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LIMITING FUTURE PROLIFERATION AND SECURITY RISKS

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ABSTRACT

A major new technical tool for evaluation of proliferation and security risks has emerged over the past decade as part the activities of the Generation IV International Forum. The tool has been developed by a consensus group from participating countries and organizations and is termed the Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology. The methodology defines a set of challenges, analyzes system response to these challenges, and assesses outcomes. The challenges are the threats posed by potential actors (proliferant states or sub-national adversaries). It is of paramount importance in an evaluation to establish the objectives, capabilities, resources, and strategies of the adversary as well as the design and protection contexts. Technical and institutional characteristics are both used to evaluate the response of the system and to determine its resistance against proliferation threats and robustness against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of a set of measures, which thereby define the PR&PP characteristics of the system. This paper summarizes results of applications of the methodology to nuclear energy systems including reprocessing facilities and large and small modular reactors. The use of the methodology in the design phase a facility will be discussed as it applies to future safeguards concepts.

Key Words: proliferation, security, risk, methodology

1 INTRODUCTION

A major new technical tool for evaluation of proliferation and security risks has emerged over the past decade as part the activities of the Generation IV International Forum. The tool has been developed by a consensus group from participating countries and organizations and is termed the Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology. The Generation IV Roadmap [1] recommended the development of an evaluation methodology to define measures for PR&PP and to develop a methodology for evaluating them for the six NESs proposed within the Generation IV program. Accordingly, the Generation IV International Forum (GIF) formed a Working Group in December 2002 to develop a methodology. The current version of the methodology (Revision 5) has been approved by GIF for open distribution and is available at the GIF website [2]. Revision 6 of the methodology is currently in preparation and is expected to be approved for open distribution in mid 2011.

The methodology enjoys some methodological similarities with the probabilistic risk assessment (PRA) approach that is very familiar to the reactor safety community [3]. In particular:

- Both methodologies must consider the behavior of the nuclear energy systems under abnormal conditions, caused by a spectrum of challenges,
- Both rely on systematic approaches to the evaluation of off-normal conditions and to alternative design features that would prevent or mitigate the effects of challenges,

- Target identification for various categories of threats in PR&PP evaluations has many similarities with the hazard identification process used in safety analysis,
- Uncertainty of information is an essential characteristic in both areas, particularly at early phases of design, and where possible the assumptions introduced to address uncertainties should be translated into functional requirements and documented in a design bases document that can then provide guidance during detailed design,
- Potential conflicts between the goals in each area and other high-level Generation IV goals (costs, sustainability) need to be understood and reflected in the development of an optimized design.

In addition to such commonalities, significant distinctions between PRA and PR&PP assessments must be recognized and accommodated:

- The focus of PRA is on the health and safety of the public and workers as a result of accidents and during the operation of these systems. In contrast PR&PP focuses on the prevention and mitigation of malevolent events instigated by nation-states (PR-related threats) that would possess these systems or by non-host-state entities (PP-related threats).
- The likelihoods of accidents for future nuclear energy systems, and their associated uncertainties, can be estimated. The likelihoods of malevolent acts involve strategic actions by a proliferant State or a sub-national adversary, and predicting their frequency requires an understanding of motivation, objective, strategy, and capability of the malevolent parties, along with new analytical tools to make such predictions. In general PR&PP studies do not assume a frequency of malevolent acts, but instead consider the response of the system contingent upon a malevolent act occurring. Nations establish “design basis threat (DBT)” definitions to set PP requirements based on their assessments of the likelihood of different potential types of attack. DBT information is sensitive, but at the conceptual design stage the general categories of potential attacks can be defined, and the system optimized to be resistant against these different categories of threats. For PR it is difficult to assess the probability that a State would choose to proliferate, so PR analysis is typically performed contingent on the assumption that an attempt would be made.

Accordingly the PR&PP and PRA evaluation methodologies share a common framework/paradigm.

The following paradigm underlies the PR&PP assessment approach:

THREATS → SYSTEM RESPONSE → OUTCOMES.

The PRA paradigm can be defined in a similar way:

ACCIDENT SYSTEM INITIATORS → RESPONSE → CONSEQUENCES.

2 TECHNICAL OBJECTIVES OF PR&PP ASSESSMENTS

The Technology Goals for Generation IV nuclear energy systems (NESs) highlight Proliferation Resistance and Physical Protection (PR&PP) as one of the four goal areas along with Sustainability, Safety and Reliability, and Economics:

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.

Proliferation resistance and physical protection are defined here as follows.

Proliferation resistance is that characteristic of an NES that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices.

Physical protection (robustness) is that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices (RDDs) and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries.

The challenges to the NES are the threats posed by potential proliferant States and by sub-national adversaries. The technical and institutional characteristics of the Generation IV systems are used to evaluate the response of the system and determine its ***resistance*** to proliferation threats and ***robustness*** against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of PR&PP ***measures*** and assessed.

The evaluation methodology assumes that an NES has been at least conceptualized or designed, including both the intrinsic and extrinsic protective features of the system. Intrinsic features include the physical and engineering aspects of the system; extrinsic features include institutional aspects such as safeguards and external barriers. A major thrust of the PR&PP evaluation is to elucidate the interactions between the intrinsic and the extrinsic features, study their interplay, and then guide the path toward an optimized design.

The structure for the PR&PP evaluation can be applied to the entire fuel cycle or to portions of an NES. The methodology is organized as a *progressive* approach to allow evaluations to become more detailed and more representative as system design progresses. PR&PP evaluations should be performed at the earliest stages of design when flow diagrams are first developed in order to systematically integrate proliferation resistance and physical protection robustness into the designs of Generation IV NESs along with the other high-level technology goals of sustainability, safety and reliability, and economics. This approach provides early, useful feedback to designers, program policy makers, and external stakeholders from basic process selection (e.g., recycling process and type of fuel), to detailed layout of equipment and structures, to facility demonstration testing.

Figure 1 provides an expanded outline of the methodological approach. The first step is *threat definition*. For both PR and PP, the threat definition describes the challenges that the system may face and includes characteristics of both the actor and the actor's strategy. For PR, the actor is the Host State for the NES, and the threat definition includes both the proliferation objectives and the capabilities and strategy of the Host State. For PP threats, the actor is a sub-national group or other non-Host State adversary. The PP actors' characteristics are defined by their objective, which may be either theft or sabotage, and their capabilities and strategies.

To facilitate the comparison of different evaluations, a standard Reference Threat Set (RTS) can be defined, covering the anticipated range of actors, capabilities, and strategies for the time period being considered. Reference Threat Sets should evolve through the design and development process of nuclear fuel cycle facilities, ultimately becoming Design Basis Threats (DBTs) upon which regulatory action is based.

For PR, the threats include

- Concealed diversion of declared materials
- Concealed misuse of declared facilities
- Overt misuse of facilities or diversion of declared materials
- Clandestine dedicated facilities.

For PP the threats include

- Radiological sabotage
- Material theft
- Information theft.

The PR&PP methodology does not determine the probability 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. In other words, PR&PP evaluations are contingent on the challenge occurring.

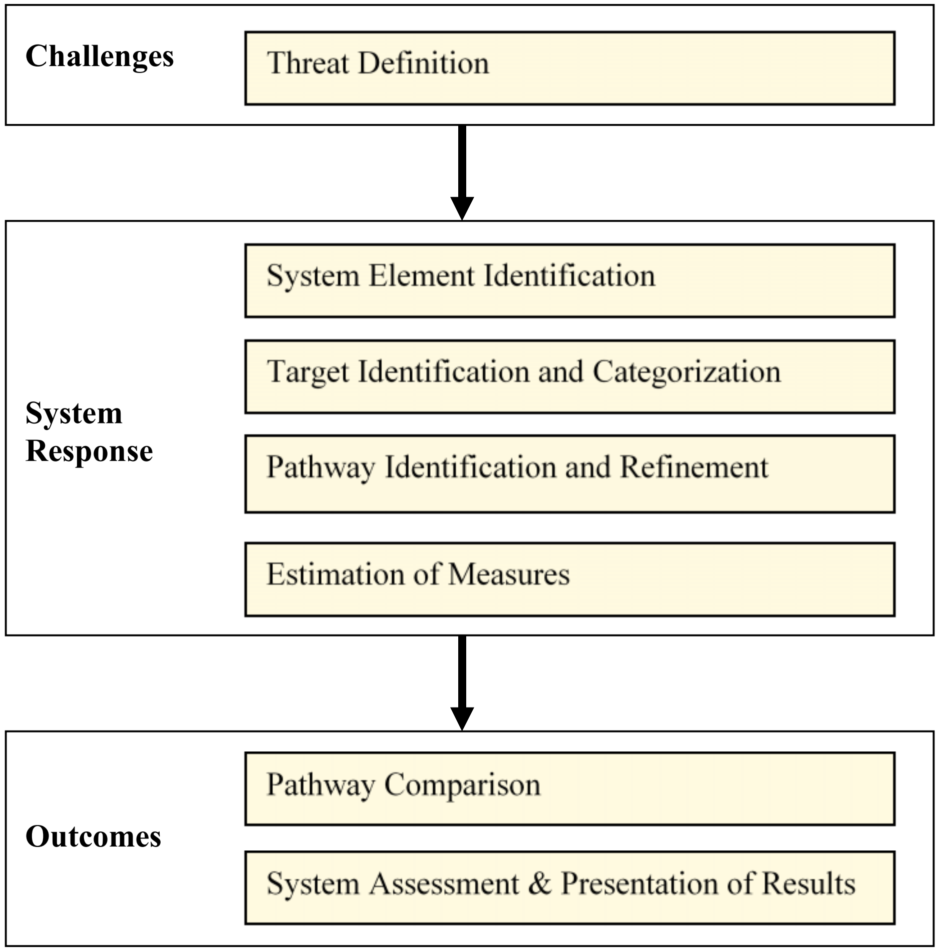

Figure 1. Framework for the PR&PP Evaluation Methodology

The detail with which threats can and should be defined depends on the level of detail of information available about the NES design. In the earliest stages of conceptual design, where detailed information is likely limited, relatively stylized but reasonable threats must be selected. Conversely, when design has progressed to the point of actual construction, detailed and specific characterization of potential threats becomes possible.

When threats have been sufficiently detailed for the particular evaluation, analysts assess system response, which has four components:

1. **System Element Identification**. The NES is decomposed into smaller elements or subsystems at a level amenable to further analysis. The elements can comprise a facility (in the systems engineering sense), part of a facility, a collection of facilities, or a transportation system within the identified NES where acquisition (diversion) or processing (PR) or theft/sabotage (PP) could take place.

2. **Target Identification and Categorization.** Target identification is conducted by systematically examining the NES for the role that materials, equipment, and processes in

each element could play in each of the strategies identified in the threat definition. PR targets are nuclear material, equipment, and processes to be protected from threats of diversion and misuse. PP targets are nuclear material, equipment, or information to be protected from threats of theft and sabotage. Targets are categorized to create representative or bounding sets for further analysis.

3. **Pathway Identification and Refinement.** Pathways are potential sequences of events and actions followed by the actor to achieve objectives. For each target, individual pathways are divided into segments through a systematic process, and analyzed at a high level. Segments are then connected into full pathways and analyzed in detail. Selection of appropriate pathways will depend on the scenarios themselves, the state of design information, the quality and applicability of available information, and the analyst's preferences.

4. **Estimation of Measures.** The results of the system response are expressed in terms of PR&PP measures. Measures are the high-level characteristics of a pathway that affect the likely decisions and actions of an actor and therefore are used to evaluate the actor's likely behavior and the outcomes. For each measure, the results for each pathway segment are aggregated as appropriate to compare pathways and assess the system so that significant pathways can be identified and highlighted for further assessment and decision making.

For PR, the measures are

- *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.
- *Proliferation Cost* – The economic and staffing 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 Host State for the project)
- *Fissile Material Type* – A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives.
- *Detection Probability* – The cumulative probability of detecting a proliferation segment or pathway.
- *Detection Resource Efficiency* – The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the NES.

For PP, the measures are

- *Probability of Adversary Success* – The probability that an adversary will successfully complete the actions described by a pathway and generate a consequence.
- *Consequences* – The effects resulting from the successful completion of the adversary's action described by a pathway.

- *Physical Protection Resources* – the staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

By considering these 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 operator intervention. The final steps in PR&PP evaluations are to integrate the findings of the analysis and to interpret the results. Evaluation results should include best estimates for numerical and linguistic descriptors that characterize the results, distributions reflecting the uncertainty associated with those estimates, and appropriate displays to communicate uncertainties.

The information is intended for three types of users: system designers, program policy makers, and external stakeholders. Thus, the analysis of the system response must furnish results easily displayed with different levels of detail. Program policy makers and external stakeholders are more likely to be interested in the high-level measures, while system designers will be interested in measures and metrics that more directly relate to the optimization of the system design.

3 APPLICATIONS

The PR&PP working group has been engaged in various applications of its methodology. In addition, specialized studies have been carried out with the methodology by organizations that have particular technical issues that they sought to inform with results of the methodology. These are briefly outlined below.

<u>Example Sodium Fast Reactor (ESFR) Case Study</u>

The PR&PP Working Group has developed its methodology with the aid of a series of studies. The ESFR consists of four sodium-cooled fast reactors of medium size co-located with an on-site dry fuel storage facility and a pyrochemical spent fuel reprocessing facility. The Case Study results can be obtained at Reference [4].

The objectives of the Case Study were to exercise the GIF PR&PP methodology for a complete Gen-IV reactor/fuel cycle system; to demonstrate, via the comparison of different design options, that the methodology can generate meaningful results for designers and decision makers; to provide examples of PR&PP evaluations for future users; to facilitate transition to other studies; and to facilitate other ongoing collaborative efforts (e.g., INPRO) and other national efforts.

<u>Interactions with Nuclear Energy System Designers</u>

In 2007 discussions began between the PR&PP working group (WG) and representatives of the GIF System Steering Committees (SSCs) for each of the six GIF design concepts on the exploration of ways that the two entities could cooperatively pursue joint projects. Three workshops of interested parties were held which resulted in a program plan for future joint activities. Three broad goals were defined for future joint activities: 1) capture in the near term salient features of the design concepts that impact their PR&PP performance, 2) conduct crosscutting studies that assess PR&PP measures against design or operating features common to various GIF systems, and 3) derive functional requirements for the global layout of future nuclear energy systems. As of this writing, white papers on the PR&PP aspects and issues of each of the six design concepts have been developed jointly by representatives of the SSCs and the PR&PP WG and have been approved by the respective SSCs. A compendium report which includes these six white papers is in preparation and it will be available for open distribution in 2011 after approval is received from GIF.

Proliferation Risk Reduction Assessment

In January 2009, the U.S. Department of Energy (DOE) Office of Nonproliferation and International Security released a draft Non-Proliferation Impact Assessment (NPIA) of the Global Nuclear Energy Partnership (GNEP) for public comment [5]. The draft NPIA analyzes the U.S. domestic nuclear fuel alternatives identified in the draft GNEP Programmatic Environmental Impact Statement (PEIS) for their potential impacts on the risk of nuclear proliferation and on U.S. nonproliferation goals.

In its conclusions on separations technologies the NPIA drew on a multi-laboratory study [6]. The study focused on determining whether three alternative reprocessing technologies – COEX, UREX+, and pyroprocessing – provide nonproliferation advantages relative to the PUREX technology because they do not produce separated plutonium. It considered how a facility may be threatened under various proliferation scenarios. For each alternative, the measures of proliferation risk considered include the relative difficulty of achieving the objective, the time required, the cost to the adversary, the likelihood of detection, the cost of safeguards and physical protection, and the characteristics of the material acquired. This evaluation found only a modest improvement in reducing proliferation risk over existing PUREX technologies and these modest improvements apply primarily for non-state actors.

In addition, a multi-laboratory team [7] evaluated the proliferation resistance technical risk characteristics of a number of generic nuclear reactors designs using the GIF PR&PP methodology. Three general types of material acquisition scenarios were evaluated for each reactor type: 1) concealed diversion of material; 2) concealed misuse of the reactor to produce materials; and 3) breakout. The evaluations took into account both the intrinsic and extrinsic PR&PP characteristics of each reactor. This study showed that each reactor type has particular features affecting its respective PR&PP characteristics and that no type was clearly superior or inferior for the material acquisition scenarios considered. Areas were identified where safeguards approaches and technology could be improved. Similarities and differences among the reactors were highlighted and paths forward for improving both the intrinsic and extrinsic aspects of reactor concepts to meet nonproliferation goals were identified. These evaluations are the first systematic, comprehensive proliferation resistance studies covering the spectrum of reactor design concepts.

International Safeguards by Design Activities

There are ongoing and planned efforts both nationally [8,9] and internationally [10] to promote and implement the concept of safeguards by design (SBD) in the nuclear facility design process. The goals of an SBD program are generally to consider: 1) design principles that facilitate the effective implementation of safeguards without overly burdening facility operations staff, 2) cost saving measures for implementing safeguards, 3) facility design features that would improve inspection conditions as compared to present standards, 4) better understanding among facility designers of safeguards principles, and 5) information exchange on advancements in safeguards technologies.

A recent application of the PR&PP methodology to a CANDU-type reactor has been presented by J. Whitlock [11]. The pathway comparison consisted of a simplified qualitative ranking based on expert judgment. Results of this exercise were used stimulate discussions involving the design team, the state regulator, and the IAEA, and propose steps that accommodate safeguards without negatively impacting other design requirements.

Towards Harmonization with INPRO

In parallel with the multi-national effort by GIF PR&PP WG, and over the same time period, the International Atomic Energy Agency (IAEA) has been sponsoring development of an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) to help to ensure that nuclear energy is available in the 21st century in a sustainable manner. See Pomeroy et al [12] for additional information. The INPRO approach [13] is primarily designed for nuclear energy system *users* (and thus guides the INPRO assessor in confirming that adequate proliferation resistance has been achieved in the nuclear energy system under consideration), but it can also give guidance to the *developer* of nuclear technology on how to improve proliferation resistance.

4 FUTURE WORK

As the world increase its use and reliance on nuclear technologies for energy and other peaceful applications, there will be a need for a corresponding effort to assure that nonproliferation goals as enunciated by the IAEA, are realized. There are many national and international programs that are aimed at providing this assurance. The PR&PP methodology is an analysis tool that can help to assess and manage the risks posed by threats to the peaceful use of nuclear technologies. Some areas in which PR&PP studies could prove effective in reducing proliferation risk are indicated below.

Both national and international initiatives have proposed schemes for managing fuel cycle arrangements among participating nations. These schemes typically involve assured fuel supply and management of spent fuel. Some studies have been performed [5, 14, 15] in this regard and further evaluations using the PR&PP methodology would be warranted as alternative architectures are proposed.

In its Report to Congress [19], the U.S. Department of Energy's Office of Nuclear Energy (NE) presented "Understanding and minimizing the risks of nuclear proliferation and terrorism" as one of its four key long range research and development objectives. The report notes that: "Any fuel cycle technologies deployed in the U.S. must be considered in light of how other nations might choose to incorporate them into their own nuclear enterprises. Towards this end, it is important for NE to develop a means of understanding how these new technologies would be viewed by other countries in the context of their national goals."

Finally, in light of the President Obama's decision not to proceed with the Yucca Mountain nuclear waste repository, he directed Secretary Chu to establish a Blue Ribbon Commission [17] on America's Nuclear Future to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle. The Commission will provide advice and make recommendations on issues including alternatives for the storage, processing, and disposal of civilian and defense spent nuclear fuel and nuclear waste. Criteria for evaluation include cost, safety, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals.

5 CONCLUSIONS

In any enterprise aimed at designing future nuclear energy systems, the PR&PP methodology will be an essential tool in guiding new concepts because each of the measures that are obtained within a PR&PP are key discriminators for defining and enhancing the proliferation resistance and physical protection robustness of a potential design alternative. The GIF PR&PP evaluation methodology was initially motivated by the need to have an approach to the assessment of new nuclear energy design concepts that were envisioned within the GIF program. The methodology that has been developed now enjoys wide international consensus and has been used in applications beyond the initial purpose. It is expected that subsequent applications of the methodology will 1) lead to refinement of the approach which will streamline and focus it to address issues of interest to end-users of the results and 2) have application to a more diverse set of applications that will enhance decision making in the PR&PP arenas.

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7 REFERENCES

1. DOE (U.S. Department of Energy), Nuclear Energy Research Advisory Committee and the Generation IV International Forum. December 2002. A Technology Roadmap for Generation IV Nuclear Energy Systems. GIF002-00, DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, Washington, D.C.

2. *"Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems,"* Revision 5, Generation IV International Forum, GIF/PRPPWG/2006/005, November 30, 2006; www.gen-4.org/Technology/horizontal/PRPPEM.pdf

3. H. Khalil, R. Bari, G-L. Fiorini, T. Leahy, P.F. Peterson, R. Versluis, "Integration of Safety and Reliability with Proliferation Resistance and Physical Protection for Generation IV

Nuclear Energy Systems,"" Proceedings of the Global 2009 Conference, Paris, France, September 6-11, 2009.

4. http://www.gen-4.org/Technology/horizontal/documents/PRPP_CSReport_and_Appendices_2009_10-29.pdf.

5. Draft Non-Proliferation Impact Assessment (NPIA) of the Global Nuclear Energy Partnership (GNEP), December 2008, *http://brc.gov/library/docs/GNEP_NPIA.pdf*

6. R. A. Bari, L-Y Cheng, J. Phillips, J. Pilat, G. Rochau, I. Therios, R. Wigeland, E. Wonder, M. Zentner, "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing Technologies," Proceedings of the 50th Institute of Nuclear Materials Management Annual Meeting, Tucson, AZ, July 12-16, 2009.

7. M. Zentner, I. Therios, R. Bari, L. Cheng, M. Yue, R. Wigeland, J. Hassberger, B. Boyer, J. Pilat, G. Rochau, and V. Cleary, "An Expert Elicitation Based Study of the Proliferation Resistance of a Suite of Nuclear Power Plants," Proceedings of the 51th Institute of Nuclear Materials Management Annual Meeting,,, Baltimore, MD July 11-15, 2010.

8. See http://nnsa.energy.gov/mediaroom/factsheets/nextgenerationsafeguards.

9. E. Wonder, P. Durst, J. Hockert, M. Zentner, R. Bari, and R. Wigeland, "Facility Safeguardability Analysis in Support of Safeguards by Design," Proceedings of the IAEA Symposium on International Safeguards: Preparing for Future Verification Challenges, Vienna, AU, November 1-5, 2010.

10. "Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards," IAEA STR-360, February 2009, (Workshop conducted from October 28-31, 2008 at IAEA Headquarters in Vienna, Austria)..

11. J. Whitlock, "Incorporating the GIF-PRPP Proliferation Resistance Methodology in Reactor Design," Proceedings of the 51th INMM Conference, Baltimore, MD July 11-15, 2010.

12. G. Pomeroy, E. Wonder, R. Bari, M. Zentner, "Approaches to Evaluation of Proliferation Resistance of Nuclear Systems," Proceedings of the 49th Institute of Nuclear Materials Management Annual Meeting, Nashville, TN, July 13-17, 2008.

13. International Atomic Energy Agency. Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Proliferation Resistance Volume 5 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1575, October 2007.

14. V. Reis, M. Crozat, J.-S. Choi, and R. Hill, "Nuclear Fuel Leasing, Recycling, and Proliferation: Modeling a Global View," Nuclear Technology, 150, 121 (2005)

15. M. Yue, L-C. Cheng, R. A. Bari, "Relative Proliferation Risks of Different Fuel Cycle Arrangements," Nuclear Technology, 165, 1 (2009).

16. Report to Congress on Nuclear Energy, April 2010, http://www.ne.doe.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf.

17. See www.brc.gov.