IV systems. PR&PP analysis can be applied to systems under development through fully designed systems. The scope and complexity of the assessment can be appropriate to the level of detailed design information available, and the level of detail with which the threat space can be specified. Important design information exists even at the very earliest stages of system design. Target identification can begin as soon as flow diagrams are first developed. Because target categorization uses information about each target's location, early target identification and categorization can help guide early physical arrangement design activity. Therefore, the methodology itself will help to guide the design evolution through a successive progression of iterations between design development and design evaluation. The progressive system evaluation begins with the collection and organization of information, identification of representative targets, and the development of coarse pathway models. Information is collected on each nuclear energy system: properties of the fuel cycle, designs of each system element, physical characteristics.

A representative set of threats, including characterization of the actors and strategies is defined. To facilitate comparison of different evaluations, a set of standard reference threats is required, covering the anticipated range of actors, capabilities, and strategies for the time period being considered. A formal identification process for the targets and pathways is then applied. Pathways for each target are identified and screened to eliminate those that are implausible or are clearly subsumed into other, more representative pathways. The evaluation of system response is then performed for the reduced pathway set.

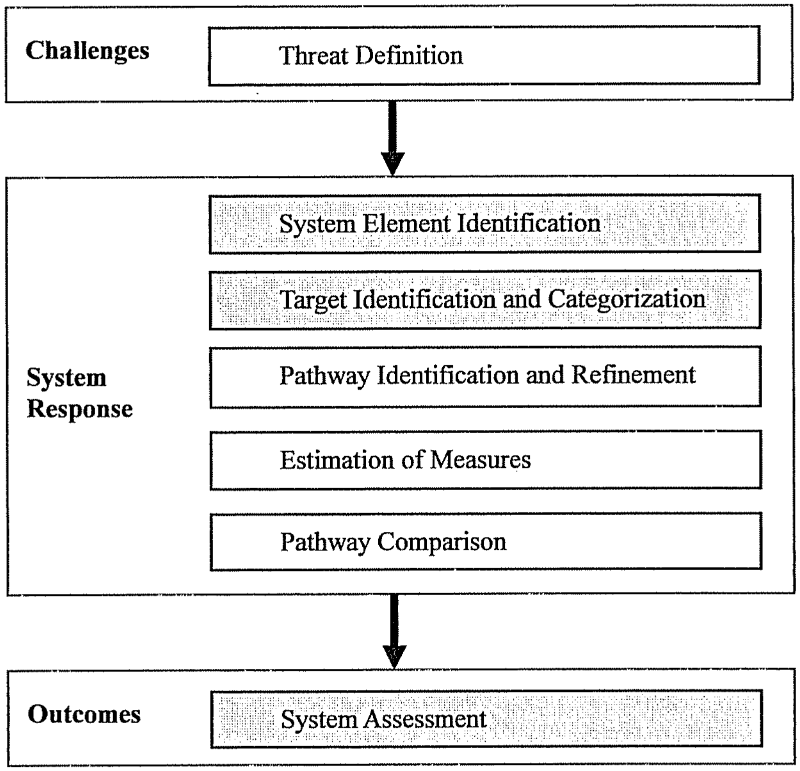

Figure 2. Framework for PR&PP Evaluation.

In the most thorough application of the approach, the design will be far enough along to identify component characteristics, points of possible human interaction, safeguards protocols, procedures and training, and physical mechanisms that apply. Mechanistic calculations can range from simple mass and energy balances to the systematic consideration of uncertainty. It is necessary to apply judgment to such information and adapt what is available to what is needed; this transformation always results in uncertainty that needs to be considered in the analysis. Several forms exist to structure the pathway analysis (directed graphs, event tree/fault tree models, simulation models, etc.) and selection will depend on the scenarios themselves, the state of design information, the quality and applicability of available information, and the analyst's preferences.

Challenges

To evaluate either PR or PP 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 PP system response.

For PR&PP evaluations, a detailed framework is provided for defining the set of threats that could potentially challenge nuclear energy systems over their full lifetime. 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

1. Proliferation objectives (e.g. number and characteristics of nuclear explosives sought);
2. Capabilities (skills, resources) of the State; and
3. Strategy (e.g. concealed or overt (abrogation) diversion of declared materials, concealed or overt production using declared facilities, and the construction of completely separate, clandestine facilities).

For PP threats, the actor, or adversary, is an individual or group composed of some combination of outsiders and insiders. Similarly to PR, the PP adversary's characteristics are further defined by:

1. Objective, which may be either the theft of nuclear material, radioactive material or information, radiological sabotage, or sabotage to disrupt operations;

2. Capabilities, which include their knowledge, skills, weapons and tools, number, and level of dedication; and
3. Strategy that is defined by the adversary's mode of attack, which may range from ground-based to standoff to cyber; and the adversary's tactics, including stealth, deceit, and overt force.

The PR&PP methodology does not determine the frequency that a given threat might or might not occur. Therefore the selection of what potential threats to include is performed at the beginning of a PR&PP evaluation, preferably with input from a peer review group organized in coordination with the evaluation sponsors. The uncertainty in the system response to a given threat is then evaluated independently of the probability that the system would ever actually be challenged by the threat. In other words, PR&PP evaluations are contingent upon the challenge occurring.

The detail with which threats can and should be defined depends upon the level of detail of information available about the nuclear system design and the locations where the nuclear 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 nuclear system location and potential threats become possible.

To facilitate the comparison of different evaluations, a common reference threat set is required. This must cover the range of proliferant States and PP adversaries, including their objectives, strategies and capabilities. Over time, the capabilities, strategies and objectives of the threats will change, and the reference threat set must include projections of these threat characteristics over the full lifetime of the nuclear system. In the case of long-term waste storage, projections should extend as far tractable, recognizing that uncertainty about the threat characteristics will increase with time.

System Response

System Element Identification

To analyze the nuclear energy system response to the specific threats identified, the boundaries of the system, which will limit the scope of the evaluation, must be clearly defined. Subsequently, the analyst identifies elements of the system in ways that facilitate the analysis. The term System Element is formally defined as 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 transportation system within the identified nuclear energy system where acquisition (diversion) or processing could take place (PR) or theft/sabotage could take place (PP).

Target Identification and Categorization

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

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.

Pathway Identification and Refinement

A system pathway analysis for a set of threats consists of identification of potential sequences of events and actions that lead to the undesirable outcome (proliferation, sabotage or theft) and the evaluation of the system response. Given that there are uncertainties associated with predicting the response of the system with respect to a given set of threats, a probabilistic pathway analysis is a natural structure for assessing system response to different types of threats.

Pathways suggest a natural data structure for the analysis of a system's performance. Each pathway defines a scenario for which the measures can be evaluated. Given a threat, the nuclear energy system responds through the pathways with a number of stumbling blocks, barriers and challenges, and the outcome of this will be, for each pathway, a set of specific values for the measures.

The pathways can be graphically represented in the form of functional event trees. The functional event tree shown in Figure 3 summarizes the main branch points of the paths to proliferation (acquisition, processing, and fabrication) and displays the six measures of interest.

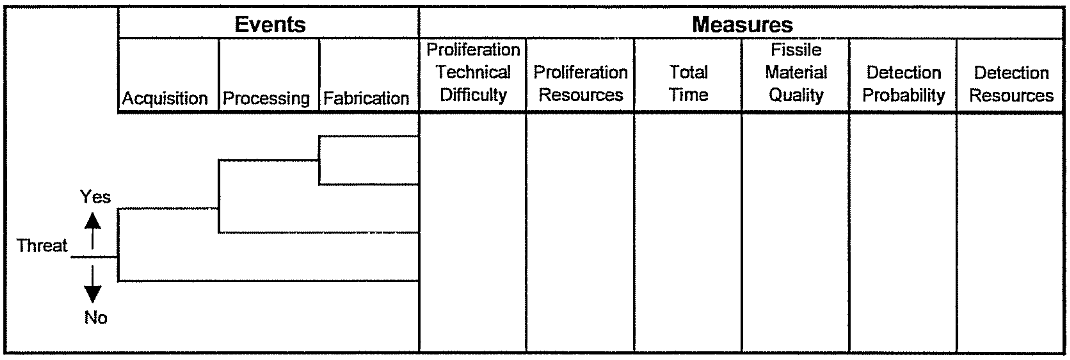

Figure 3. Functional Event Tree for Proliferation Resistance

Estimation of Measures

For both PR and PP, measures are defined, which are the high-level characteristics of a pathway that include information important to the evaluation methodology users and to the decisions of a proliferant State or adversary.

For PR the measures are:

1. *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 will be reflected in proliferation resources, proliferation time, and detection probability).
2. *Proliferation Resources* – The economic and manpower investment required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities.
3. *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.
4. *Fissile Material Quality* – The degree to which the characteristics of the material affects its utility for use in nuclear explosives.
5. *Detection Probability* – The cumulative probability of detecting a proliferation segment or pathway.
6. *Detection Resources* – manpower, equipment, and funding required to apply international safeguards to the nuclear energy system.

For PP, the measures are:

1. *Probability of Adversary Success* - The probability that an adversary will successfully complete a pathway and generate a consequence.
2. *Consequences* – The consequences of a failure to neutralize a threat; mitigation following the attack can control the extent of the consequences.
3. *Physical Protection Resources* – The manpower, capabilities, and costs required to provide PP (background screening, detection, interruption, and neutralization).

By considering the measures, system designers can identify design options that will improve system PR&PP performance. For example, designers can reduce or eliminate active safety equipment that requires frequent surveillance. This can reduce the requirement for access to such vital equipment by plant personnel, reducing the potential for insider action as well as permitting simple, passive measures to delay access to vital equipment to prevent sabotage.

Although the measures are not redundant, each providing some unique information, there are interdependencies between them. For example, detection probability is linked to the level of detection resources applied to a nuclear system. Such interdependencies must be clearly identified in a PR&PP evaluation and addressed in the estimation of measures.

For PR, a new measure at the system level, *Safeguardability*, has been introduced in revision 3 [13] for use at the conceptual design level, and is defined as the degree of ease with which a system can be effectively [and efficiently] put under international safeguards. Safeguardability is a property of the whole nuclear system and is estimated on targets on the basis of intrinsic characteristics related to the involved *nuclear material, process implementation and facility design.* A preliminary list of characteristics affecting *Safeguardability* is contained in Table I together with a preliminary definition for each identified characteristic (the ones with asterisks are adapted from the TOPS study [14 and 15]). The concept can be also used a checklist for helping designers at the very stage of design. Another newly introduced concept, the Technology Readiness Level (TRL) will help the designers to evaluate the degree to which ready off the shelf solutions exist for safeguarding the nuclear energy system elements.

Table I: Nuclear System Characteristics Affecting Safeguardability

Characteristic	*Definition*
Uniqueness of material signature*	The intrinsic material characteristics that contribute to the easiness of identifying/recognizing the nuclear material type and composition.
Hardness of radiation signature*	An intrinsic material characteristic that contributes to the difficulty of concealing nuclear material radiation signature for identification purposes.
Possibility of applying passive measurement methods*	The intrinsic material characteristics that enable to characterize the nuclear material with passive measurement methods instead of requiring active measurement methods.
Radiation field	Radiological hazard that impact accessibility to areas where nuclear material is kept.
Item/Bulk*	Whether the nuclear material is stored/handled/processed in item or in bulk or form. It affects the accuracy of nuclear material accounting.
Uncertainties of detection equipment*	The intrinsic features that contribute to uncertainties in detection equipments.
Throughput inventory	The amount of nuclear material produced by the process in a given period of time. It affects the absolute uncertainty of the material accountancy.
Extent of Automation	The extent to which procedures are carried out without the need of human intervention in the interested area. It may affect transparency and convertibility of the process.
Availability of data	Availability of sufficient information to trace materials in the process.
"Authenticability" of data	The extent to which the authenticity of information provided about the process can be proved.
Operational Practice	The procedures to be followed during the functioning of the nuclear energy system. It may affect traceability, accessibility etc..
Batch/Continuous/ process	Whether the foreseen process will be carried out in a batch way or in a continuous or way. It affects traceability of nuclear material and measurements accuracy.
Applicability of C/S measures	The intrinsic features that contribute to the easiness of implementing effective C/S techniques.
Transparency of facility design	The intrinsic feature that contributes to the easiness of detecting design modifications and traceability of materials etc.
Un-convertibility of the process	The intrinsic features that contribute to the difficulty of converting the process in order e.g. to produce material not described in the design information.

Pathway Comparison

A pathway analysis is performed by considering multiple pathway segments. There will be measures estimated for the individual segments that will need to be aggregated to estimate the measure for the pathways. 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 system evaluation is then the identification of the dominant pathways and the measures associated with them.

Outcomes and Presentation of Results

The presentation of results is an important aspect of the evaluation, especially because the results are intended for two types of users: system designers and program policy makers. Thus, the analysis of the system response must be amenable to being expressed in different levels of detail. Program policy makers are likely to be interested in the high level measures, while system designers will be interested in measures and metrics that are more directly related to the system design characteristics.

Over time, results will be estimated and presented in different forms through the progressive approach. During early phases, the methodology will utilize qualitative information and identify areas of uncertainty (technical knowledge gaps), while more quantitative analysis will be expected later.

The results of the PR&PP assessments will be given in terms of the high level measures presented above. While the resources employed to protect against proliferation, theft, or sabotage will ultimately be subsumed in the overall cost of the nuclear energy system, it is necessary to include assumptions about resources in order to assess the time required for detection by safeguards, or the effectiveness of physical protection.

A "final" top level result for a program policy maker or a system designer could take the form, for example, of the well known spider ("radar") diagrams. The estimated values for the measures can be shown on six concurrent axes, which are separated into two groups, intrinsic and extrinsic. The scales for the measures are defined so that smaller values represent greater proliferation resistance. Bars are used to represent uncertainty. This representation provides a concise overview of the overall PR for a pathway, target, system element, or nuclear system, with the inverse of area in the polygon representing the overall PR and the lengths of the radii representing the values for each of the measures. The final steps in PR&PP evaluations are to integrate the sub-elements of the analysis and to interpret the results. This includes presentation of best estimates for numerical and linguistic descriptors that characterize the results, development of distributions reflecting the uncertainty associated with those estimates, and development of appropriate displays to communicate about uncertainties.

Implementation

The performance of a PR&PP evaluation follows a sequence of well-defined steps that starts with the initial process of scope definition and ends with the final peer review of the evaluation report and its conclusions.

THE WAY FORWARD AND CONCLUSIONS

The development of the Proliferation Resistance and Physical Protection Evaluation Methodology is a collective effort carried out by the PR&PP Expert Group within GIF. The Methodology aims at progressive implementation as more detailed design in formation becomes available and should be suitable for implementation since early design stages. The approach is based on the paradigm Challenges, Systems Response and Outcomes and is being developed coherently for both the Proliferation Resistance and Physical Protection robustness evaluation. It is developed within an international working group by means of a consensus approach.

On January 2004, an example case study, named the Development Study has been initiated with reference to a medium size Sodium Fast Reactor with on site re-fabrication of fuel elements by means of pyro-processing techniques. As a result of the work done during the development study, and of a workshop held in November 2004 with systems designers, a number of areas for further work and refinement emerged. This paper presented the status of the evaluation methodology as described in the Revision 3 report issued in September 2005 [14]. The adopted measures for the characterization of the PR and PP pathways have been revised in order to cover all the relevant characteristics of the pathways. The measures have to be complete, non redundant, informative and the least possible. Moreover for each measure a suitable set of metrics (i.e. measurements units) and measurements scales have been preliminary identified, together with a suitable scheme of aggregation within the pathways segment estimates. The development case will be continued in the course of 2006 and further extended to constitute a Demonstration Case. An implementation guide based on the methodology and on the demonstration case is also under development.

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