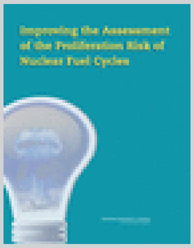

Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles

ISBN
978-0-309-28532-2

92 pages
8 1/2 x 11
PAPERBACK (2013)

Committee on Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles; Nuclear and Radiation Studies Board; Division on Earth and Life Studies; National Research Council

THE NATIONAL ACADEMIES
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Committee on Improving the Assessment of the Proliferation Risk of
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Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Award No. DE-PI0000010/DE-DT0002373 between the National Academy of Sciences and the U.S. Department of Energy, Office of Nuclear Energy and National Nuclear Security Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 13:978-0-309-28532-2
International Standard Book Number 10:0-309-28532-1

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313 Internet, http://www.nap.edu

Printed in the United States of America

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PREFACE

This study originated from a joint request from the Department of Energy Office of Nuclear Energy (DOE-NE) and the National Nuclear Security Administration (NNSA) Office of Nonproliferation and International Security to understand the extent to which technical analysis of proliferation risk could be improved for policy makers. Phase 1 of this two-phase study was a workshop that focused on the first task of the study charge: identifying key policy questions that were capable of being answered by a technical assessment of host-state proliferation risk and the utility of these questions for informing nonproliferation policy decisions. The workshop, summarized by a rapporteur-authored report, brought together nonproliferation policy decision makers and key technical developers of proliferation assessment tools.

During our first committee meeting, we heard from DOE-NE[a] that it believed that the workshop adequately addressed the first task, whereas NNSA reported that the workshop did not.[b] This consensus report, which addresses the full statement of task, is the result of the second phase of the study.

When the committee and I began working on this study, we had long discussions on the meaning and motivation of the statement of task. We tried to better understand the individual tasks by dissecting them into components, and then by looking at them in total. We set off to gather information on "how the U.S. government makes nonproliferation policy decisions" searching for a well-defined process. At the same time, we began the significant work of "assessing the assessments." Specifically, we reconsidered what key policy decisions could be answered by technical analysis of proliferation risk.

What we discovered throughout the study was that the task statement, although complex in its charge, can be reduced to asking how far technical analysis can go toward guiding nonproliferation policy-based decisions. How developed are the current technical methods? Do the policy makers need additional information that they are not getting?

We realized that the U.S. government does not follow a scripted process for every nonproliferation policy decision but that there are well-developed pathways to address the technical analysis that supports these decisions. I gained respect for the complexities of the issues faced by policy makers and the impact of the decisions that they make. It is clear that nonproliferation policy makers do make use of technical analyses when making decisions but also weigh many other factors.

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[a] Griffith, A. 2012. DOE-NE Perspectives on the National Academies Proliferation Risk Assessment Project. Presentation to committee, January 16.

[b] Lockwood, D. 2012. Proliferation Risk Assessments: A Policy-Maker's Observations. Presentation to the committee, January 16.

The committee had lively discussions on the current limits of science-based approaches toward guiding these decisions. Ultimately, we determined that at the current time, science-based approaches for quantifying aspects of proliferation risk are best limited to engineering-based assessments (e.g., an assessment of proliferation *resistance* as opposed to the proliferation *risk* of a future fuel cycle). We did see that decision makers from other organizations found value in these approaches but only when they were actively involved in the process.

This complex study would not have been as interesting or enjoyable if not for the diverse and dedicated committee that supported it. The committee members came from different backgrounds and across many disciplines, spanning the usually vast chasm between technical and policy perspectives. For this committee, this division was not a problem. We all learned a great deal from each other and listened respectfully from divergent viewpoints on some issues.

Robert C. Dynes, *Chair*

ACKNOWLEDGEMENTS

A number of individuals and organizations contributed to the successful completion of this report. The committee received many briefings that were necessary for the study's success. Its questions were nearly always answered with clarity and candor. This report could not have been written without the support of the people listed below who made presentations to the committee. The information and cooperation that the committee received from these organizations and individuals were critical to the success of this study.

The committee would particularly like to acknowledge the excellent support it received from the project sponsors, the U.S. Department of Energy National Nuclear Security Administration and Office of Nuclear Energy. The committee is especially grateful for the support it received from Dunbar Lockwood, Dan Vega, Karyn Durbin, Ed Wonder, and John Murphy.

The committee gratefully acknowledges the following people who provided presentations at its information-gathering sessions:

Robert Bari, Brookhaven National Laboratory
Jeff Bedell, Los Alamos National Laboratory
Kory Budlong-Sylvester, Los Alamos National Laboratory and current member of the International Atomic Energy Agency's (IAEA's) Standing Advisory Group on Safeguards Implementation (SAGSI)
Tod Caldwell, NNSA Office of Nuclear Controls
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Joyce Connery, National Security Council
Lisa Owens Davis, Lawrence Livermore National Laboratory
Phillip Dolliff, Office of Cooperative Threat Reduction, Department of State
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Jeff Kaplaw, University of California San Diego
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Susan Koch, Missouri State University
Warren "Pete" Miller, Bipartisan Policy Center
John Murphy, Pacific Northwest National Laboratory
Mary Beth Nikitin, Congressional Research Service
Gordon Oehler, Potomac Institute University
Rafail Ostrovsky, University of California Los Angeles
Jon Phillips, Pacific Northwest National Laboratory
Joe Pilat, Los Alamos National Laboratory
M.V. Ramana, Princeton University
William Rhodes, NNSA Office of Nuclear Controls
Ray E. Richardson, Central Intelligence Agency
Gary Rochau, Sandia National Laboratories
Michael Rosenthal, past member of the IAEA's SAGSI
James Smith, Los Alamos National Laboratory
James Sprinkle, IAEA Department of Safeguards
Sharon Squassoni, Center for Strategic and International Studies
John Steinbruner, University of Maryland
Richard J. K. Stratford, Director of the Office of Nuclear Energy Safety and Security, Department of State
Steven Streetman, Data Architecture Solutions, Inc.
David Sweeney, Texas A&M University
Lynn Timmons, NNSA, Office of Nuclear Controls (contractor)
Michael Uzzle, NNSA
Mary Beth Ward, Lawrence Livermore National Laboratory
Christopher Way, Cornell University
Anatoli Welihozkiy, NNSA Office of Nuclear Controls
Ed Wonder, NNSA Office of International Regimes and Agreements

The committee would also like to thank the individuals that assisted in the logistical preparation at the sites the committee visited. Their assistance greatly aided the committee in their task. These include:

Reid Pauly, Stanford University
Jessica Groom, Lawrence Livermore National Laboratory
Suzanne Cordoza, Sandia National Laboratories
Kathy Loeppky, Sandia National Laboratories
Peggy Desko, Sandia National Laboratories
Susan Washburn, Sandia National Laboratories

The committee extends special thanks to the staff of the National Research Council for supporting this study. Staff members who contributed to this effort include Jenny Heimberg (study director), Benjamin Rusek (staff member of the Committee on International Security and Arms Control), Kevin Crowley (director of the Nuclear and

Radiation Studies Board), Erin Wingo (senior program assistant), and Toni Greenleaf (financial and program associate).

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council. The purpose of this independent review is to provide candid and critical comments that will assist the National Research Council in making its published report as sound as possible and will ensure that this report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report:

Robert Bari, Brookhaven National Laboratory
Steven Becker, Old Dominion University, School of Public Health
Matthew Bunn, Harvard University
Mona Dreicer, Lawrence Livermore National Laboratory
Steve Fetter, University of Maryland
Alan Icenhour, Oak Ridge National Laboratory
Thomas Isaacs, Lawrence Livermore National Laboratory
Sharon Squassoni, Center for Strategic and International Studies
John Steinbruner, University of Maryland
James Timbie, U.S. Department of State
Larry Turnbull, Riverside Research
Kevin Wood, U.S. Naval Postgraduate School
Michael Zentner, U.S. Department of Energy

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations of this report, nor did they see the final draft of the report before its release. The review of this report was overseen by Richard Meserve, Carnegie Institution for Science, and Granger Morgan, Carnegie Mellon University. Appointed by the National Research Council, Drs. Meserve and Morgan were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were considered carefully. Responsibility for the final content of this report rests entirely with the authorizing committee and the institution.

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APPENDICES

EXECUTIVE SUMMARY

The Department of Energy Office of Nuclear Energy (DOE-NE) and the National Nuclear Security Administration (NNSA) Office of Nonproliferation and International Security requested that the National Academy of Sciences (NAS) perform a study on improving the assessment of proliferation risk of nuclear fuel cycles for use by nonproliferation policy makers and decision makers. Both sponsors are considering how technical assessments of proliferation risk can more effectively contribute to

- improved programmatic decisions on research and development (R&D) of future nuclear fuel cycles including scientific engagement;
- better information for nonproliferation policy decisions, for example, on nuclear export and peaceful nuclear engagement; and
- clearer communication of those decisions to other U.S. government agencies, the public, and international partners.

The committee found that nonproliferation policy makers use a variety of data and information sources to guide their decisions. One type of technical assessment methodology, which the committee terms “predefined frameworks,” guides a subset of decisions by comparing future nuclear fuel cycles to existing ones. This methodology typically divides the nuclear fuel cycle into processing steps, assigns values to intrinsic (material- and fuel cycle-specific technical details) and extrinsic (safeguards, inspections, and facility operational details) proliferation barriers at each step, combines the results using weighting functions, and determines the overall proliferation resistance of fuel cycle options using a predefined approach. A more common type of technical assessment uses multidisciplinary teams of experts to address technical topics as they arise. These have been termed “case-by-case” assessments to differentiate them from predefined frameworks.

The committee evaluated several predefined framework methodologies and found benefits as well as shortcomings. Relative differences in intrinsic barriers among fuel cycles can be considered robust and enduring because the characteristics tend to be quantifiable (e.g., decay rates of the radionuclides within the proposed fuel). However, even the quantifiable values of intrinsic barriers are not purely objective because expert knowledge is required to assign limit and threshold values associated with many of the measures. The committee is aware of calls to improve future expert elicitation practices, but the proposed changes still fall short, for example, by relying on surveys to collect information. Further, the applications seen by the committee had shortcomings in assigning uncertainties and determining sensitivity to the information collected.

The analysis of intrinsic barriers can highlight points of low proliferation resistance within a proposed fuel cycle so that safeguards or other extrinsic barriers can be applied at those points to increase the overall proliferation resistance. However some extrinsic measures—such as facility layout, transportation paths, or the piping between critical processes—are not known until a facility has been designed, but are critical in determining the final level of proliferation resistance. All technical assessments are limited by details not yet known or defined.

The frameworks present a reasonable and consistent approach for organizing known technical information of complex nuclear fuel systems, but they have so far not highlighted previously unknown technical issues (determined by other technical analysis methods). Further, the existing frameworks assess proliferation resistance but not proliferation *risk*, which includes, among other things, an assessment of a host state's proclivity to proliferate. Although there is a significant amount of work being performed on various approaches (e.g., probabilistic risk assessment, game theory, and political science) for modeling the intent of host states to proliferate, the committee did not see results that are compelling enough to recommend the use of these approaches for this application or to endorse the inclusion of this assessment into the predefined frameworks' analysis at this time. Furthermore, the committee notes that although increased proliferation resistance can raise barriers to proliferation, a highly motivated host state will be able to overcome them.

The committee has identified the following applications as opportunities in which the current predefined frameworks can provide value and utility to policy makers if the shortcomings in their execution are addressed:

1) Comparing the proliferation resistance of fuel cycles and identifying locations to apply safeguards or material monitoring,
2) Educational applications (e.g. academic applications or new nuclear energy states), and
3) Enabling consistent communication with international partners or the public on nuclear energy decisions by providing analysis through the application of a predefined, internationally accepted and known methodology.

Nonetheless, the committee does not support a new or expanding R&D program in this area. Based on discussions with policymakers, the committee determined that the existing tools have limited utility to inform their nonproliferation decisions beyond what a case-by-case analysis would produce. Case-by-case analysis also uses expert knowledge and can suffer from the same challenges listed above regarding predefined frameworks. However, their use of expert opinion and knowledge is clear and understood by policymakers while predefined frameworks' use of expert knowledge is less clear because it is often combined and presented as an integrated result.

The committee recommends that fuel cycle R&D decisions include proliferation resistance instead of proliferation risk as one factor among others (such as cost and safety) to guide those decisions. Technical assessments are limited by the availability of technical details associated with future nuclear fuel cycles. Therefore, the committee recommends that DOE-NE and NNSA jointly decide upon a set of high-level questions comparing the proliferation resistance of proposed future fuel cycles to the current once-through fuel cycles. Assessments should be revisited at key milestones throughout the technologies' development and eventual deployment as new and better information and data emerge.

Finally, the committee finds that the terms "proliferation risk" and "proliferation resistance" are frequently used interchangeably and incorrectly, which hampers communication at all levels (within the U.S. government, industry, the public and international partners). There is a distinct difference between these terms: "proliferation risk" includes host state and region-specific considerations while "proliferation resistance" is focused on the nuclear energy system's intrinsic and extrinsic barriers. The U.S. government (e.g., DOE-NE and the NNSA) could improve communication by initiating efforts to define "proliferation risk" and lead by example with proper and consistent use of these terms.

SUMMARY

The material that sustains nuclear reactions to produce nuclear energy can also be used to make nuclear weapons, and so the development of nuclear energy by a non-nuclear weapons state is considered one of multiple pathways to potential proliferation and represents a subset of issues within nuclear nonproliferation. The risk of proliferation through the nuclear energy development pathway can be described as containing several components: an intrinsic component (e.g., the amount of weapons-usable material produced throughout the particular fuel cycle) and many external components such as host-state factors (e.g., political and regional stability and technical capability) and facility design details (layout of buildings and application of safeguards).

Assessments associated with proliferation risk are performed using subject-matter experts (both technical and nontechnical) who can provide:

- quantifiable data for intrinsic aspects of the fuel cycle and facility data, if the data are available, and
- opinions and knowledge about host-state factors.

This study considers how the current methods of quantification are being used and implemented. It also considers if existing or new methods of quantification can be extended to account for host-state factors. Methods that have been proven to have impact in other complicated systems that include human decisions (such as nuclear safety) are of particular interest.

The Department of Energy Office of Nuclear Energy (DOE-NE) and the National Nuclear Security Administration (NNSA) Office of Nonproliferation and International Security requested that the National Academy of Sciences perform a study to understand the extent and limitations of technical analysis of proliferation risk of nuclear fuel cycles for use by nonproliferation policy makers and decision makers. DOE-NE would like guidance in assessing proliferation risk as one of several critical factors guiding U.S. potential future choices for nuclear fuel cycles (by programmatic decision makers). NNSA would like guidance for better characterizing the near-term and future proliferation risk associated with the use of nuclear technology and nuclear power throughout the world (for nonproliferation policy makers). Both sponsors are considering how technical assessments of foreign host-state proliferation risk contribute to improved programmatic research decisions, nonproliferation policy decisions, and communication between U.S. government agencies, the public, and international partners.

Six findings and three recommendations emerged from this study. These are grouped with the relevant tasks and are presented and summarized below. Further supporting information can be found in the body of the report.

DEFINITIONS AND TERMINOLOGY

The International Atomic Energy Agency (IAEA) defines proliferation resistance as

> The characteristics of a nuclear energy system that impede the diversion of undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices. . . . The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures. (IAEA 2002).

Proliferation resistance assessments frequently break the fuel cycle down into individual processing steps and follow a specified framework to assess the proliferation resistance at each step. These frameworks typically contain predefined lists of detailed attributes of the fuel cycle and its processing steps and a predetermined approach for scoring and combining the attributes to determine the cycle's overall proliferation resistance. Attributes can be intrinsic (e.g., inherent to the nuclear fuel cycle's materials) or extrinsic (e.g., external to the fuel cycle such as safeguards and operations). The committee has termed these methodologies "predefined frameworks."

Proliferation risk is a more complex concept than proliferation resistance and includes analysis of country-specific issues. Although it does not have an internationally accepted definition, some analysts in the proliferation resistance assessment community have attempted to define proliferation risk through an equation that relates proliferation risk to three terms: the probability that a host state will choose to proliferate along a particular or multiple pathways (L), the probability of success along that path (P), and the consequences of proliferation (C) (NSSPI 2010, NRC 2011a, Charlton 2012). A full risk assessment sums over all possible pathways—a difficult and changing task given that a motivated host state may continuously invent new pathways, which affects the probabilities that attach to some of the above-defined terms. Country-specific factors such as motivation, technical capability, access to technology, and intent are needed to assess L (and would likely include intelligence information). Proliferation resistance could contribute to P and L. Because proliferation resistance is one component of the problem of proliferation risk and because it is not infinite (there is no proliferation-proof fuel cycle), other country-specific factors will determine whether and how a host state proliferates.

FINDINGS AND RECOMMENDATIONS

TASK 1: IDENTIFY KEY PROLIFERATION POLICY QUESTIONS CAPABLE OF BEING ANSWERED BY A TECHNICAL ASSESSMENT OF THE HOST STATE PROLIFERATION RISK POSED BY A GIVEN NUCLEAR FUEL CYCLE, AND DISCUSS THE UTILITY OF THESE QUESTIONS FOR INFORMING INTERNATIONAL NONPROLIFERATION POLICY DECISIONS.

FINDING 1.1: Technical assessments related to aspects of proliferation risk do make valuable contributions to nonproliferation policy decisions on a broad range of topics such as peaceful international nuclear cooperation, export control, nuclear fuel cycle R&D, and nuclear safeguards. However, technical assessments do not fully answer nonproliferation policy questions. Final decisions also include consideration of a much broader set of political, security, economic, and cultural issues.

The committee approached the study by first understanding a broad set of nonproliferation decisions related to the nuclear fuel cycle, and the factors that U.S. and international decision makers take into account when making these decisions. The types of decisions that require an assessment of proliferation risk include peaceful international nuclear cooperation agreements and treaties, nuclear export control decisions, international safeguards, domestic regulatory decisions and domestic nuclear fuel cycle research. The committee notes that in these cases proliferation risk is one factor among many that policy makers and decision makers must take into account. Indeed, political, economic, environmental, and safety considerations are almost always relevant and, depending on the circumstances surrounding the decision that needs to be made, may be given more weight than issues related to nonproliferation in arriving at the final outcome.

While acknowledging the importance of nontechnical factors, the committee found that for all of the nonproliferation policy issues above, technical assessments related to proliferation risk were routinely used—directly or indirectly—to inform policy makers and decision makers. Most technical assessments requested by nonproliferation policy makers are designed to inform on a specific issue and consequently are focused on a particular nuclear technology or capability in the context of a specific country or region or terrorist group. For these proliferation assessments, multidisciplinary teams of experts, often in close collaboration with the intelligence community, tailor their analysis to the specific question, including systematic assessment of both technical and country-specific issues. While addressing a very specific topic or question, these types of analyses are adapted to the variety of topics that require assessment and are the most commonly used method to inform policy makers and decision makers on technical issues (including issues that extend beyond the proliferation risk associated with nuclear fuel cycles). This approach is not unique to nuclear nonproliferation policy issues. In order to differentiate it from the predefined framework or risk assessment approaches discussed below, the phrase "case-by-case" assessments is used throughout this report.

Among the broad set of nonproliferation-related topics requiring technical assessment, questions about host state proliferation risk of a given nuclear fuel cycle represent a small subset. The technical assessment of proliferation resistance represents an even smaller subset. Regardless, predefined framework methodologies have been developed specifically for assessing the relative proliferation resistance of a given nuclear fuel cycle. They can and have been used to address questions such as:

- Are there significant differences in resistance to proliferation (e.g., time to breakout, cost, physical barriers, safeguard ability, or transparency) associated

with different types of potential future fuel cycles compared with those that exist today?
- Can extrinsic measures, such as physical security and international safeguards and/or intrinsic measures, such as reactor design, or material composition, or new operational concepts significantly increase resistance of a particular nuclear fuel cycle?
- For a given nuclear fuel cycle or facility, where are barriers to proliferation lowest? Where can safeguards be most effective in raising these barriers?

Case-by-case assessments can be, and have been, used to address these same questions.

TASK 2: ASSESS THE UTILITY FOR DECISION-MAKERS OF EXISTING AND HISTORICAL METHODOLOGIES AND METRICS USED BY DOE AND OTHERS (SUCH AS THE INTERNATIONAL ATOMIC ENERGY AGENCY) FOR ASSESSING PROLIFERATION RISK, BOTH FOR CONSIDERING THE DEPLOYMENT OF THESE FACILITIES DOMESTICALLY AND THE IMPLICATIONS OF DEPLOYMENT OUTSIDE OF THE UNITED STATES.

FINDING 2.1: Predefined frameworks have been developed and used to assess the proliferation resistance of partial or full nuclear fuel cycles. These methods provide a useful framework for comparing the intrinsic metrics or “attributes” of existing and potential future nuclear fuel cycles and for identifying where safeguards can be most effective in raising barriers to proliferation. However, these comparisons address a small subset of the wider range of issues faced by policy makers and the committee was able to determine that the frameworks have rarely been used to inform policy decisions. Additionally, there have been shortcomings in their execution.

In addressing this task, the committee notes that the “utility” of a methodology is subjective and dependent on the individual and/or organization. The committee considered the frequency of use as an indirect measure of utility and discussed the apparent impact of the methodologies’ results with policy makers and decision makers.

Predefined frameworks are methodologies designed to consistently and transparently evaluate proliferation resistance of a nuclear fuel cycle through a standardized set of predetermined attributes applied to the nuclear fuel cycle’s processing steps.[1] However, these frameworks are not objective models or simulations of nuclear facilities, operations, safeguards, material flows, or proliferation pathways. Rather, they use expert knowledge as the source of data to score the attributes at each step.[2] Such data

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[1] In 2000, the Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) Task Force formulated a set of qualitative attributes (barriers) relevant to assessing the proliferation resistance of nuclear fuel cycles and termed the approach “attributes methodologies.” The committee has used the term “predefined frameworks” to account for how the attributes are combined.

[2] The committee reviewed a broad set of current predefined frameworks starting with the original approach defined by TOPS and including more developed methodologies such as the Generation IV International

are gathered, weighted, and combined into higher-level scores to give an overall measure of proliferation resistance (usually high, medium, or low). Typical attributes of proliferation resistance include technical difficulty of proliferation, cost required to overcome barriers to proliferation, time needed to proliferate, and the probability of detection. The process of scoring, aggregating, and arriving at a final assessment of proliferation resistance may give the impression of objectivity often associated with a model while masking the reliance on subject-matter experts.

When considering that future fuel cycles would be deployed between 20 and 30 years in the future, evaluations necessarily have been for a conceptual future fuel cycle, without details about facility design, operational concept, or the country in which it might eventually be deployed. Therefore, the intrinsic details of the fuel cycles were the main focus of these evaluations with assumptions necessarily made about the type of future host state and the facility's future physical and operational details. Intrinsic attributes of proliferation resistance assessments do contain measures that can be considered robust, such as the expected decay rates of the radionuclides within the proposed fuels or required materials. The details of the extrinsic components (safeguards, inspections, and facility operational details)—an equally important component of proliferation resistance—can significantly change with time and affect the overall resistance of the fuel cycle. For example, large distances between facilities requiring transportation of material without adequate monitoring or the details of how pipes have been laid between processes with low proliferation resistance will significantly lower barriers to material diversion by a motivated host state. Additionally, the inclusion of country-specific factors will alter the assessment results when the broader concept of proliferation risk is considered.

The committee found only a few examples in which predefined framework assessments were performed with the goal of guiding decisions about research and development (R&D) for future nuclear energy systems (Bari et al. 2007, 2008b; DOE 2008b).[3] However, the committee found several examples in other domains within the U.S. government in which decision makers use predefined framework-like tools to inform decisions. Examples include prioritizing countries for engagement on nuclear, chemical, and biological security (the Office of Cooperative Threat Reduction within the Department of State; Dolliff 2012), and using risk assessment methods for optimizing architectures for global nuclear detection (the Domestic Nuclear Detection Office within the Department of Homeland Security; Streetman 2012). These examples show that some policy and decision makers do find utility in frameworks that can deconstruct complex problems into their component parts. In these instances, the policy and decision makers were actively involved in the analysis process and not interested only in the final results. The frameworks provide a structure for organizing complex problems with a large number of variables and assessing which factors are most important to the results.

Forum Proliferation Resistance and Physical Protection scenario-based assessment and Texas A&M's multi-attribute utility analysis approach. For the full list and discussion of the analysis, see Chapter 3 in the report.

[3] These reports were not directly cited by policy or decision makers, so it is not clear to the committee if and how actual decisions were made based on these reports.

The committee considered a set of predefined frameworks and found the following shortcomings in their execution:

- poor and/or undocumented expert elicitation processes, and
- lack of sensitivity and uncertainty analyses

Inherent limitations of applicability included:

- for future fuel cycles, unknown facility and host-state details, and
- limited shelf life of assessments

TASK 3: ASSESS THE POTENTIAL FOR ADAPTING RISK ASSESSMENT METHODOLOGIES DEVELOPED IN OTHER CONTEXTS (SUCH AS SAFETY AND SECURITY) TO HOST STATE PROLIFERATION RISK ASSESSMENTS—INCLUDING BOTH QUALITATIVE AND QUANTITATIVE APPROACHES—THEIR BENEFITS, LIMITATIONS, AND THE CHALLENGES ASSOCIATED WITH ADAPTING THESE METHODOLOGIES TO PROLIFERATION RISK ASSESSMENT.

FINDING 3.1: Some of the identified deficiencies in the implementation of the existing predefined frameworks for assessing proliferation resistance could be improved by adopting expert elicitation and data-gathering practices developed by other fields of risk assessment. For example, probabilistic risk assessment (PRA) methods have well-defined and established processes for gathering, quantifying, analyzing, and presenting data that could benefit the nonproliferation community. However, the challenges of an adaptive adversary and of lack of data on proliferation events in particular limit applicability of all of the risk-based methodologies to the assessment of proliferation risk considered by the committee.

Probabilistic risk assessment (PRA) methods provide a compelling example of how a risk assessment methodology can be applied to engineered systems. PRAs have developed proven processes for gathering, quantifying, analyzing, and presenting data. Additionally, PRA experts have significant and relevant experience identifying data that might otherwise be overlooked. Predefined framework methodologies could be improved by adopting the practices established by PRA practitioners, especially regarding the elicitation of expert knowledge and accounting for uncertainties.[4]

The committee is aware of efforts to understand factors that may influence a country to pursue nuclear weapons, including some efforts to develop models of how factors such as security concerns, type of government, and technical capability influence decisions (Way 2012; Gartzke 2012; Coles et al. 2009). The committee also found that

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[4] For example, expert elicitation practices that have proven to be effective in gathering knowledge and assigning uncertainties have been defined in (Kotra et al. 1996; EPA 2009).

there is a significant amount of research being performed on modeling an adaptive adversary (e.g., risk-based, social science-based, game theory-based).

Assuming that the limitations in execution are addressed, the assessment of proliferation resistance via predefined framework methodologies can provide a relative comparison between nuclear fuel cycles of the difficulty to evade barriers. However, two significant challenges exist in extending predefined framework methodologies' assessment of proliferation resistance to host-state proliferation risk assessment via the application of risk-based methodologies: 1) assessing host state factors such as motivations and intent and 2) the lack of data on the process of proliferation. Since the process of proliferation is generally carried out in secret, detailed data on the factors relevant to the probability that an adversary would choose to proliferate along a particular path or the probability of success along that pathway are not readily available. The challenge of assessing the changing conditions of a host state exacerbates these problems. Choices about proliferation pathways could change over time, based on the ability to overcome safeguards and avoid detection, as well as the ability to acquire technology covertly. The resources a host state might allocate to achieving success would depend on the strength of its motivation, which in turn would depend on its perception of the benefits of nuclear weapons. Because of the limited number of cases of proliferation in general, data on all these factors are very limited. Historical case studies provide some relevant data about countries that have given up nuclear weapons programs in the past, but limited data are available on successful efforts.

Although there is a significant amount of work being performed on the modeling of adaptive adversaries (e.g., probabilistic risk assessment, game theory), the committee did not see results that were supported by evidence of success in real-world applications and therefore does not endorse the inclusion of this assessment into the predefined frameworks' analysis at this time. Furthermore, the committee notes that although increased proliferation resistance can raise barriers to proliferation, a highly motivated, technically capable state will be able to overcome them.

RECOMMENDATION 3.1: DOE-NE and NNSA should consider whether elements of a formal PRA approach could improve multidisciplinary assessments of proliferation risk, especially the quantification of uncertainties. Although the committee concluded that work on understanding motivations to develop nuclear weapons and modeling an adaptive adversary do not have evidence-based records of success in real-world situations, it supports the inclusion of such approaches into proliferation risk analysis when and if they have an established quantitative basis.

TASK 4: IDENTIFY R&D AND OTHER OPPORTUNITIES FOR IMPROVING THE UTILITY FOR DECISION MAKERS OF CURRENT AND POTENTIAL NEW APPROACHES TO THE ASSESSMENT OF PROLIFERATION RISK.

FINDING 4.1: The committee has identified several specific applications as opportunities in which the current predefined frameworks could provide value and utility to decision makers as long as the shortcomings in their execution are addressed. While aware of their existence, decision and policy makers have rarely

used predefined framework assessments to inform their decisions. They have noted that the predefined frameworks have not highlighted previously unknown proliferation issues related to nuclear fuel cycles. Because these issues are not addressed by expansion or further development of existing predefined frameworks, the committee does not support a new or expanding R&D program.

The committee found that nonproliferation policy and decision makers routinely use multidisciplinary teams on a case-by-case basis and their own knowledge to provide analysis across a broad range of topics including proliferation risk. Policy makers have found that proliferation resistance assessments using predefined frameworks address a subset of their issues, and the predefined frameworks have not produced significant results that were not previously understood. Additionally, some policy makers have expressed concern with predefined frameworks that integrate many factors or produce a single-valued result for a complex problem. They are also concerned that they would be bound by the results. Therefore, in general policy makers find little utility in using predefined frameworks or formal risk-based approaches for such applications.

Proliferation resistance assessments for potential future fuel cycles have limited information on technical design features, operational modalities, institutional arrangements and safeguards measures. The cost and time of executing a predefined framework or any other detailed technical assessment to inform R&D decisions is difficult to justify. For R&D decisions, it would be more useful to simplify the analysis to addressing a few key questions, tailored to the level of known detail. As the technology is developed and comes closer to deployment, many more details may be known and the use of a predefined framework may be justified.

The committee found several examples of nonproliferation policy makers and decision makers using a checklist of high-level questions to consistently address proliferation risk-related issues. For example, all Nuclear Cooperation Agreements (NCAs) have nine requirements to be addressed in the Nuclear Proliferation Assessment Statement (NPAS), and the NNSA's Office of Nuclear Controls uses a set of seven questions that must be answered for each export review that is performed.

RECOMMENDATION 4.1: The committee recommends that fuel cycle R&D decisions include proliferation resistance (rather than proliferation risk) as one factor among others (such as cost and safety) to guide those decisions. Technical assessments are limited by the availability of technical details associated with future nuclear fuel cycles. Therefore, the committee recommends that DOE-NE and NNSA jointly decide upon a set of high-level questions comparing the proliferation resistance of proposed future fuel cycles to the current once-through fuel cycles to determine as early as possible in their development whether the former have significantly different intrinsic proliferation resistance (either for the better or for the worse). Assessments should be revisited at key milestones throughout the technologies' development and eventual deployment; they should become more detailed as appropriate as new and better information and data emerge.

In determining the set of questions, DOE-NE and NNSA may consider existing metrics or questions. It may not be necessary to develop a new set of high-level questions.

TASK 5: IDENTIFY AND ASSESS OPTIONS FOR EFFECTIVELY COMMUNICATING PROLIFERATION RISK INFORMATION TO GOVERNMENT AND INDUSTRY DECISION MAKERS, AS WELL AS THE PUBLIC AND THE NON-GOVERNMENTAL ORGANIZATION (NGO) COMMUNITY BOTH WITHIN THE UNITED STATES AND INTERNATIONALLY.

The nonproliferation community consists of many segments: U.S. and international policy makers and decision makers, technical analysts, non-governmental organizations, academics, as well as the interested public. Communication among these communities is often impeded by issues such as lack of common vocabulary, differences in technical background, knowledge of social or political issues, lack of access to classified information, and overall distrust.

FINDING 5.1: The terms "proliferation risk" and "proliferation resistance" frequently are used interchangeably and incorrectly when discussing nuclear energy systems. In addition, technical methods for assessing proliferation resistance are often referred to as methods for assessing proliferation risk. This creates confusion, is misleading, and impedes communication.

FINDING 5.2: Predefined framework assessments provide a structured approach that can enhance communication and education as long as their purpose, scope, assumptions, and limitations are clearly stated and understood.

Predefined framework methodologies can facilitate communication about proliferation resistance by providing a structure for organizing and discussing complex data. For example:

- *Domestic and international communities*: Predefined frameworks provide a common lexicon and vocabulary during international expert discussion, thereby facilitating communications (e.g., Gen IV International Forum Proliferation Resistance and Physical Protection Working Group).
- *Policy makers, public, and international partners*: Predefined frameworks can help establish a common lexicon and provide a useful structure for communicating how a large number of factors contribute to proliferation resistance, and facilitate communication of policy decisions to NGOs, the interested public, and international partners.

Predefined framework assessments can also be useful for training academics and next-generation policy makers on proliferation-relevant features of the nuclear fuel cycle, the role of international safeguards, and approaches to increasing proliferation resistance.

However, the purpose, scope, and assumptions of framework methodologies must be clear, if results are to be interpreted appropriately. It should be clear that assessments of proliferation resistance or risk are not absolute, evolve with time, and are one factor among many that contribute to nonproliferation decisions.

RECOMMENDATION 5.1: To build trust and increase transparency with domestic and international stakeholders, policy makers and decision makers should refrain from technical jargon in communicating proliferation risk, refer to information available to all parties whenever possible, and always include discussion of the assumptions and limitations inherent in any assessment.

1

BACKGROUND AND INTRODUCTION

The challenge of balancing the benefits of nuclear energy against the risks of nuclear proliferation has been recognized since the dawn of the nuclear age (Barnard et al. 1946 [Acheson–Lilienthal Report]; Eisenhower 1953). In the last 10 years, interest in nuclear energy has increased significantly, and the number of countries with interest in nuclear power reactors is still expected to increase despite the events at Fukushima (Amano 2013). This expansion has provoked renewed concern about nuclear proliferation and efforts among nuclear supplier states to revise nonproliferation policies and to develop new fuel cycles that do not increase proliferation risks. Much of the focus has been on technologies that can be used to produce nuclear weapons material from natural uranium and spent nuclear fuel, widely referred to as enrichment and reprocessing (E&R) technology. A number of E&R facilities (approximately 10 enrichment facilities and half a dozen reprocessing facilities; IPFM 2011) currently exist. Limiting the future expansion of E&R technology is a widely accepted nonproliferation goal (NRC 2009).

As the primary source of funding for nuclear fuel cycle research and development (R&D) in the United States the Department of Energy Office of Nuclear Energy (DOE-NE) makes decisions about how to invest its resources to develop cost-effective and environmentally sustainable fuel cycles that do not have increased proliferation risks. The DOE National Nuclear Security Administration (NNSA) is a major player in the U.S. interagency team that makes decisions about U.S. nonproliferation policy, including international nuclear cooperation and nuclear export control. The NNSA also funds R&D in nuclear safeguards technology to detect and impede misuse of civilian nuclear technology and material for military purposes.

The missions of DOE-NE and NNSA occasionally can be in conflict because DOE-NE is focused on developing and deploying future nuclear energy systems and technologies whereas the NNSA is focused on minimizing and managing proliferation risks of nuclear energy. Over the years, both DOE-NE and NNSA have invested in developing nonproliferation assessment tools to help evaluate and compare proliferation factors between different future fuel cycles. As they consider further development and use of these tools, they have requested advice from the National Academy of Sciences.

The sponsors requested that the study be carried out in two consecutive phases. Phase 1 was a workshop that was held August 1-2, 2011, at the National Academies' Keck Center in Washington, D.C. It focused on encouraging discussion between policy makers and the technical assessment community but was not designed to produce

BOX 1.1
Statement of Task

1. Identify key proliferation policy questions capable of being answered by a technical assessment of the host state proliferation risk posed by a given nuclear fuel cycle, and discuss the utility of these questions for informing international nonproliferation policy decisions;
2. Assess the utility for decision makers of existing and historical methodologies and metrics used by DOE and others (such as the International Atomic Energy Agency) for assessing proliferation risk, both for considering the deployment of these facilities domestically as well as the implications of deployment outside the United States;
3. Assess the potential for adapting risk assessment methodologies developed in other contexts (such as safety and security) to host state proliferation risk assessments—including both qualitative and quantitative approaches—their benefits, limitations, and the challenges associated with adapting these methodologies to proliferation risk assessment;
4. Identify R&D and other opportunities for improving the utility for decision-makers of current and potential new approaches to the assessment of proliferation risk; and
5. Identify and assess options for effectively communicating proliferation risk information to government and industry decision-makers, as well as the public and the NGO community both within the United States and internationally.

This study will not address the risk associated with the physical security of the facility or materials against attack, theft, or diversion of nuclear materials. The study may examine policy options but will not make specific policy recommendations.

consensus findings or conclusions. A summary of the briefings and discussions was released as a workshop report in January 2012 (NRC 2011a). Phase 2, a study completed by a separately constituted committee, addresses the full statement of task (Box 1.1) and produces findings and recommendations agreed by consensus.

COMMITTEE MEMBERSHIP

The study was carried out by a committee of experts appointed by the National Research Council (NRC). The committee's 12 members have a breadth of experience, including risk assessment and communication methods, proliferation metrics and research, nuclear fuel cycle and power plant design and engineering, international nuclear nonproliferation and national security policy, and nuclear weapons design. Special attention was given to including diverse perspectives on methods for assigning values to risk or approaches for quantifying critical aspects of complex systems; a balance of nuclear fuel cycle research knowledge and real-world nonproliferation security expertise; and practical program evaluation experience with an understanding of how metrics could be applied to policy decisions. Biographical sketches of the committee members are provided in Appendix A.

SCOPE, DEFINITIONS, AND TERMINOLOGY

The focus of this study is on methods to assess the "host-state proliferation risk" of a given nuclear fuel cycle. In other words, the committee was not asked to evaluate methods for assessing the risks that a terrorist organization or non–state actor will acquire and use a nuclear fuel cycle for purposes of proliferation, nor that they will attack a nuclear facility to acquire material or technology. Although the risk associated with the physical security of the facility or materials against attack, theft, or diversion is an important challenge, and clearly related to host-state proliferation risk, it is outside the request and hence beyond the scope of this study. We note that these two types of risk cannot be separated completely, and attempting to do so may lead to overlooking or minimizing significant factors. In fact, a host state could easily access any material that would be plausible for non–state actor diversion scenarios. Any material that non–state actors could potentially steal, a host state could more easily divert.

The committee notes that the terminology widely used to discuss the concept of proliferation risk is subject to inconsistency. In particular, the terms "proliferation risk" and "proliferation resistance" frequently are used interchangeably and incorrectly when discussing nuclear energy systems. Proliferation resistance is one factor among many that contribute to proliferation risk, and most technical assessment methodologies assess proliferation resistance, rather than risk.

> The International Atomic Energy Agency defines proliferation resistance as the characteristics of a nuclear energy system that impede the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices. . . . The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures. (IAEA 2002)

Proliferation resistance assessments focus on the engineering-aspects of the fuel cycle under consideration. Often, these assessments follow a specified framework that defines a given fuel cycle by individual processing steps, assesses a predefined list of detailed attributes against a proliferation threat, and uses a predetermined approach for scoring and combining the attributes to determine the cycle's overall proliferation resistance. They can also be used to identify the steps within the cycle with the least resistance. The committee has termed these methodologies "predefined frameworks."

Proliferation risk is a more complex concept and includes, among other things, analysis of country specific issues. Although it does not have an internationally accepted definition, some analysts in the proliferation resistance assessment community have attempted to define proliferation risk through an equation that relates proliferation risk to three terms: the probability that an adversary will choose to proliferate along a particular pathway (L), the probability of success along that path (P), and the consequences of proliferation (C) (NSSPI 2010, NRC 2011a, Charlton 2012). A full risk assessment sums over all possible pathways. The committee notes that this is a difficult and evolving task for situations in which a motivated host state may continuously invent new pathways (including illegal acquisition) or regional stability alters that motivation; both examples affect the probabilities that attach to the terms above. Country-specific factors such as motivation, technical capability, access to technology, and intent clearly are needed to assess L. Proliferation resistance could contribute to both P and L. Because proliferation resistance is one component to the problem of proliferation risk and because it is not infinite (there is no proliferation-proof fuel cycle), other country-specific factors will determine whether and how a host state proliferates.

REPORT ROADMAP

The report is organized into five chapters that correspond to the five tasks in the study charge.

Chapter 2 describes the types of proliferation-related topics faced by decision makers and identifies questions that can be informed by a broad range of technical assessments. It ends with a discussion of the types of questions that can be addressed by technical assessment of proliferation resistance.

Chapter 3 describes historical and existing methods for assessing proliferation risk, with a particular focus on predefined framework methodologies, identifies their strengths and weaknesses, and discusses their utility to decision makers.

Chapter 4 considers how risk assessment methodologies from other fields might be applied to the problem of proliferation risk assessment. It also discusses how application of these approaches could be applied to address deficiencies in implementation of predefined framework assessments.

Chapter 5 addresses needs for future R&D to improve assessments of proliferation risk, based on the findings of Chapters 3 and 4. Chapter 6 focuses on approaches for better communicating results of technical assessments to different audiences, including policy makers, the international community, and the public.

2

KEY PROLIFERATION POLICY QUESTIONS

In this chapter, the committee addresses the first task in the study charge:

TASK 1: Identify key proliferation policy questions capable of being answered by a technical assessment of the host-state proliferation risk posed by a given nuclear fuel cycle, and discuss the utility of these questions for informing international nonproliferation policy decisions.

The first section addresses peaceful nuclear cooperation with target states with attention to Nuclear Cooperation Agreements. The second describes export controls and licenses of nuclear material through the Nuclear Suppliers Group guidelines. The last part of the chapter presents policy questions aimed toward research and development (R&D) of future safeguards.

The committee approached this task by first identifying a broad set of policy decisions that are often made and are related to the proliferation risk of the nuclear fuel cycle. These include whether and how to peacefully engage in a nuclear cooperation with a specific country, whether to approve a company's request for an export license, future directions for U.S. nuclear fuel cycle R&D, priorities for nuclear safeguards, and possible changes in regulatory policy. In each of these cases, technical assessment of proliferation risk plays an important role in informing the decision-making process but is not the only input. Indeed, political, economic, environmental, and safety considerations are almost always relevant and, depending on the circumstances, may be given more weight in arriving at the final outcome.

Technical assessments are made using a variety of approaches, depending on the issue. In many cases, technical assessments are designed to address a question about the risk of a particular nuclear technology or capability in the context of a specific country or region. Such assessments are frequently performed by multidisciplinary teams, often in close collaboration with the intelligence community. They bring technical analysis together with in-depth knowledge of the country in question, and utilize a variety of approaches including hypothesis testing, scenario building to examine possibilities, trend analysis to look at patterns over time, and analysis of host-state technical capabilities. As far as the committee was able to determine, these assessments do not use probabilistic risk assessment[5] in their analysis. For a relatively small subset of questions concerning the relative proliferation resistance of a particular nuclear fuel cycle against existing fuel cycles (usually once-through cycles), technical assessments have been made using a "predefined framework" methodology. Such methodologies provide a structured approach for comparing the technical barriers to the proliferation of different generalized nuclear fuel cycles (see Chapter 3).

To illustrate the role of technical assessments in nonproliferation policy decisions related to the nuclear fuel cycle, we identify questions in three interrelated categories and discuss how technical assessments contribute to answering them. These categories are

- peaceful international nuclear cooperation agreements,
- export control, and
- nuclear fuel cycle R&D and nuclear safeguards.

PEACEFUL INTERNATIONAL NUCLEAR COOPERATION

Peaceful International nuclear cooperation takes many forms, ranging from cooperation on nuclear safety to fuel cycle R&D. Section 123 of the U.S. Atomic Energy Act[6] stipulates that a Nuclear Cooperation Agreement must satisfy specific nonproliferation requirements (see Box 2.1). Decisions to enter into Nuclear Cooperation Agreements (often referred to as 123 Agreements) require extensive interagency evaluations and must ultimately be approved by Congress. A Nuclear Proliferation Assessment Statement (NPAS) is prepared as part of this process, which includes

- background of the nonproliferation policies of the country in question;
- anticipated general areas of potential cooperation;
- summary of anticipated issues requiring U.S. advanced consent before the partner country can carry out certain activities using U.S.-supplied nuclear material, equipment, technology, or facilities;
- review of how the agreement will meet the nine criteria established by Section 123 of the U.S. Atomic Energy Act (see Box 2.1); and
- assessment of how the agreement is in the interests of the United States.

The NPAS is not a technical document and generally does not provide details of specific topics for cooperation. It is anticipated that these specific topics would be negotiated at a future time and be subject to additional approval processes, including export control. There is often a classified annex to the NPAS, which can provide greater technical details about potential issues.

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[5] See Appendix E: Glossary for a short definition of and reference for probabilistic risk assessment.

[6] Atomic Energy Act of 1954 as amended, Public Law 83-703, Section 123.

Although technical assessments of proliferation risk might not be requested explicitly during the process of preparing the NPAS, technical analysis informs the discussion of the nonproliferation issues and bona fides of the country in question. Technical assessments would also be relevant during the negotiating process in delineating particular restrictions that should apply to the cooperation. Analysis to inform the process would be done on a case-by-case basis tailored to the particular country in question and would synthesize information about technical capabilities, political motives, past behaviors, as well as overall analysis of the regional security situation. Of all of these factors, host-state motivation is perhaps the most difficult to assess because it ultimately depends on the subjective decision making of political leaders.

Examples of questions addressed in the NPAS that require some level of technical judgment include:

- Is the country compliant with international nonproliferation commitments? Is it engaged in nuclear cooperation with countries of proliferation concern?
- Has the country engaged in R&D relevant to nuclear weapons now or in the past? Does it have the technical capability to make nuclear weapons?
- What are the country's civilian nuclear energy aspirations, capabilities, expertise, and infrastructure?
- What will be the nonproliferation impacts of the anticipated cooperation (e.g. increased security)?

NUCLEAR EXPORTS

While Congress makes export control laws, the U.S. government officials within the Executive Branch implement the laws through policies and international commitments about nuclear exports. International policies require consensus and are harmonized within the Nuclear Suppliers Group (NSG). International policies provide guidelines for specific nuclear exports according to a series of conditions. International guidelines are not mandatory, but they often become the basis for the national export controls that nuclear exporters are required to impose on particular commodities and technologies destined for specific countries.

Internationally, the NSG has a particularly important role.[7] The NSG is a group of nuclear supplier countries that seeks to hinder if not prevent the proliferation of nuclear weapons through the implementation of general "guidelines" for nuclear energy and

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[7] The Nuclear Suppliers Group is an international, consensus-based group of participating governments (PGs) which seeks to contribute to the non-proliferation of nuclear weapons by defining and maintaining guidelines for nuclear exports and nuclear related exports. See the website for the Nuclear Suppliers Group: http://www.nuclearsuppliersgroup.org/Leng/default.htm . The NSG Guidelines have been published in the IAEA document, INFCIRC/539: http://www.iaea.org/Publications/Documents/Infcircs/1997/inf539.shtml.

BOX 2.1
Atomic Energy Act Section 123 Agreement Analysis Requirements

The nine nonproliferation requirements listed within the Atomic Energy Act's Section 123 are:

- All nuclear material and equipment transferred to the country will remain under safeguards in perpetuity.
- For non–nuclear weapon states, full-scope International Atomic Energy Agency (IAEA) safeguards must be applied to all nuclear facilities and materials under their control.
- Non–nuclear weapons states commit that transferred material, equipment, technology (or material made from them) will not have a role in development or research into nuclear weapons.
- For non–nuclear weapon states, the United States has the right to demand the return of transferred items should the country detonate a nuclear device or violate an IAEA safeguards agreement.
- The United States must consent to any retransfer of material, facility, or restricted data received under the 123 Agreement, or material produced from these.
- Adequate physical security must be applied to transferred nuclear material and all special nuclear material produced from materials or facilities transferred under the agreement.
- Prior consent from the United States must be provided before enriching, reprocessing, or otherwise altering any material obtained or produced under the agreement.
- Prior consent from the United States must be provided before storing plutonium, uranium-233 (U-233), or uranium enriched above 20% obtained or produced under the agreement.
- Any special nuclear material or production or facilities produced or constructed under the agreement will be subject to all of the above conditions.

nuclear energy–related technology transfer exports while also supporting legitimate trade within the industry. NSG Guidelines address items in two categories: trigger list items especially designed for nuclear use (materials, equipment, facilities, or technologies) and which can be directly used to make nuclear weapons (for example, centrifuges); and dual-use items that can make a major contribution to an unsafeguarded nuclear fuel cycle or nuclear explosive activity, but which have nonnuclear uses as well (e.g., high-strength aluminum tubes).

Member states of the NSG meet periodically to review the items on these lists as well as the guidelines. In preparation for these reviews, technical assessments are requested to answer questions (Bedell 2012) such as

- Does the item have an important function in the nuclear fuel cycle or in nuclear weapon design, manufacturing, or testing?
- Have countries seeking nuclear weapons sought the item in the past or might they do so in the future?
- Is controlling access to the item feasible or is the item internationally accessible?
- What would be the impact on nonnuclear trade? What would be the licensing burden?
- How many suppliers are there for the item? Are there sources of supply outside the control regime?
- Are there cost-effective substitutions for item?
- Would alternative paths to proliferation also need to be identified and safeguards developed to prevent them?

At a national level, an export license is required to export certain items or commodities (e.g., a reactor cooling pump) to certain countries. The interagency process of reviewing requests for export licenses includes technical assessments to address questions such as the following:[8]

- Is the commodity categorized correctly? What are the restrictions on export of this commodity?
- Is the commodity appropriate for the stated end use?
- Is the stated end use a proliferation concern?
- Does the commodity have application to other uses of concern? If so, what would be required to divert the item to these uses?
- Are the potential concerns significant relative to the country's current capabilities?
- Are appropriate measures in place to prevent re-export of the technology without U.S. permission?

The committee notes that the technical assessments requested to support export control policy makers on both international and national decisions must systematically address a set of predefined questions, but do not utilize a formal methodology. Subject matter experts familiar with the commodities and the countries in question perform the analyses and produce reports to document their findings.

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[8] Export Control Review and Compliance, Enforcement and Interdiction Support, Office of Nuclear Controls (DOE, NA-242), (Welihozkiy 2012a–d). Note that this office provides the technical analysis to support decisions but does not make decisions itself. These are made by the U.S. State Department, Department of Commerce, or the Nuclear Regulatory Commission, unless the item is only technology, that is, not tangible, but information, in which case DOE NA-24 makes the recommendation and the general counsel and deputy secretary make the final decision. Use of the word "technology" here is consistent with its use in nuclear exports and refers to information, blueprints, software, or knowledge passed to others.

NUCLEAR FUEL CYCLE R&D AND NUCLEAR SAFEGUARDS

As the nuclear energy market evolves globally, the next generation of nuclear fuel cycle technology proposes safer and cheaper designs. As the primary source of funding for nuclear fuel cycle R&D in the United States and a participant in international R&D forums, such as the Generation IV Forum,[9] the DOE-NE currently makes decisions about how to invest its R&D dollars based on several criteria including cost, sustainability, and proliferation risk.[10] The committee notes that assessment of proliferation risk of a particular nuclear fuel cycle includes analysis of country-specific factors such as the probability that a country's leadership would choose to proliferate using a specific fuel cycle and the probability that it would be successful if it chose to do so. The proliferation resistance of the fuel cycle in question could contribute to both of these factors. Potential questions about proliferation resistance of potential future fuel cycles were discussed and determined by the committee to include

- Are there significant differences in resistance to proliferation (e.g., time, cost, physical barriers, safeguard-ability, or transparency) associated with different potential future fuel cycles compared with those that exist today?
- Can extrinsic measures such as physical security and international safeguards, intrinsic measures such as reactor design or material composition, or new operational concepts significantly increase resistance?

Questions about the larger issue of proliferation risk are highly dependent on the intent and motivation of the host state, which include political and technical conditions at the time of fuel cycle deployment as well as the details of the facility design and application of safeguards. It is difficult to project how these conditions could feasibly contribute to decisions about R&D for new fuel cycles that might not be deployed for 20–30 years.

In addition to questions about proliferation resistance of future nuclear fuel cycles, policy makers in the United States and internationally continually grapple with questions about how to invest resources effectively to detect and impede proliferation. These issues are important in arguing for new approaches to IAEA safeguards and in determining R&D priorities for "next-generation safeguards," where increasing proliferation resistance of existing fuel cycles whether through intrinsic (inherent to the fuel cycle) or extrinsic (application of safeguards) approaches is an important goal.[11] An example of a question that requires technical analysis is

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[9] In nuclear energy systems, current designs are referred to as "Generation III." Future fuel cycles are referred to as "Generation IV" (GENIV).

[10] The DOE-NE Technology Roadmap currently includes "proliferation risk" as one of four central criteria to be used to guide decisions on R&D for future nuclear fuel cycles. Therefore, the committee purposefully uses "risk" instead of "resistance" in this example.

[11] The IAEA uses the Physical Model to organize existing data into the major components of a full nuclear fuel cycle in order identify weaknesses in safeguards.

For a given nuclear fuel cycle and facility, where are barriers to proliferation lowest? How can safeguards be most effective in raising these barriers?

A number of "predefined framework methodologies" have been developed to address questions about proliferation resistance and are discussed further in Chapter 3. Indeed, the remainder of this report is concerned primarily with these predefined methodologies and their applications.

FINDING 1.1: Technical assessments related to aspects of proliferation risk do make valuable contributions to nonproliferation policy decisions on a broad range of topics such as peaceful international nuclear cooperation, export control, nuclear fuel cycle R&D, and nuclear safeguards. However, technical assessments do not fully answer nonproliferation policy questions. Final decisions also include consideration of a much broader set of political, security, economic, and cultural issues.

3

UTILITY OF PROLIFERATION ASSESSMENTS

The preceding chapter focused on the first task by identifying the types of policy questions that technical analysis of host-state proliferation risk could inform. This chapter focuses on the second charge of the study task:

TASK 2: Assess the utility for decision makers of existing and historical methodologies and metrics used by DOE and others (such as the International Atomic Energy Agency [IAEA]) for assessing proliferation risk, both for considering the deployment of these facilities domestically as well as the implications of deployment outside the United States.

The committee describes the general characteristics of a selected set of predefined framework methodologies, discusses their strengths and weaknesses, and then comments on their utility to policy makers and decision makers. The first part of the chapter describes the characteristics of each of the methodologies used by the Department of Energy (DOE) and others to assess technical aspects of proliferation risk, recognizing that the methodologies were originally developed to assess proliferation resistance. The committee then evaluates the methodologies and their execution, and identifies shortcomings and applications for which the methodologies are well-suited. The chapter concludes with the committee's evaluation of the utility of predefined frameworks for decision makers.

In Chapter 2 the committee noted that technical assessments related to proliferation risk are made using a variety of approaches and often are designed to address a question about a particular nuclear technology or capability in the context of a specific country or region. Such assessments are frequently performed on a case-by-case basis by multidisciplinary teams of subject matter experts, often in close collaboration with the intelligence community. As far as the committee was able to determine, these assessments were systematic but did not follow predefined, structured frameworks or use probabilistic risk assessment.

Within the area of nonproliferation policy, questions concerning technical analysis of host-state proliferation risk of a given nuclear fuel cycle represent a relatively small subset. Technical assessments of proliferation resistance address an even smaller subset because, as noted previously, proliferation resistance is contained within the analysis of proliferation risk.[12] Regardless, "predefined framework methodologies" have been developed specifically for assessing proliferation resistance. Such predefined frameworks provide a generic structured approach for comparing the technical features of different generalized nuclear fuel cycles by breaking the full fuel cycle into individual processing steps and analyzing each step against a threat using a set of metrics (or attributes). These predefined framework methodologies will be the focus of this chapter because they are used by both the Department of Energy Office of Nuclear Energy (DOE-NE) and National Nuclear Security Administration (NNSA) and are being developed by others such as the International Atomic Energy Agency (IAEA) (ANS 2012, Herczeg 2012, Lockwood 2012). The committee has not included other methodologies for assessing proliferation resistance in the structured evaluation in this chapter. However, the committee did consider other analyses in Chapter 2, such as case-by-case analyses, and in Chapter 4 in which other methods for assessing risk are reviewed.

BACKGROUND OF THE DEVELOPMENT OF PREDEFINED FRAMEWORKS

Numerous methods for analyzing technical aspects of proliferation risk of the nuclear fuel cycle have been developed over the decades (GENIV Forum 2011a; Charlton 2012). The *Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems* (TOPS; NERAC TOPS Task Force, 2001) report formulated a set of qualitative attributes relevant to the intrinsic (materials and inherent properties of the fuel cycle) and extrinsic (institutional and application of safeguards) aspects of a nuclear fuel cycle. The TOPS report was also used as a basis for identifying R&D priorities for DOE and recommended, "Development of improved methodologies for assessing the proliferation resistance of different systems, including those that further the understanding of the trade-offs between intrinsic and extrinsic measures." Most predefined frameworks under consideration today were developed in response to the TOPS report and the R&D priorities that it identified.

In 2001, a program plan for development of a nonproliferation assessment methodology was prepared for NNSA's Office of Nonproliferation and International Security (NA-24) (NNSA 2001). The goal of the program and eventual working group (DOE 2002, Mladineo et al. 2003; DOE 2002) was to:

- Develop a standardized methodology or set of methodologies for assessing proliferation resistance of different reactor and fuel cycle systems, and other nuclear systems and processes.
    - The methodology must be capable of measuring trade-offs among concepts and systems.
    - The methodology must include quantitative tools to ensure technical rigor.

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[12] As discussed in the Introduction, "proliferation resistance" focuses on the engineering aspects of a particular nuclear fuel. "Proliferation risk" is a broader concept and includes analysis of country-specific issues such as the probability that an adversary will choose to proliferate along a particular pathway, and the probability of success along that path. For more details, see Chapter 1.

In 2002, NA-24 issued functional requirements for development of a nonproliferation assessment methodology (NPAM) (DOE 2002) which identified the need for the methodology to:

- address a broad range of questions to be addressed by the methodology including country-specific analyses;
- address uncertainties and sensitivity analysis;
- incorporate weighting techniques to vary priorities; and
  facilitate use of expert knowledge

On the basis of the NPAM documents discussed above, NNSA and DOE-NE and several countries within the Generation IV International Forum (GIF) embarked on a joint effort to develop a methodology for use in diverse applications including country-specific applications, which resulted in the Proliferation Resistance and Physical Protection (PR&PP) methodology.

OVERVIEW OF PREDEFINED FRAMEWORKS

Predefined frameworks are methodologies designed to consistently and transparently evaluate proliferation resistance through a standardized set of predetermined attributes (or metrics) that are evaluated throughout the individual processing steps of a given fuel cycle (Mendez et al. 2006, Ford 2010).They provide a framework to gather and organize data to score the attributes, which requires expert knowledge and experiential data. Such data are gathered and combined into higher-level scores to give the fuel cycle an overall measure of proliferation resistance (usually high, medium, or low or numerical equivalents). This “black box” approach can mask the underlying reliance on subject-matter experts and lead to assumptions that the frameworks are objective models or simulations. They are not.

A typical set of metrics of proliferation resistance includes

- technical difficulty of proliferation,
- cost required to overcome barriers to proliferation,
- time needed to proliferate,
- type of material to be acquired for proliferation purposes, and
- the probability of detection (or transparency).

The committee judges these metrics to be reasonable, and many are cited in the proposed key policy questions found in Chapter 2.

The committee identified six predefined framework methodologies for more thorough review based on their variety of approaches for combining assessments at each processing step (e.g., multi-attribute utility analysis or event-tree logic). Several were selected on the basis of their use internationally and their use most commonly in the United States. This list and the committee’s assessment of the methodologies were reviewed by a set of practitioners of various predefined frameworks (see Appendix B). The following frameworks were selected:

- TOPS methodology,
- Japan Atomic Energy Agency (JAEA) methodology,
- Simplified Approach for Proliferation Resistance Assessment (SAPRA) methodology,
- Texas A&M University Multi-Attribute Utility Analysis (TAMU MAUA) methodology,
- Risk-Informed Proliferation Analysis (RIPA) methodology, and
- Generation IV International Forum Proliferation Resistance & Physical Protection (GIF PR&PP) methodology.

Perhaps noteworthy by its absence is the IAEA's International Project on Innovative Reactors and Nuclear Fuel Cycles (INPRO). Initial efforts to use INPRO precepts to assess proliferation resistance led by the Republic of Korea under IAEA auspices (IAEA 2011b; Lee et al. 2012) have been published, for example, the Proliferation Resistance: Analysis/Diversion Pathway Analysis (PRADA) project on Direct Use of Pressurized Water Reactor Spent Fuel in CANDU (DUPIC). However, in the most recent guidance on use of the INPRO assessment methodology (IAEA 2008 volume 5, Annex A, p. 39) it is stated:

> The goal of a PR [proliferation resistance] evaluation is to provide guidance for the nuclear energy system development groups that will develop the proliferation resistant technology, and to present results, showing how the non-proliferation goals will be met, to institutions responsible for deciding which nuclear concepts to pursue.

and

> At present, the [INPRO] evaluation method in the field of proliferation resistance is not complete. The group of consultants working in this area did not come to a common conclusion on scales for some indicators as well as on acceptance limits of criteria. Thus, final presentation of the evaluation results is not yet defined.

Thus, the Korea-led effort which involved developing detailed metrics within high-level INPRO basic principles of proliferation resistance and five general "user requirements" has not yet been adopted by the IAEA. Rather than further developing a framework for INPRO, the international community is pursuing an approach of harmonizing the relatively broad INPRO methodology with the more detailed PR&PP methodology (ANS 2012) in the Proliferation Resistance and Safeguardability Assessment (PROSA) project which began in February 2012. Therefore, the committee chose not to review a work in progress. Assessment of the PR&PP methodology can be seen below.

Below, the committee provides high-level descriptions of these six methodologies. Additional details on their characteristics are also noted in a summary table in Appendix B.

Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems

The TOPS task force was established by DOE-NE's Nuclear Energy Research Advisory Committee (NERAC). The task force was charged "to identify near- and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems." This included an R&D focus on methods for assessing proliferation resistance by evaluating "the relative proliferation resistance of specific fuel cycles in terms of a generic set of 'attributes.' The attributes are derived by first defining the barriers to proliferation inherent in the design of the system, its materials and facilities, and its modes of operation" (NERAC TOPS Task Force 2001). The approach followed a few basic steps for each fuel cycle under consideration:

- Define the different processing steps.
- Identify potential proliferation pathways in each processing step.
- Assign values to the attributes based on the threat (e.g. host state or subnational threat).

Attributes describe the relationship between the elements of a fuel cycle, the threats to those elements, and the effectiveness of barriers to inhibit these threats. Intrinsic attributes are technical features such as material properties (isotopic or chemical barriers, amount of material, detectability) and extrinsic attributes are institutional and operational barriers such as safeguards and inspections. The evaluation of the attributes relies on subject matter expertise and existing data.[13] Although the 2001 TOPS report made an initial attempt at comparative assessment of a set of fuel cycles following its proposed attributes methodology, it is not currently a methodology that is used. It is included in this list as a historic methodology.

The proliferation resistance attributes for a proposed fuel cycle (Fuel Cycle A) against a generic threat (sophisticated host state, covert diversion) are shown in a notional example of a TOPS-like assessment in Table 3.1. The table includes the list of intrinsic and extrinsic barrier attributes, the weighting factors for aggregation, a list of processing steps, and values of each attribute for each processing step. The values within this particular table are purely randomly assigned because it is a notional example; in a real assessment, the values would be determined by subject matter experts. Other fuel cycle

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[13] It should be noted that among the quantitative measures, some require underlying judgments made by experts. For example, the determination of threshold values for seemingly technical attributes, such as the 100-rem/h dose rate at 1 m below which nuclear material is assumed to not be self-protecting (NRC 2011a) may be an important demarcation in a proliferation risk assessment, but it has been questioned by other experts who believe a value of 500-rem/h at 1 m is more appropriate (Bathke et al. 2009).

Fuel Cycle A Against Sophisticated State, Covert											
Process Step		Intrinsic Barrier					Extrinsic Barrier				
Weighting factors		Isotopic	Chemical	Radiological	Mass & Bulk	Detect-ability	Facility access-ibility	Facility unattract-iveness	Detectability of diversion	Technical capability	Time
		0.2	0.2	0.4	0.5	0.8	0.5	0.3	0.2	0.8	0.2
Front-end	1 Enrichment	low	low	low	med	med	low	low	low	med	med
	2 Fresh Fuel Fabrication	low	low	low	med	med	low	med	med	med	med
	3 Fresh Fuel Storage	low	low	low	med	med	high	high	med	med	med
Reactor Site	1 Fresh Fuel Storage	low	high	med	med	med	med	med	med	high	med
	2 Fuel Loading/Irradiation	low	high	med	high	high	med	low	high	high	high
	3 Spent Fuel Storage	low	high	high	high	med	low	low	high	high	high
	4 Spent Fuel Transportation	low	high	high	high	med	low	low	high	med	high
Back-end	1 Spent Fuel Storage	low	high	high	high	med	med	low	med	med	med
	2 Reprocessing	low	med	high	low	low	med	med	high	low	high
	3 TRU Waste Storage	low	med	high	low	med	low	med	high	low	high
	4 Recovered NM Storage	low	high	high	low	med	low	low	high	low	med
	5 Fuel Fabrication	low	high	med	low	med	med	med	med	med	med
	6 Fuel Storage	low	high	med	med	high	low	med	med	low	med
	7 Fuel Transportation	low	high	med	med	high	med	med	med	med	med
	8 HLW Disposal	low	high	high	med	high	high	med	high	med	high

TABLE 3.1 Notional Example of a TOPS-Like Assessment of Proliferation Resistance Attributes for a Proposed Fuel Cycle A Against a Generic Threat (Sophisticated Host State, Covert Diversion). SOURCE: Modified from Inoue et al (2004).

and/or threat options would have a similar spreadsheet developed to allow for relative comparison at this or fully aggregated levels. The values within the table can be combined through weighting functions so that a final, single value of proliferation resistance is determined and can be compared with other fuel cycles.

Japan Atomic Energy Agency Methodology

The Japan Atomic Energy Agency (JAEA) developed an assessment methodology based primarily on the TOPS attributes methodology to provide a qualitative relative assessment of the proliferation resistance of systems, processes, and nuclear facilities as part of its strategy to commercialize fast-reactor technology. Two threats are considered: a covert diversion by a state and theft by a subnational group. The methodology defines material and technical barrier attributes of mass and volume of material, radiation fields and isotopic and chemical composition and, like TOPS, primarily relies on qualitative expert knowledge to evaluate the attributes. Sensitivity analyses have been performed against specific attributes, but the characterization of uncertainties of each attribute and how the uncertainties are carried through the analysis are not discussed or included in the results.

Simplified Approach for Proliferation Resistance Assessment

SAPRA was developed by the French Working Group on Proliferation Resistance and Physical Protection, which includes representatives from the Foreign Affairs and Industry ministries, French Safety Institute (IRSN), Atomic Energy and Alternative Energies Commission (CEA), Electricity of France (EDF) and AREVA, Inc. SAPRA further expands TOPS and JAEA (Greneche et al 2007) by delineating the steps to proliferation as four stages: diversion, transportation, transformation and nuclear weapons fabrication. SAPRA also introduces several different attributes (e.g. "dangerousness" instead of isotopic and chemical barriers to include other factors, such as reactivity of a chemical to water) but the approach to assigning values using experts and combining the values to a single result is consistent with the TOPS approach. The result of the analysis is a quantitative result that includes an assessment of each of the four defined stages of proliferation. At each stage, the values of the attributes are aggregated and normalized to 1. SAPRA considers only the case of state proliferation, not acquisition of material or a weapon by a subnational group. Uncertainty is not included in the assessment of the attributes nor is it reported in the final results. Sensitivity of the barriers to different threats is considered but an analysis of which attributes are most affected was not reported.

Texas A&M University Multi-Attribute Utility Analysis

A methodology for computing proliferation resistance was developed at Texas A&M University (TAMU) using a multi-attribute utility analysis (MAUA) method that assigns utility functions to each proliferation attribute (Charlton 2007, 2012). The result of this method is a numeric ”nuclear security measure” on a scale from 0 to 1, where "0" implies complete vulnerability to proliferation and "1" complete proliferation resistance or proliferation-proof. The method assigns weighting factors to a set of critical material and facility attributes of which there are 14 (further expanding the list of attributes beyond the SAPRA method for the purpose of decoupling interdependencies between previous attribute lists). The weighting factors are based on input from various experts in nuclear proliferation–related fields and contain both objective and subjective information.

The methodology focuses the proliferation resistance assessment on the flow of material through the fuel cycle as a function of time—from its initial input into the fuel cycle to its eventual disposal. The TAMU MAUA methodology limits the threat to diversion of nuclear material by a host state but does not address other threats such as theft or terrorism. It accounts for the intent of the host state to proliferate by assigning it a maximum and constant value in the analysis.

Uncertainty is not included in most of the utility functions that are established for each of the attributes, although "measurement uncertainty" is included as part of the higher-level metric of "Difficulty of evading detection by the accounting system." There is no mention of sensitivity analysis.

Risk-Informed Probabilistic Analysis

The RIPA methodology assesses the most likely paths for proliferators to acquire nuclear weapons, including the cost and time required for each using various risk-informed assessment techniques (Blair et al. 2002, Rochau et al. 2012). The goal of RIPA was to create a set of separable components of the proliferation risk problem that could be analyzed by experts and reused as needed for future analysis. RIPA includes (1) influence diagrams and resulting proliferation pathways, (2) proliferation scenarios, and (3) the proliferation measures. The influence diagrams present the steps (nodes) that must be followed to succeed in building a nuclear weapon. There were no examples of RIPA being used for specific applications. The documentation reviewed by the committee did not specify how uncertainties would be analyzed or reported nor did it mention sensitivity analysis.

Generation IV International Forum Proliferation Resistance & Physical Protection

The PR&PP methodology was developed as an approach for assessing the proliferation resistance of advanced nuclear energy systems and is the outcome of the NPAM documents described earlier. It is one of the more developed methods for analyzing proliferation resistance in the current literature and is used by GIF and others.[14] For a given system, the goal of the method is to define a set of challenges, analyze the system response to those challenges, and assess the outcomes (see Figure 3.1). The challenges to the nuclear energy systems are the threats posed by potential proliferant states and by subnational adversaries. The response to these challenges is determined by evaluating the technical and institutional attributes of the proposed Generation IV nuclear energy systems. The outcomes of the system response are expressed in terms of proliferation resistance and physical performance measures.

The PR&PP approach considers multiple facility types and activities to enable the proliferation pathways from acquisition and processing of material to fabrication of a nuclear explosive device as concealed and overt misuse of nuclear facilities. Types of proliferation considered are overt and concealed diversion, concealed breakout from treaty agreements and misuse, and clandestine facilities. For proliferation resistance, the top-level metrics are technical difficulty, proliferation cost, proliferation time, fissile material type, detection probability, and detection resource efficiency. The final steps in the methodology are the integration of the findings of the analysis and the interpretation of the results. The form of the results includes best estimates from subject matter experts for numerical and linguistic descriptors that characterize the overall proliferation resistance of the fuel cycles (GENIV Forum 2007, 2011b).

The PR&PP studies to date have focused on comparing the proliferation resistance of existing and future fuel cycles. The challenges (threats) are defined by descriptions of generic (not specific) states and adversaries, and limited details are included on the fuel cycle facilities.[15]

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[14] For example, safeguards design for new CANada Deuterium Uranium (CANDU) reactors, and accelerator-driven nuclear systems, MYRRHA, in Belgium.

[15] General assumptions and categories have been made regarding the technical capabilities of the proposed host state. More information can be found at http://www.gen-4.org/Technology/horizontal/proliferation.htm.

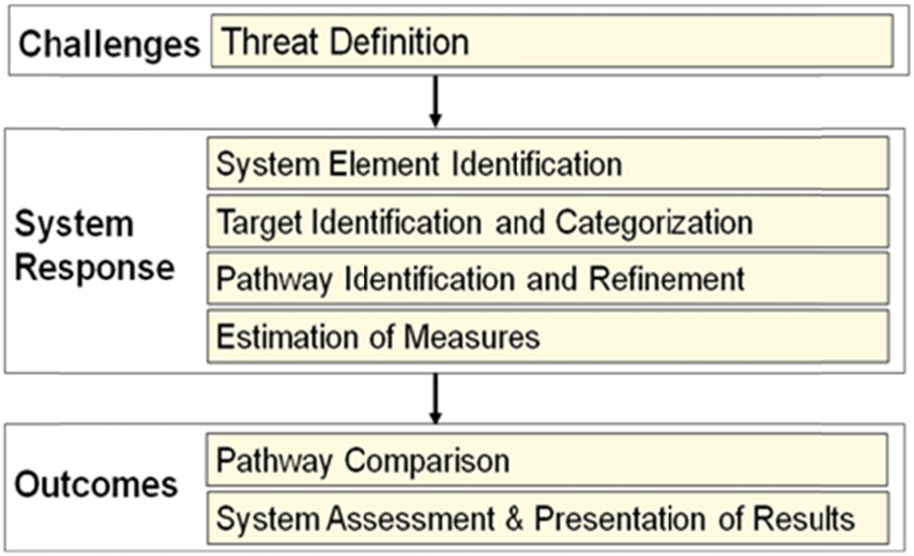

FIGURE 3.1. PR&PP’s methodology for assessment of proliferation resistance and physical protection. SOURCE: GENIV (2011a).

EVALUATION OF METHODOLOGIES

The methodologies were evaluated against a set of characteristics developed by the committee. Appendix B describes the evaluation and provides a summary table of the results.

The committee found that none of the methodologies currently capture *specific* host-state factors and therefore none currently assess proliferation risk, for example, the probability that a specific host state will choose to proliferate along a particular pathway, the probability of success along that path, and the consequences of proliferation summed over all possible pathways (Takakai et al. 2005, Pomeroy et al. 2008). The methodologies do assess proliferation resistance to allow for relative comparison between a set of given fuel cycles. There are some attempts to capture state-specific aspects via generic descriptions (e.g., a non–nuclear weapons state with nuclear energy systems, technically competent, and a signatory to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT, GENIV Forum2011b or by assuming the intent to proliferate is maximized and constant but there are no examples of a specific host state or an existing nuclear energy facility.[16]

The general approach to assessing proliferation resistance is the same for all of the methodologies: to outline the detailed steps of the given nuclear fuel cycle and to evaluate a set of metrics (or attributes) that characterize barriers to proliferation against a given threat. The number and details of the attributes and how they are combined differ between methodologies but the results are consistent with each other and are in agreement with general accepted judgments on proliferation barriers within nuclear fuel

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[16] Breakout scenarios could be assessed by considering only the intrinsic resistance (and removing any barriers introduced by extrinsic measures such as safeguards).

cycles (e.g., enrichment and reprocessing steps have the lowest proliferation barriers).. The committee judges this predefined framework approach to be sound in defining a set of steps in a complex system for analysis and organization of data to allow for comparisons between fuel cycles. However, the committee determined that there were shortcomings in the execution of the assessments and inherent limitations on their application.

Shortcomings in Execution

Expert Elicitation

At their core, all predefined frameworks rely on expert knowledge. Information is obtained from subject matter experts leading to a score for each attribute and weighting factors for aggregation. Because expert knowledge is combined into higher-level outputs, the details of these practices and their impact on the results can be obscured.

The committee found that two important processes related to gathering data from experts were found to be poorly implemented: selection of experts and expert elicitation.

The U.S. Nuclear Regulatory Commission (USNRC) has published a technical position (NUREG-1563) on expert elicitation that "describe[s] acceptable procedures for conducting expert elicitation when formally elicited judgments are used to support a demonstration of compliance" (Kotra et al. 1996). The U.S. Environmental Protection Agency has also developed clear procedures for gathering expert judgment and knowledge (EPA 2009). These practices when implemented have produced results of higher quality than other methods and are therefore considered "best practices" for expert elicitation. The guidance from the USNRC describes how formal expert elicitations should be performed:

> Expert elicitation is a formal, highly structured, and well-documented process whereby expert judgments, usually of multiple experts, are obtained. Although informal expert judgment involves only subject-matter experts, formal expert elicitations usually involve normative experts, generalists, and subject-matter experts. (Kotra et al. 1996, p. 3)

A normative expert is one trained in decision analysis, statistics, and probability; a generalist has broad training across the entire elicitation subject area; and subject matter experts are specialists concerning subparts of the subject area. In none of the six methodologies was the selection process of experts identified nor was there mention of the use of a normative expert (GENIV Forum 2011a) or a generalist. The most recent PR&PP documentation (GENIV Forum 2011a) does provide some general guidance on criteria for selection of experts, although the need for a normative expert or generalist is not part of the guidance.

The USNRC and EPA guidance also describes methods for eliciting information from the experts and the importance of documenting the results. In most of the methodologies, the process for collecting expert information was not stated. Some of the methodologies did indicate that expert knowledge was collected through the use of questionnaires and surveys (TAMU MAUA and PR&PP). Additionally, the committee notes that surveys and questionnaires have been found to be problematic in the methods of expert elicitation. The impact of poor execution of expert elicitation was recently recognized by the PR&PP GIF working group:

> informal expert elicitations often provide demonstrably biased or otherwise flawed answers to problems. Without a formal process and strong controls, experts may be asked to provide judgments on issues that go beyond their expertise, or their estimates might be combined in misleading ways which distort the results (GENIV Forum 2011a, p.67; Budlong-Sylvester et al. 2006).

However, the committee has found the proposed changes to the process of expert elicitation in PR&PP Revision 6 to be insufficient to effectively address these specific shortcomings (GENIV Forum 2011a) because experts are still solicited through a survey form, for example.[17]

Uncertainty Analysis

In technical assessments utilizing expert knowledge, the aggregate uncertainty of the results to changes in assumptions and information is an important factor in determining the confidence level of the results. It is important to define the uncertainties at the expert elicitation phase and to properly account for the uncertainties through their aggregation to the final result. In the predefined framework methodologies that were reviewed, the TAMU MAUA methodology accounts for measurement uncertainties as part of one high-level attribute but does not otherwise include them in its analysis. The PR&PP methodology notes that the results contain uncertainties because the measurement ranges are gross (high, medium, low).

The PR&PP, TAMU MAUA, and RIPA methodologies are, in theory, capable of being extended to doing quantitative uncertainty analyses. To date, these methodologies, in practice, do not provide a mechanism for addressing or quantifying uncertainty, although guidance for using the PR&PP framework indicates that this should be done (see PR&PP overview above).

Sensitivity Analysis

Sensitivity analysis of the final results (which may not be a single number or qualitative rating) to changes in the information gathered and the underlying assumptions by the experts often provides significant insight and may be more important than the final result per se. Only the SAPRA and JAEA methodologies reported sensitivity analyses against a subset of attributes and highlighted the effect on the results. As noted above for uncertainty analyses, the PR&PP, TAMU MAUA, and RIPA methodologies, in theory, can perform quantitative sensitivity analyses but did not include these analyses in the examples seen by the committee.

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[17] In best practices for expert elicitation established by the EPA and USNRC, a discussion leader requires the experts to explain the basis for their evaluation in front of the other experts. This leads to (a) making sure that each expert has the same understanding of the question, and (b) questions and challenges from other experts and modification of views in response to new facts and assumptions. The reason surveys are undesirable is that this interaction of the experts is lost or is not as efficient.

Limited Applicability

Facility details (e.g. technical design features, operational modalities, institutional arrangements and safeguards measures) are not known for deployments of future fuel cycles and may not be known during and throughout construction, especially for some countries in which the United States may have proliferation concerns. Country-specific and facility-specific factors will strongly affect the final proliferation resistance of a particular fuel cycle facility at the time of fuel cycle deployment and for several decades thereafter. Therefore, proliferation resistance assessments of future fuel cycles are limited to the known engineering details related to the intrinsic attributes of the proposed fuel cycle. Expert-guided assumptions and estimates are made for extrinsic attributes (which should have well-documented uncertainties associated with them). These assessments have a "shelf life" because the proliferation resistance will change as the barriers to proliferation are further defined throughout the development of the fuel cycle and the design of the facility. Assessments should not be considered final and should be periodically updated as more details of the specific fuel cycle or facility are determined.

Unfortunately, decision makers and policy makers need to make informed decisions related to future fuel cycles, nuclear exports, and peaceful nuclear agreements, as discussed in Chapter 2. This leads to an inherent limitation for the predefined frameworks because in these applications, the facility and host-state details are not defined. Of course, the case-by-case and other analyses are similarly limited by lack of data.

To summarize, the committee considered a set of predefined frameworks and found the following:

- shortcomings in their execution because of
    - poor and/or undocumented expert elicitation processes and
    - lack of sensitivity and uncertainty analyses;
- inherent limitation of applicability because of
    - unknown facility and host-state details for future fuel cycles and
    - limited shelf life of assessments.

UTILITY OF PREDEFINED FRAMEWORKS FOR DECISION MAKERS

In addressing this task, the committee notes that the "utility" of a methodology is subjective and dependent on the individual and/or organization. The committee considered the frequency of use as an indirect measure of utility and discussed the apparent effect of the methodologies' results with policy makers and decision makers to determine their subjective opinions.

The committee considered the extent to which predefined frameworks are used and have been applied to various types of decisions. Only two examples were provided despite requests to both sponsors and to many of the policy and decisions makers who provided briefings or information to the committee (see Appendix D). These two examples involve the use of the PR&PP methodology: (1) during the process of

BOX 3.1
Examples of the Use of Predefined Framework Methodologies

When asked for examples in which predefined framework analysis played a part in policy or decision making within the U.S. government, the following two examples were cited by NNSA.

GNEP: During the process of formulating plans for the Global Nuclear Energy Partnership (GNEP) initiative, the Unites States used a predefined framework methodology (PR&PP) to comparatively assess the resistance to proliferation of different future fuel cycle alternatives in three categories: once-through, full actinide recycle, and partial actinide recycle (DOE 2008b). Results highlighted strengths and weaknesses of the different fuel cycles and summarized the results as follows: “Because the alternatives present complementary risks and benefits, this assessment does not identify a preferred alternative or alternatives” (DOE 2008b, p. xv). This assessment was performed in parallel with preparation of the draft GNEP Programmatic Environmental Impact Statement (PEIS) (DOE 2008b) which stated that change to a closed fuel cycle represented DOE’s preferred option.

Pyroprocessing: In the context of discussions with South Korea about renewing its Nuclear Cooperation Agreement with the United States, South Korea has asked the United States for its consent to use pyroprocessing for its U.S.-origin spent fuel. When pyroprocessing was first considered by South Korea, the United States made a decision that pyroprocessing was not considered to be reprocessing and was acceptable. A more recent technical analysis using the PR&PP methodology (DOE 2008b, p. 68) determined that there was negligible difference in proliferation resistance between pyroprocessing (now further developed) and PUREX as compared to the once-through fuel cycle. This study was used in part to justify a change in policy with respect to pyroprocessing, which the South Koreans continue to contest. The two countries have subsequently undertaken a joint 10-year study on spent fuel management, one part of which will consider the proliferation resistance of pyroprocessing. This example highlights that proliferation resistance assessments made on technologies under development should be performed throughout the development cycle as further details are determined and new information that may have significant impact on proliferation resistance becomes known.

formulating plans for GNEP and (2) to compare pyroprocessing with traditional approaches to recycling. Details are provided in Box 3.1.

In its meetings with DOE and its contractors this committee heard that NNSA did not usually use any predefined framework methodology to guide nonproliferation decisions, especially in cases involving country-specific considerations. Reasons given for this include:

- not wanting to rely on a single rolled-up measure,[18]
- concern that the framework will make (instead of inform) a decision or might "box the decision maker in,"
- concern that "proliferation resistance" may be misinterpreted as "proliferation-proof."

As noted in Chapter 2, the committee found that nuclear nonproliferation policy makers and decision makers use their own knowledge, coupled with technical analysis by multidisciplinary teams of subject matter experts established on a case-by-case basis to provide insight into nuclear proliferation risk, and have shown little interest in multidisciplinary teams using predefined frameworks or formal risk-based approaches for such decision making. Based on the results to date, there is little expectation that predefined framework methodologies will provide additional insight, a view supported by previous findings including a brief, initial proliferation resistance assessment referenced in the TOPS report (NERAC TOPS Task Force 2001, p.15): "In some respects, most of the findings from the analyses were not new and simply reinforced the judgments that had arisen over the years."

The committee found several examples in other domains within the U.S. government in which decision makers utilize predefined framework-like tools to inform decisions. Examples include the Office of Cooperative Threat Reduction within the Department of State in which an assessment tool is used to inform the prioritization of countries for engagement on nuclear, chemical, and biological security (Dolliff 2012); and the Domestic Nuclear Detection Office within the Department of Homeland Security, which uses a risk-based tool to guide the optimization of architectures for global nuclear detection (Streetman 2012). Such methodologies are apparently useful to policy makers and decision makers dealing with complex problems and with a willingness to engage in the analysis process and not simply the results. In these cases, the users recognize that the tools are not predictive and that they are not beholden to the results. Rather, the tools provide a structure for organizing complex problems with a large number of variables and assessing which factors are most important to the results that inform the final decisions.

While recognizing the limitations of predefined frameworks, the committee judges that those frameworks can have value if well executed. They provide a structured approach that causes the analyst to explore a range of possibilities in assessing proliferation resistance. They also have value as a way to consistently compare the attributes of potential future nuclear fuel cycles and for identifying where safeguards can be most effective in raising barriers to proliferation. They provide a common lexicon and structure for communicating with international partners about nuclear energy decisions. In addition, they provide a valuable structure for education of the next generation of experts on nuclear energy and nonproliferation.

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[18] In the committee's review of the frameworks, it was noted that many predefined framework approaches do not yield only a single output and none of them have to do so.

FINDING 2.1: Predefined frameworks have been developed and used to assess the proliferation resistance of partial or full nuclear fuel cycles. These methods provide a useful framework for comparing the intrinsic metrics or “attributes” of existing and potential future nuclear fuel cycles and for identifying where safeguards can be most effective in raising barriers to proliferation. However, these comparisons address a small subset of the wider range of issues faced by policy makers and the committee was able to determine that the frameworks have rarely been used to inform policy decisions. Additionally, there have been shortcomings in their execution.

4

APPLICATION OF OTHER RISK METHODOLOGIES

This report has reviewed the current assessment methods that inform policy makers and decision makers on technical issues related to proliferation risk of a given nuclear fuel cycle. Case-by-case analyses conducted by multidisciplinary teams of subject matter experts are most frequently used to address a variety of technical issues related to host-state proliferation risk (see Chapter 2). Predefined framework methodologies have been used to evaluate the proliferation resistance rather than proliferation risk of nuclear fuel cycles (see Chapter 3). These types of methodologies focus on the technical details of fuel cycle processes and have not considered factors of specific countries or been used to evaluate the probability that a host state would choose to proliferate using a particular fuel cycle technology, nor have they been used to evaluate the consequences of a successful attempt. In addition to these limitations on scope, the committee identified a number of deficiencies in the execution of predefined frameworks (Finding 2.1). This chapter focuses on the third task:

TASK 3: Assess the potential for adapting risk assessment methodologies developed in other contexts (such as safety and security) to host-state proliferation risk assessments—including both qualitative and quantitative approaches—their benefits, limitations, and the challenges associated with adapting these methodologies to proliferation risk assessment.

We consider whether other risk assessment methodologies could be useful in evaluating the larger question of proliferation risk and whether their established practices might address the noted deficiencies of the predefined frameworks. The chapter is split into three sections. The first section considers the most challenging component of the proliferation risk problem: the analysis of host-state factors. The next section focuses on probabilistic risk assessment (PRA) and how it has contributed to other engineering-based problems. The chapter concludes with identification of benefits and limitations of PRA and other approaches to the problem of proliferation risk assessment.

In addressing this task, the following types of risk assessment methodologies were considered by the committee: adaptive adversary models (including PRA and game theory), quantitative methods proposed by social and political science approaches, and nuclear safety risk assessments (using PRA).

ASSESSING HOST-STATE PROLIFERATION RISK

Evaluation of proliferation risk of a fuel cycle deployed in a particular host state is a more complex concept than proliferation resistance and includes analysis of country-specific issues such as the probability of host-state proliferation (including its intent, motivations, and technical capabilities) and the consequences of proliferation. Proliferation is an act carried out by a motivated host state, not a failure of an engineered system. Because the process of proliferation generally occurs in secret, detailed data on the factors relevant to the probability that a host state would choose to proliferate along a particular path or the probability of success along that pathway are not readily available. In addition, factors influencing proliferation risk will change over time, for example, a change in regime or in perceptions of regional security. Choices about proliferation pathways also could evolve over time, based on the ability to overcome safeguards and avoid detection, as well as advances in technical capabilities or the ability to acquire technology covertly. The resources a host state might allocate to achieving success would depend on the strength of its motivation, which in turn would depend on its perception of the benefits of nuclear weapons. Because of the limited number of cases of proliferation in general, and the secrecy of the process, data on all these factors are very limited, and trends that could guide a technical analysis of probability have been difficult to determine. Historical case studies provide some relevant data about countries that have given up nuclear weapons programs in the past, but limited data are available on successful efforts. Close cooperation with inside experts familiar with successful proliferation efforts (either in the past, or ongoing) is unlikely.

Several National Research Council reports have addressed the issue of whether and how risk assessment could be applied in contexts where, unlike traditional risk assessments for natural hazards, action by intelligent adversaries gives rise to the risk. A 2010 report on the use of risk assessment for terrorism concluded:

> However, with the exception of risk analysis for natural disaster preparedness, the committee did not find any DHS risk analysis capabilities and methods that are yet adequate for supporting DHS decision making, because their validity and reliability are untested. Moreover, it is not yet clear that DHS is on a trajectory for development of methods and capability that is sufficient to ensure reliable risk analyses other than for natural disasters. (NRC 2010, p. 80)

Similarly, a more recent report (NRC 2011) concluded that, because adversaries may be intelligent, creative, and adaptive, a basis for assigning probabilities of attack has not been established.

A somewhat more optimistic view of the potential for using risk assessment in the context of intelligent adversaries was taken in *Department of Homeland Security Bioterrorism Risk Assessment: A Call for Change* (NRC 2008). This report includes a table titled "Natural Hazards Versus Terrorism Risks: Comparison of Key Characteristics" and makes the observation that:

> When dealing with an intelligent, goal-oriented, and resourceful adversary, not with a force such as nature that randomly determines whether unwanted events occur, this committee believes that the use of probabilities to represent bioterrorism decisions must be tempered by a thorough understanding of how these probabilities have been assessed (whether by means of formal game-theoretical models, elicitation of subject-matter experts, or other means). For decision problems as complex as those motivating BTRA [bioterrorism risk assessment], the assessment of the probabilities that adversaries will choose courses of action should be the outputs of analysis, not required input parameters. The BTRA has reversed this preferred approach by requiring that subject-matter experts predict, *a priori,* how adversaries will behave. For this approach to make sense, the subject-matter experts must grasp nuances of alternatives and outcomes and render opinions founded on an analysis of the entire decision process, which would be very difficult for a process this complex. The committee saw no evidence that this level of analysis was used. Moreover, the static probabilities used are not appropriate when intelligent adversaries can observe and react dynamically to any earlier decisions made by the United States. (NRC 2008, p. 27)

The committee considered risk analysis approaches proposed for situations with intelligent adversaries, including those based on game theory, but concluded that although such approaches appear promising, their effectiveness has not been demonstrated via evidenced-based records of success in real-world situations.

The committee is aware of risk-based approaches for assessing other security-related problems. The committee learned about Department of Homeland Security's PRA approach (Streetman 2012) for modeling an adaptive adversary. Modeling an adaptive adversary is an area of longstanding interest to the intelligence community, but the field is not yet mature, and its potential for success is a matter of debate. There are also efforts to use PRA as an analytical tool for assessing the risk of terrorism, but these remain controversial (NRC 2010). We were unable to identify successful applications of PRA in the security context, possibly because of classification issues.[19]

As noted above, predefined framework assessments have not included country-specific factors such as compliance with nonproliferation norms and obligations, historical interest in nuclear weapons, or possible motivations to develop nuclear weapons. Some have suggested that value could be added by combining these predefined framework methodologies with results of political science methodologies that seek to establish correlations between country-specific factors and proliferation. To evaluate this suggestion, the committee reviewed selected literature and held a focused meeting on social science–based research to understand factors that may influence a country to pursue nuclear weapons, including some efforts to develop models of how factors such as security concerns, type of government, and technical capability influence decisions (Coles et al. 2009, Gartzke 2012, Way 2012).

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[19] The fact that we could not identify such cases does not mean they do not exist.

Political science research using both detailed historical case studies and statistical methods has produced four main findings. First, historically, there are examples of states (fewer than 20) that have either tentatively explored or actively pursued a nuclear weapons program but have abandoned their efforts before successful development (Singh and Way 2004; Sagan 2011). Second, there is a positive correlation between the level of security threat that senior state leaders perceive and their subsequent level of nuclear weapons interest. States that face enduring rivalries with nuclear-armed states are more likely to explore getting their own nuclear deterrent than are other similar states without such rivals, although this proliferation interest can be reduced if the state has a security guarantee with another nuclear weapons state (Jo and Gartzke 2007). Third, the majority of states that are non–nuclear weapons state (NNWS) members of the Nuclear Nonproliferation Treaty (NPT) have neither explored nor pursued nuclear weapons since they joined the treaty. Indeed, one study estimates that of the 184 NNWSs in the NPT, fewer than 10 have cheated on their treaty commitment not to seek or acquire nuclear weapons after they joined the treaty. Fourth, although both democracies and autocracies have developed nuclear weapons and started nuclear programs historically, only autocratic governments have started nuclear weapons programs while they were forbidden to do so under their NPT commitments (Sagan 2011, Way and Weeks 2012).

These insights from the political science literature are consistent with considerations of nonproliferation decision makers and multidisciplinary teams performing systematic technical assessments. However, these methods do not ameliorate the challenges of lack of evidence about decisions to proliferate, the most likely pathways, or consequences of proliferation.

PROBABILISTIC RISK ASSESSMENT

The committee considered how PRA methodologies might be applied to the problem of assessing proliferation risk. We reviewed the underlying principles of PRA, as well as examples of their application to evaluate risks in a range of fields including nuclear power plants, space exploration, chemical munitions cleanup, and natural disasters.

A PRA starts with a definition of the full system under consideration and its desired state. Next, it identifies and characterizes threats to the system and develops scenarios for “what can go wrong” (see Box 4.1). The scenarios are then quantified in terms of their likelihood and consequences. Structuring the scenarios is a complex undertaking and requires evidence to support both the listing of threats, the system response to the threats, and the likelihood of any particular event occurring. Evidence is also needed to quantify consequences. Evidence can be provided by either physical data or expert judgment. PRA methodologies are particularly good at dealing with incomplete information or uncertainties. Incomplete information is addressed by assigning probability distributions based only on the evidence that is available. However, a comprehensive understanding of the system is essential to performing a PRA. Without detailed knowledge of how a system works and responds to threats, no amount of probabilistic analysis will answer the risk question.

The thought process of PRA is valuable as a tool to guide analysis and collect data (see Box 4.1). PRA experts have significant and relevant experience identifying data

BOX 4.1
Practitioners' Thoughts on Probabilistic Risk Assessment

In evaluating the applicability of PRA to the problem of nuclear proliferation, it is important to recognize the tenets of the probabilistic thought process on which PRA is based. Its image is often one of logic diagrams (e.g., fault trees and event trees) supported by an extensive amount of experiential information and system details. However, PRA is fundamentally a thought process based on the rules of logic and plausible reasoning for answering three basic questions about events, systems, or activities. The questions are: What can go wrong? How likely is that to happen? What are the consequences if it does happen? It is not a formula, a computer program, a detailed formalism, or an event tree, even though all may be involved. This set of questions and thought processes leads to probabilistic, evidential, and inferential analysis of the response of events, systems, or activities to different challenges.

PRA was developed to provide insights on matters for which there was very little information, thus leading to an often-heard phrase, "the less information one has about the risk of something, the more important it is to do a quantitative risk assessment." This of course, is only if it is an important risk that is not statistically obvious or easily exposed by simplified methods.

The basic thought process of PRA generally applies to any situation. Thus, the overarching question is not so much does it apply to a particular situation, but rather does it add value to the question being asked and is it correctly implemented.

SOURCE: B. John Garrick

that might otherwise be overlooked. In many ways it is compatible with the case-by-case assessment methods used by multidisciplinary teams, as described in Chapter 2. Of particular relevance to this study, PRA methods have strengths in

- full representation of a complex system;
- evidential and inferential analysis of information sources, such as subject matter experts;
- rigor of the expert elicitation practices; and
- accounting for uncertainties and sensitivities

Benefits

The committee judges that the strengths of PRA previously identified regarding the elicitation of expert knowledge and accounting for uncertainties and sensitivities could address the shortcomings identified in the execution of predefined framework methodologies and might be useful for case-by-case assessment approaches. The U.S. Nuclear Regulatory Commission and the Environmental Protection Agency use PRA approaches to manage risk and guide decisions. They have provided guidance for rigorous expert selection and elicitation (Kotra et al. 1996, Savy et al. 2002). For example, PRA methods require that experts provide evidence and underlying assumptions to support their judgments. This increases repeatability of the assessments and reduces variances among the judgments. PRA methodologies quantify uncertainties and carry them through to the results, which provide a measure of additional information needed to improve the quality of the analysis.

However, not all situations require such in-depth assessments as provided with a comprehensive PRA. Bounding and approximation methods may be adequate for many generic applications. Consideration should be given as to which approach would add the most value to predefined framework methodologies.

Limitations

Because proliferation resistance assessments generally have been made on fuel cycle concepts, but not on deployed systems, there will be little available expertise on the way a particular fuel cycle system works in a particular country and what might constitute a threat.

The application of PRA to the safety of nuclear energy facilities has been widely adopted and presents an interesting analogy for proliferation risk. Nuclear power safety PRAs using detailed information on existing facilities can highlight unintended interactions and vulnerabilities. One important lesson learned from the experience with nuclear power plant PRAs (and all U.S. plants have done such an assessment) is that each plant is different and that the risk is very plant-specific. The results can differ significantly even for the same type of unit, located side-by-side. This highlights the importance of facility details in the assessment of risk (or proliferation resistance). In the case of limited shelf-life of an assessment based on unknown details, the PRA thought process or expert elicitation practices cannot overcome the lack of facility detail and does not add value to the question being asked.

Finally, the committee notes that a potential weakness of PRA (as with the predefined frameworks or case-by-case analyses) is the failure to consider all pathways and scenarios.

To summarize, PRA methodologies have proven highly valuable for assessing risk in engineered systems. They have well-established practices for selecting experts, eliciting expert judgment, and for dealing with uncertainties. Adopting these practices could improve the execution of predefined framework methodologies. However, a successful PRA requires detailed data or information about the system under consideration as well as the ability to quantify the likelihood of threats to that system and consequences of failure. A successful PRA of proliferation risk of a particular fuel cycle in a particular state would therefore require detailed data about the facility, the motivations and thought processes of host-state decision makers, possible clandestine technical capabilities and activities, as well as other information. The committee notes that the risk assessment methods considered by the committee cannot overcome the lack of these important data.

The thought process of PRA is valuable as a tool to guide analysis and account for uncertainties, and in many ways is compatible with the methods used by multidisciplinary teams. It would be worthwhile to consider whether elements of the PRA process could improve such analysis.

FINDING 3.1: Some of the identified deficiencies in the implementation of the existing predefined frameworks for assessing proliferation resistance could be improved by adopting expert elicitation and data-gathering practices developed by other fields of risk assessment. For example, probabilistic risk assessment (PRA) methods have well-defined and established processes for gathering, quantifying, analyzing, and presenting data that could benefit the nonproliferation community. However, the challenges of an adaptive adversary and of lack of data on proliferation events in particular limit applicability of all of the risk-based methodologies to the assessment of proliferation risk considered by the committee.

RECOMMENDATION 3.1: DOE-NE and NNSA should consider whether elements of a formal PRA approach could improve multidisciplinary assessments of proliferation risk, especially the quantification of uncertainties. Although the committee concluded that work on understanding motivations to develop nuclear weapons and modeling an adaptive adversary do not have evidence-based records of success in real-world situations, it supports the inclusion of such approaches into proliferation risk analysis when and if they have an established quantitative basis.

5

IDENTIFICATION OF R&D FOR IMPROVING ASSESSMENTS

This chapter continues to look at ways to improve the utility of proliferation risk assessment. This chapter assesses whether the application of additional R&D research could improve the utility for decisions makers of the existing predefined framework methodologies or potential new methods (see Task 4 of the study charge):

TASK 4: Identify R&D and other opportunities for improving the utility for decision makers of current and potential new approaches to the assessment of proliferation risk.

In previous chapters, the committee found that although the predefined frameworks provide a good structure for identifying intrinsic and extrinsic barriers to proliferation, they address a subset of issues and questions faced by policy makers and have not highlighted significantly new or different findings. Additionally, the committee observes that policy makers have shown little interest in using them, and few examples could be found in which they informed decision making. Policy makers and decision makers prefer using multidisciplinary teams to provide technical analysis of proliferation risk coupled with their own knowledge to address specific nonproliferation issues (NRC 2011a, Bedell 2012, Goorevich 2012, Owens-Davis 2012, Stratford 2012). In addition, we note that many suggest that the overall risk that a country will pursue nuclear weapons is dominated by security, political, and cultural issues and not by the deployment of a particular fuel cycle. In addition, problems with the implementation of the predefined frameworks for the assessment of proliferation resistance were identified, including lack of documentation in selecting and eliciting experts, and accounting for sensitivities and uncertainties.

Given these considerations, the committee notes that a sufficient number and variety of framework methodologies exist to address the subset of questions related to proliferation resistance, and do not recommend R&D to develop more methodologies or to extend them to evaluating proliferation risk. The committee observes that there might be benefit in reanalysis of existing predefined framework assessments using improved expert elicitation practices and uncertainty and sensitivity analyses in order to increase the credibility and confidence of the results. However, the committee also notes that the applicability of these proliferation resistance studies remains of very limited value to policy makers for reasons mentioned previously: limited scope and lack of significantly new or different conclusions.

Because deployment of a future fuel cycle would not occur until 20 or 30 years in the future, the details of the facility design (e.g., technical design features, operational modalities, institutional arrangements, and safeguards measures) may not be known for deployments of future fuel cycle facilities.[20] Also, further technical details about the new fuel cycle may emerge throughout the development process, such as piping and placement of parts of the facilities. These factors will strongly affect the final proliferation resistance of a fuel cycle facility. As was shown with nuclear safety risk assessments in Chapter 4, details can strongly affect the final risk.

Because proliferation resistance assessments for potential future fuel cycles have limited information on technical design features, operational modalities, institutional arrangements, and safeguards measures, the cost and time of executing a predefined framework is difficult to justify. For R&D decisions, it would be more useful to simplify analysis to address a few key questions, tailored to the level of known detail. As the technology is developed and closer to deployment, many more details may be known and the use of a predefined framework may be justified for determining proliferation resistance.

In Chapter 2, the committee noted several examples of nonproliferation policy makers and decision makers using a checklist of high-level questions to consistently address proliferation risk–related issues. For example, all Nuclear Cooperation Agreements (NCAs) have requirements that are addressed in the Nuclear Proliferation Assessment Statement (NPAS), and the National Nuclear Security Administration’s Office of Nuclear Controls uses a set of seven questions that must be answered for each export review that is performed.

FINDING 4.1: The committee has identified several specific applications as opportunities in which the current predefined frameworks could provide value and utility to decision makers as long as the shortcomings in their execution are addressed. While aware of their existence, decision and policy makers have rarely used predefined framework assessments to inform their decisions. They have noted that the predefined frameworks have not highlighted previously unknown proliferation issues related to nuclear fuel cycles. Because these issues are not addressed by expansion or further development of existing predefined frameworks, the committee does not support a new or expanding R&D program.

The committee found that the predefined frameworks have value in the following applications:

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[20] Even as facilities are designed and built, it is unlikely that these details will be readily available, especially for some countries in which the United States may have proliferation concerns. This does not mean that policy makers do not use technical assessments. As mentioned in Chapter 1, they have repeatedly chosen case-by-case technical analyses.

1) comparing the proliferation resistance of fuel cycles and identifying locations to apply safeguards or material monitoring,
2) educational applications (e.g. academic applications or informing new nuclear energy states about nuclear fuel cycles),
3) enabling consistent communication with international partners or the public on nuclear energy decisions by providing analysis through the application of a predefined, internationally accepted and known methodology.

RECOMMENDATION 4.1: The committee recommends that fuel cycle R&D decisions include proliferation resistance (rather than proliferation risk) as one factor among others (such as cost and safety) to guide those decisions. Technical assessments are limited by the availability of technical details associated with future nuclear fuel cycles. Therefore, the committee recommends that DOE-NE and NNSA jointly decide upon a set of high-level questions comparing the proliferation resistance of proposed future fuel cycles to the current once-through fuel cycles to determine as early as possible in their development whether the former have significantly different intrinsic proliferation resistance (either for the better or for the worse). Assessments should be revisited at key milestones throughout the technologies' development and eventual deployment; they should become more detailed as appropriate as new and better information and data emerge.

In determining the set of questions, it may not be necessary to start with a blank sheet of paper. For example, a useful list of high-level questions might be based on questions such as those identified in Chapter 2 of this report.

The committee was briefed on the current proliferation risk assessment approach that DOE-NE plans to take for its selection of next-generation nuclear energy systems. The proposed approach acknowledges that it is not possible to assess country-specific factors (e.g., intent, regional stability, technical capability) for all of the proposed systems (Wigeland 2012). However, the proposed approach considers the materials and quantities that would be created by the proposed fuel cycle and rates them against a Figure of Merit (FOM). By focusing solely on the FOM, there are other aspects of proliferation resistance that could be overlooked. For example, the FOM approach does not consider what processing steps would be needed to convert a "low risk" material into a "higher risk" material, which was a problem for pyroprocessing.

The committee notes that the questions developed by NE and NNSA could be answered by a variety of approaches (case-by-case, subject matter expert analysis, policy-maker knowledge, expert checklists, or even simplified frameworks), but the committee also notes that the amount of data available should guide the choice of the method. Also, a comparison with the "current once-through fuel cycle" can be revisited in the future as aspects of the current fuel cycle (e.g., fuel type and burnup) evolve.

6

COMMUNICATION OF PROLIFERATION RISK

The previous chapters have focused on how technical aspects of proliferation risk and the various method assessments are of utility to policy makers and decision makers. The logical next question then is how are proliferation resistance and risk findings communicated between all relevant groups and where are the difficulties in this intergroup communication? In this chapter, the committee offers recommendations to improve communication between different relevant groups, including technical analysts to decision makers; technical analysts to each other domestically and internationally; government decision makers to their international counterparts; and government decision makers communicating with stakeholders (task 5 of the study charge):

TASK 5: Identify and assess options for effectively communicating proliferation risk information to government and industry decision makers, as well as to the public and the nongovernmental organization (NGO) community both within the United States and internationally.

The audience for proliferation risk information includes U.S. and other governments and industry decision makers, NGOs, journalists and other media, as well as the general public. Among these groups, there is great diversity in technical and political understanding, attitudes about nuclear energy, and access to information. Examples of these likely interactions between these groups include

- technical analysts communicating with government sponsors and decision makers;
- technical analysts communicating with each other and international counterparts;
- government decision makers communicating with international counterparts; and
- government decision makers communicating with U.S. and international nuclear industry, the public, and the NGO community.

This breadth and diversity poses numerous challenges for effective communication, including

- different access to classified or sensitive information
- different levels of technical ability and political understanding, and
- clarifying the critical issues without oversimplification of a complex technology or political situation.

Complicating all these challenges is the fact that the term “proliferation risk” is not widely understood, nor does it have a universally agreed definition. The terms “proliferation risk” and “proliferation resistance” frequently are used interchangeably and incorrectly when discussing nuclear energy systems. In addition, “proliferation resistance” is sometimes incorrectly construed to mean “proliferation-resistant” or “proliferation-proof.” Confusion about terminology affects both technical analysts and government decision makers. Clarifying terminology at the outset of any discussion and using it consistently would *significantly* improve communication.

COMMUNICATION OPTIONS

For each of the groups listed above, several communication options are presented and assessed.

Technical Analysts/Government Sponsors

This may be the least challenging of the communication groups listed because these two entities have a mutual interest and a common goal: the government sponsors have provided funding to study a particular topic, and the technical analysts are presenting the results.

Communicating effectively to decision makers is a critical step in ensuring that proliferation risk information is understood correctly, used appropriately, and well integrated with other factors affecting decisions. Many technical assessments are designed to address questions posed by a government sponsor about the risk of a nuclear technology or capability in the context of a particular country or region. Such assessments are frequently performed by a multidisciplinary team of subject matter experts established on a case-by-case basis that includes both technical and country specialists, and often are conducted in close collaboration with the intelligence community. In briefings and discussions, the committee observed that decision makers, the intelligence community, and the technical community seemed to communicate effectively about such assessment results.

Communicating the results of technical assessments made using predefined frameworks is more challenging. Policy makers are wary of methodologies that assign absolute or numerical values to complex problems. They are concerned that a seemingly “quantitative” result would determine a policy decision. To improve communication about such assessments, technical analysts could be particularly clear that they are assessing proliferation resistance, rather than risk, and that predefined frameworks provide a structured approach for comparing the technical features of different generalized fuel cycles. They could describe the attributes they have chosen in a determination of proliferation resistance, the assumptions underlying the analysis, the limitations of the methodology, and the credentials of the experts whose judgment has contributed to the results. As was noted earlier with other assessment tools, the decision makers could be involved in the technical assessment process. This is particularly important because the frameworks have been (incorrectly) understood to be objective models.

For both of the assessment approaches listed above, results could be communicated more clearly as relative to the once-through fuel cycle (or other fuel cycles in existence today) and uncertainties in the results should be clearly carried through the analysis and could be displayed and described in the results. The results should not be presented as or understood to be final, because all such assessments have a limited lifespan, and as with case-by-case assessments, they will need to be performed again periodically because circumstances will change. Analysts should also refrain from technical jargon and exhibit an understanding that decisions about proliferation risk involve more than technical considerations.

Technical Analysts/Other Analysts (International Counterparts)

The structured approach of predefined frameworks has facilitated communication among technical experts from different countries, by providing a common lexicon and structure for discussing proliferation resistance and ways to increase it. This could ease communication among analysts advising governments (the U.S. and other governments) on the development of new nuclear technology, and also among analysts assessing new approaches to international safeguards. Again, articulation of the purpose, scope methodologies, participants, uncertainties, and limitations of such assessments is critical to avoid misperceptions about the results of any assessment. The Generation IV International Forum Proliferation Resistance and Physical Protection (GIF PR&PP) Working Group which is composed of 17 members spanning seven countries provides a good example.

Predefined framework assessments can also have useful educational roles because they provide a framework for exploring how different features of the nuclear fuel cycle contribute to proliferation resistance and which ones may be the most sensitive (which, because of the fuel cycle's complexity, may not be obvious from a policy perspective or a technical one to those just entering the nonproliferation field from a policy perspective or a technical one).

U.S. Government/International Counterparts

Effective communication about proliferation risk is critical to achieving international consensus on approaches to nonproliferation, including export controls, international safeguards, and sanctions against violators of international norms. If technical analysts have been successful in communicating risk information to U.S. decision makers, the task of communication with international counterparts will be much easier. Communication between U.S. and international technical experts will also help because they are likely to use similar concepts and terms in communicating with their leaders. Nevertheless, challenges will remain, especially in cases in which classified information is involved.

Information related to nuclear weapons is tightly held by the U.S. government. This presents a difficult challenge for the U.S. government in discussing nuclear proliferation risk with the public and international partners. To address this challenge, the National Nuclear Security Administration (NNSA) has developed an approach to generically categorize material that may be used for proliferation purposes into a Figure of Merit (FOM). The FOM considers the material type and quantity and how readily it can be used to make a nuclear weapon when assigning its value. Sensitive details are masked by the calculation of the FOM value (Hase et al 2012; also see Bathke et al. 2009). This approach has allowed for international discussions to take place at a more detailed level than previously allowed.

The FOM assignment is one of the few solutions available to the address the challenge of properly handling sensitive information while communicating with partners that do not hold security clearances (e.g., government decision makers communicating with international counterparts; and government decision makers communicating with the U.S. and international nuclear industry, the public, and the NGO community). A negative side to this successful communication option is overreliance and misuse. In this case, the FOM for different materials is widely known and reported without considering the required processing steps to convert it into a higher-risk material. An example of this was seen by the committee in DOE-NE's downselection criteria for the next-generation energy systems (Wigeland 2012)(see Chapter 5).

Depending on the venue (bilateral, multilateral, private, public) and relationship with the other country (ally, partner, or adversary), different strategies may be used. In any case, building trust will be essential, which in turn will require respectful, simple, clear and frequent communication using information available to all parties to the discussion, and which avoids technical jargon. References to classified information that cannot be shared will be useful only in a relationship of trust and may impede communication otherwise (Bathke et al. 2009, BNL 2009, Hase et al. 2012).

U.S. Government/Industry, Public, NGOs

One of the biggest challenges with designing communication options for this larger community is the diversity of technical understanding and political perspectives and methods in which to communicate. The challenges of communicating decisions about nuclear policy to this broader community will be much the same as with international partners and can use the same communication options (structured frameworks from GIF, addressing classification issues using FOM). Another communication challenge as they relate to the impact of U.S-based decisions on nuclear energy systems on international proliferation is that the general public does not have a high-level of trust in information from the DOE (Jenkins-Smith 2012).

One option to consider as a communication tool is related to the recommendation to establish a small set of high-level proliferation-related questions (proliferation resistance—not risk, see Recommendation 4.1) to guide initial R&D decisions on future fuel cycles. If the assessments are updated throughout development, this allows for consistent and periodic communication (e.g. to the public, to Congress) of proliferation concerns. As stated earlier in this report, other nuclear topics use such a set of standard questions for communicating decisions.

Social media were briefly discussed (Jenkins-Smith 2012) as a way to both communicate and gauge public opinion on U.S. government decisions. However, the government's use of social media for topics related to nuclear proliferation is in its early stages for the reasons cited above (sensitive information related to nuclear weapons, complex problems).[21]

Recognizing that the broader community may not agree with government decisions will be critical. Mutual respect and clear communication that avoids technical jargon is important, in addition to emphasizing the scope and limitations of assessments contributing to decisions.

FINDING 5.1: The terms "proliferation risk" and "proliferation resistance" frequently are used interchangeably and incorrectly when discussing nuclear energy systems. In addition, technical methods for assessing proliferation resistance are often referred to as methods for assessing proliferation risk. This creates confusion, is misleading, and impedes communication.

The DOE-NE and NNSA may consider leading an effort to develop consensus within the U.S. government and internationally about the consistent use of the terms proliferation risk and proliferation resistance, including how proliferation resistance differs from proliferation risk.

FINDING 5.2: Predefined framework assessments provide a structured approach that can enhance communication and education as long as their purpose, scope, assumptions, and limitations are clearly stated and understood.

Predefined framework methodologies can facilitate communication about proliferation resistance by providing a structure for organizing and discussing complex data. For example:

- *Domestic–international community*: Predefined frameworks provide a common lexicon and vocabulary during international expert discussion, thereby facilitating communications (e.g., Gen IV International Forum Proliferation Resistance and Physical Protection Working Group).
- *Policy makers—public—international partners*: Predefined frameworks can help establish a common lexicon, provide a useful structure for communicating how a large number of factors contribute to proliferation resistance, and facilitate communication of policy decisions to nongovernmental organizations, the interested public, and international partners.

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[21] Acting Under Secretary of State for Arms Control and International Security, Rose Gottemoeller, supports this communication channel (https://twitter.com/Gottemoeller). See also http://www.npr.org/2012/02/08/146589700/a-new-weapon-against-nukes-social-media.

Predefined framework assessments can also be useful for training academics and next-generation policy makers on proliferation-relevant features of the nuclear fuel cycle, the role of international safeguards, and approaches to increasing proliferation resistance.

However, the purpose, scope, implementation, uncertainties, and assumptions of framework methodologies must be clear, if results are to be interpreted appropriately. It should be clear that assessments of proliferation resistance or risk are not absolute and are one factor among many that contribute to decisions concerning proliferation.

RECOMMENDATION 5.1: To build trust and increase transparency with domestic and international stakeholders, policy makers and decision makers should refrain from technical jargon in communicating proliferation risk, refer to information available to all parties whenever possible, and always include discussion of the assumptions and limitations inherent in any assessment.

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Appendix A: Biographical Sketches of Committee Members

ROBERT C. DYNES (NAS), *chair*, is president emeritus of the University of California (UC) and a professor of physics at UC San Diego. A first-generation college graduate and a distinguished physicist, Dynes served as the sixth chancellor of the UC's San Diego campus from 1996 to 2003. He came to UC San Diego in 1990 after a 22-year career at AT&T Bell Laboratories, where he served as department head of semiconductor and material physics research and director of chemical physics research. His numerous scientific honors include the 1990 Fritz London Award in Low Temperature Physics and his election to the National Academy of Sciences (NAS) in 1989 and the American Academy of Arts and Sciences in 1994. Since leaving the UC presidency in June 2008, Dynes has joined the boards of Argonne National Laboratory, the review panel for the Canadian Foundation for Innovation, the Helmholtz Foundation in Germany, and the San Diego Foundation. He is currently serving on the National Research Council's Governing Board and the National Academies of Science Council. Active in the national scientific arena, he is a fellow of the American Physical Society, the Canadian Institute for Advanced Research, and the American Academy of Arts and Sciences. He has served on the Executive Committee of the U.S. Council on Competitiveness, the California Commission for Jobs and Economic Growth, and the Governor's Nurse Education Initiative Task Force. He is a fellow of the California Council on Science and Technology and a member of the Business–Higher Education Forum. He served as chair for the Committee on Evaluating Testing, Costs, and Benefits of Advanced Spectroscopic Portals and is currently serving on the Nuclear and Radiation Studies Board (NRSB). A native of London, Ontario, Canada, and a naturalized U.S. citizen, Dr. Dynes holds a B.S. in mathematics and physics and an honorary doctor of laws degree from the University of Western Ontario, and an M.S. and Ph.D. in physics and an honorary doctor of science from McMaster University. He also holds an honorary doctorate from L'Université de Montréal.

ALLEN G. CROFF worked at Oak Ridge National Laboratory (ORNL) for 29 years, retiring in 2003, and is now an independent consultant. At ORNL he held positions in line and program management working on projects in waste management research and development, analysis of nuclear fuel cycles and nuclear materials management, and strategic planning. One of his significant achievements was creating the ORIGEN2 computer code used worldwide to calculate radionuclide buildup and decay in nuclear material and waste characterization, risk analysis, and nuclear fuel cycle analysis. He previously served as chair for a committee of the National Council on Radiation

Protection and Measurements on risk-based waste classification. He is a consultant to the Blue Ribbon Commission on America's Nuclear Future and the Nuclear Waste Technical Review Board. Mr. Croff was vice chairman of the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste and a member of the Department of Energy's Nuclear Energy Research Advisory Committee. Mr. Croff has worked on numerous NRC committees including the Committee on Management of Certain Radioactive Waste Streams Stored in Tanks at Three Department of Energy Sites. He received his B.S. in chemical engineering from Michigan State University, an M.S. in nuclear engineering from the Massachusetts Institute of Technology and an M.B.A. from the University of Tennessee.

BART EBBINGHAUS is a project manager at Lawrence Livermore National Laboratory (LLNL) where he studies the chemical and material properties of actinides, purification by pyrochemistry, recovery from wastes, and disposition in ceramics. For a number of years he also directed the plutonium analytical and materials characterization work at the LLNL plutonium facility. He was responsible for much of the technical work supporting the plutonium pit lifetime assessment. From 2006 to 2009, he was the technical advisor to the Nuclear Counterterrorism Program, which focuses on understanding the potential impact of improvised nuclear devices. He was involved in the technical review of the Department of Energy's Graded Safeguards Table from which the figure of merit of nuclear material attractiveness originated. He received his Ph.D. in high temperature chemistry from UC Berkeley in 1991.

B. JOHN GARRICK (NAE) is the retired CEO of PLG, Inc., an international applied science and engineering consulting firm. He recently completed a presidential appointment as chairman of the U.S. Nuclear Waste Technical Review Board. He served for 10 years (1994–2004), four years as chair, on the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste. He has an active consulting practice in the development and application of the risk sciences to systems in the nuclear, space, chemical, environmental, and marine fields. His research interests include the quantification and importance ranking of catastrophic risks to society and the environment to support societal decision making. He has served on or chaired numerous NRC committees, including the Committee on Evaluation of Quantification of Margins and Uncertainty (QMU) Methodology Applied to the Certification of the Nation's Nuclear Weapons Stockpile; the Committee on Engineering Aviation Security Environments—False Positives from Explosive Detection Systems; the Committee on Combating Terrorism; and the Committee on End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States. He is a past president of the Society for Risk Analysis and received that Society's most prestigious award, the Distinguished Achievement Award; is a Fellow of three professional societies; and was elected to the National Academy of Engineering (NAE) in 1993. He received his M.S. in nuclear engineering from UCLA and his Ph.D. in engineering and applied science from the University of California, Los Angeles.

CAROL E. KESSLER is currently chair of the Nonproliferation and National Security Department at Brookhaven National Laboratory. She was formerly the director of the Center for Global Security at the Pacific Northwest National Laboratory (PNNL) and built the center into a renowned program of study in international security and nonproliferation. Prior to that, she served as the deputy director general for the Nuclear Energy Agency at the Organisation for Economic Co-operation and Development, in Paris, France. From 1984 to 1988, Kessler was an export control and international safeguards analyst for the Office of International Programs at the U.S. Nuclear Regulatory Commission. In 1988, she began her career at the State Department, serving as a foreign affairs officer for the Office of Nuclear Technology and Safeguards. She became the senior coordinator for nuclear safety in the Bureau of Nonproliferation Affairs, a position she held from 1995 to 2000. She recently served on the NRC's Committee on Homeland Security and Export Controls. She received her B.S. in biogeology from Brown University. She holds one M.S. in technology and policy from the Massachusetts Institute of Technology and another M.S. in national security policy from the National War College in Washington, DC.

MILTON LEVENSON (NAE) is an independent consultant. He is a chemical engineer with 65 years of experience in nuclear energy and related fields. His technical experience includes work related to nuclear safety, fuel cycle, water reactors, advanced reactors, and remote control. His professional experience includes research and operations positions at the Oak Ridge National Laboratory, the Argonne National Laboratory, the Electric Power Research Institute, and Bechtel. He was elected to the National Academy of Engineering in 1976. Mr. Levenson is a fellow and past president of the American Nuclear Society, a fellow of the American Institute of Chemical Engineers, and recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award in Nuclear Chemical Engineering. He is the author of more than 150 publications and presentations and holds three U.S. patents. He has served on several relevant NRC committees including the Committee on the Internationalization of the Civilian Nuclear Fuel Cycle. He received his B.Ch.E from the University of Minnesota.

NANCY JO NICHOLAS joined Los Alamos National Laboratory (LANL) in 1990 where she is currently the director of Nuclear Nonproliferation Program Office. From June 2006 to June 2010 she was the nuclear nonproliferation division leader. Prior to that she headed the Nonproliferation and Security Technology Program Office where she grew the nuclear safeguards programs in Washington D.C., and Vienna, Austria. She gained significant operational experience by managing an operational Category I nuclear facility for the LANL's Advanced Nuclear Technology Group. She also serves as vice chair and founding member of the Vienna-based World Institute for Nuclear Security. She recently served a 2-year term as president of the Institute for Nuclear Materials Management. Her technical field of expertise is nondestructive assay measurements. Ms. Nicholas earned a B.S. in mathematics and physics from Albright College and an M.S. in nuclear physics from George Washington University.

ARIAN PREGENZER retired from Sandia National Laboratories in Albuquerque, New Mexico, in December 2011. At Sandia, she was senior scientist in the Global Security

Program, where her responsibilities included initiating new programs in arms control and nonproliferation and developing strategies for nuclear security that cut across laboratory missions. In 1994, she led the establishment of Sandia's Cooperative Monitoring Center to enable international technical cooperation on security problems. She worked closely with officials in the United States and Jordan to establish a Cooperative Monitoring Center in Amman in 2003. In 2012, Dr. Pregenzer was awarded the Joseph A. Burton Forum Award by the American Physical Society "For her intellectual and managerial leadership in creating centers that allow international technical and policy experts to explore confidence building measures and other arms control regimes." Prior to her career in international security, she worked at Sandia to develop lithium ion sources for particle-beam-driven inertial confinement fusion. Dr. Pregenzer is a fellow of the American Physical Society and a member of the Council on Foreign Relations. She has bachelor's degrees in physics, mathematics, and philosophy from the University of New Mexico and a Ph.D. in theoretical physics from the University of California at San Diego.

SCOTT D. SAGAN is the Caroline S. G. Munro Professor of Political Science at Stanford University and a senior fellow at the Center for International Security and Cooperation and the Freeman Spogli Institute. He also serves as the cochair of the American Academy of Arts and Science's Global Nuclear Future Initiative. Before joining the Stanford faculty, Sagan was a lecturer in the Department of Government at Harvard University and served as a special assistant to the director of the Organization of the Joint Chiefs of Staff in the Pentagon. He has served as a consultant to the Office of the Secretary of Defense and at the Sandia National Laboratories and the Los Alamos National Laboratory. Sagan has also won four teaching awards: the Monterey Institute for International Studies' Nonproliferation Education Award in 2009, the International Studies Association's 2008 Innovative Teaching Award, Stanford University's 1998–99 Dean's Award for Distinguished Teaching, and Stanford's 1996 Hoagland Prize for Undergraduate Teaching. He has written several books on nuclear nonproliferation and safety including *The Limits of Safety*. He received his B.A. in government from Oberlin College and his Ph.D. in political science from Harvard University.

AMY SANDS is the provost of the Monterey Institute of International Studies. Prior to becoming provost, Dr. Sands served for two and a half years as the dean of the Graduate School of International Policy Studies. Previous to this appointment, she was the deputy director of the James Martin Center for Nonproliferation Studies for 7 years. From August 1994 to June 1996, she was assistant director of the Intelligence, Verification, and Information Management Bureau at the U.S. Arms Control and Disarmament Agency (ACDA). Upon leaving the government, Dr. Sands received ACDA's Distinguished Honor Award and the On-Site Inspection Agency's Exceptional Civilian Service Medal. Before joining ACDA, she led the Proliferation Assessments Section of Z Division (Intelligence) at the Lawrence Livermore National Laboratory. She is a member of the Council on Foreign Relations and the International Institute of Strategic Studies. She recently served on the NRC Committee on Determining Basic Research Needs to Interrupt the Improvised Explosive Device Delivery Chain. She received her B.A. in political science from the University of Wisconsin, a Master of Arts in Law and

Diplomacy (M.A.L.D.) and a Ph.D. from Tufts University Fletcher School of Law and Diplomacy.

WILLIAM H. TOBEY is a senior fellow at Harvard University's Belfer Center for Science and International Affairs. His most recent government experience was as Deputy Administrator for Defense Nuclear Nonproliferation at the National Nuclear Security Administration. There, he managed the U.S. government's largest program to prevent nuclear proliferation and terrorism by detecting, securing, and disposing of dangerous nuclear material. Mr. Tobey also served on the National Security Council staff in three administrations, in defense policy, arms control, and counterproliferation positions. Prior to Mr. Tobey's service with the Department of Energy, he was director of counterproliferation strategy at the National Security Council (NSC) where he oversaw development and implementation of U.S. policy on nuclear programs in Iran and North Korea, was a delegate to the Six Party Talks with North Korea, managed U.S. efforts to dismantle Libya's weapons of mass destruction programs, and authored United Nations Security Council Resolution 1540 which criminalizes non-state proliferation and obligates all states to establish and maintain effective safeguards, security, and export controls. Tobey previously participated in a variety of international negotiations, including the Nuclear and Space Talks with the Soviet Union and the U.S.-Russia Space Cooperation Agreement. He holds a Master of Public Policy (MPP) degree from Harvard University and a B.S. from Northwestern University.

CHRIS G. WHIPPLE (NAE) is a principal in Environ International's Emeryville, California office. His expertise is with the management of risks to health and the environment. Major emphases of his work have been with risks associated with radioactive materials, including radioactive wastes, with hazardous air pollutants and with environmental mercury. He has served on numerous national committees to study and advise on radioactive waste management, including committees of the National Academy of Sciences, U.S. Environmental Protection Agency, and National Council on Radiation Protection and Measurements (NCRP), of which he is an elected member. He currently serves on NCRP's Program Area Committee on Environmental Radiation and Radioactive Waste, on its Advisory Committee on Public Policy, and on its Nominations Committee. He was elected to membership in the National Academy of Engineering in 2001 and is a designated National Associate of the National Academies. Dr. Whipple has chaired the National Academy of Sciences Board on Radioactive Waste Management, and NAS committees on the Review of the Hanford Site's Environmental Remediation Science and Technology Plan, Models in the Regulatory Decision Process, Medical Isotope Production Without Highly Enriched Uranium, and the Committee on Risk-Based Approaches for Securing the DOE Nuclear Weapons Complex. Dr. Whipple is also cochair of the National Academies' Report Review Committee. He was a charter member of the Society for Risk Analysis and served as its second president. In 1990, he received the society's outstanding service award. He is a fellow of the American Association for the Advancement of Science and of the Society for Risk Analysis. His experience prior to joining Environ includes positions as vice president of ICF Consulting, vice president of ICF Kaiser International, and technical manager for Environmental Risk Assessment of EPRI's Environment Division. He holds a B.S degree in engineering science from Purdue University, and an M.S. and a Ph.D., also in engineering science, from the California Institute of Technology. In 2004, he received Purdue’s Distinguished Engineering Alumni Award.

Appendix B: Evaluation of Predefined Frameworks

The tables in this appendix compare methodological qualities and potential applications of existing predefined frameworks for assessing proliferation resistance as defined in the main text. The "Fundamentals" table outlines the development and intended purpose of each methodology, the "Methodology Characteristics" table shows the composition, capabilities, and actual output of each methodology, and the "Application of Methodology" tables shows which and how each methodology was applied by decision makers. These tables were informed by a review of the available literature and input from those developing, implementing and using the results of the analysis.

The frameworks listed in the table are the six current frameworks detailed in Chapter 3 of this report:

- TOPS (Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems) methodology (information sourced from: NERAC TOPS Task Force 2001; NERAC 2000a,b; Hassberger 2001; Ford 2010; Charleton 2012; Giannangeli 2007; Mendez et al. 2006; Zentner 2011);
- JAEA (Japan Atomic Energy Agency) methodology (information sourced from: Takakai et al. 2005; Ford 2010; Charleton 2012; Giannangeli 2007; Mendez et al. 2006; Inoue et al. 2003);
- SAPRA (Simplified Approach for Proliferation Resistance Assessment) methodology (information sourced from: Charleton 2012; Zentner 2011; Ford 2010; Giannangeli 2007; Mendez 2006; Greneche et al. 2007)
- TAMU MAUA (information sourced from: Texas A&M University Multi-Attribute Utility Analysis) methodology (information sourced from: Pomeroy 2008; Ford 2010; Clarleton 2012; Giannangeli 2007; Mendez 2006; Takakai et al. 2005)
- RIPA (Risk-Informed Proliferation Analysis) methodology (information sourced from: Rochau et al. 2002; Ford 2010; Charleton 2012; Giannangeli 2007; Mendez 2006)
- GIF PR&PP (Generation IV International Forum Proliferation Resistance & Physical Protection) methodology (information sourced from: GENIV 2007; DOE 2008a; DOE 2008b;GENIV 2009; ; GENIV 2011a; GENIV 2011b; Bari et al. 2007; Bari et al. 2008a; Bari et al. 2008b; Bari et al. 2009; Bari 2012; Charleton 2012; Ford 2010; Giannangeli 2007; Mendez 2007)

For further background and evaluation of these predefined framework methodologies, see Chapter 3.

The content of these tables was reviewed by experts to ensure accuracy in their representation and content. The reviewers were:

- Robert Bari, Brookhaven National Laboratory
- Joe Pilat, Los Alamos National Laboratory
- Gary Rochau, Sandia National Laboratory
- David Sweeney, Texas A&M University

FUNDAMENTALS

Comparison Criterion	TOPS	JAEA	SAPRA	TAMU MAUA	RIPA	PRPP
Who developed the methodology and when?	DOE/NE Nuclear Energy Research Advisory Committee Developed in 2000-2001. Subsequent development in the form of SAPRA and JAEA	Japan Atomic Energy Agency [nee Japan Nuclear Cycle Development Institute (JNC)] Developed to support Japanese decisions on NESs (Inoue 2003).	French Working Group on Proliferation Resistance and Physical Protection Developed as part of a French multi-agency effort (Greneche 2007).	Texas A&M University Developed for AFCI and some predecessor programs (Krakowski 1999; Charlton 2007). Continues to be upgraded (Giannangeli 2007; Metcalf 2009)	Sandia National Laboratory Developed as part of a lab-funded project to address some weaknesses in TOPS (Rochau 2002).	Gen IV Industrial Forum (GIF) Development started in 2002, first public release in 2005. Continues to be upgraded.
What is its stated purpose?	Identify near- and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems	Characterize relative proliferation risk of NESs (and possibly technical options for steps in a NES)	Identify near- and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems.	Aid in the assessment of the effectiveness of safeguards implementation at facilities within a large-scale fuel cycle and the ability to choose proliferation deterrant technologies.	Develop a process capable of conducting a simple dynamic analysis to compare and outline probable outcomes of feasible proliferation pathways and forecast those pathways by creating likely scenarios.	Develop and demonstrate a methodology for the systematic evaluation of Generation IV NESs respect to proliferation resistance and physical protection.
Who are its intended users?	Decision makers and the public	Decision makers and the public	Decision makers and the public	Fuel cycle facility designers	Decision makers and the public	Decision makers and the public Fuel cycle designers if enough detail is included.

ASSESSMENT METHODOLOGY CHARACTERISTICS

Comparison Criterion	TOPS	JAEA	SAPRA	TAMU MAUA	RIPA	PRPP
Overall approach	Barrier attribute analysis	Barrier attribute analysis	Barrier attribute analysis.	Barrier attribute analysis with a focus on nuclear materials moving through facilities	Analyzes hypothesized proliferation scenarios using PRA-derived influence diagrams to characterize the scenarios and techniques	Utilizes a probabilistic risk assessment (PRA)-like (fault tree) approach to identify pathways.
Factors considered (Figures of Merit)	Material Barriers, Technical Barriers	Material Barriers, Technical Barriers	Material Barriers, Technical Barriers, Institutional Barriers	Measures are attractiveness level, concentration, handling requirements, type of accounting system, and accessibility.	Production time, cost, probability of non-detection, and probability of success and project observability (Rochau et al. 2012)	Measures considered: technical difficulty, cost to proliferator, time to overcome barriers, fissile material type, detection probability, detection safeguards cost.
Expert judgment used?	Yes	Yes	Yes	Yes	Yes	Yes
Output	Matrix of H-M-L. Results not aggregated into a single FOM	Normalized numerical values for barrier attributes. Graphical results for each barrier. No attempt to provide a single FOM.	Normalized numerical values for barrier attributes and single FOM.	Numerical output typically in the form of normalized proliferation values for each scenario step	Numerical values for each of four metrics and a single FOM. A number of display options were been proposed.	Ranking of alternatives or a matrix of H-M-L. Results not aggregated into a single FOM
Types of threats considered	State threats	Nation (covert), sub-national group (theft)	Covert host state diversion, non-host-state theft	State threat, sub-national/terrorist theft	State threat, sub-national/terrorist theft	State threats, non-host-state-theft
Considered country-specific factors?	No. Could assuming experts are given proper context	No. Could assuming experts are given proper context	No. Could assuming experts are given proper context	No. Could assuming experts are given proper context	No. Could assuming experts are given proper context	No. Could assuming experts are given proper context
Considered time dependence of proliferation?	No	Yes in the sense of time to acquire SNM but not changing long-term context unless a time-lapse snapshot approach is used	Yes in the sense of time to acquire SNM but not changing long-term context unless a time-lapse snapshot approach is used	Yes. Can calculate a time-dependent FOM through the fuel cycle and disposal	Yes in the sense of time to acquire SNM but not changing long-term context unless a time-lapse snapshot approach is used	Yes in the sense of time to acquire SNM but not changing long-term context unless a time-lapse snapshot approach is used
Does the methodology lend itself to sensitivity/uncertainty analysis?	No	No	No	Yes	Yes	Yes
Do the examples indicate that uncertainty (U) or sensitivity (S) analysis has been performed?	No, neither	S	S	No, neither	No, neither	No, neither
Is the methodology related to/built on another methodology? Key differences?	A precursor to SAPRA and JAEA	Yes: JAEA extended TOPS by using "expert grading" to quantify most attributes	Built on JAEA approach which was built on TOPS. Key differences are including four steps to proliferation and more metrics	This methodology is an extension and adaption of SAPRA. It adds additional layers of information and a new aggregation approach.	No	No

APPLICATION OF METHODOLOGY						
Comparison Criterion	TOPS	JAEA	SAPRA	TAMU MAUA	RIPA	PRPP
What organization has used the example predefined framework methodologies as part of the basis for a decision	Seminal work that impacted DOE's R&D program at the time including development of better proliferation assessment methodologies	None known; possibly in Japanese internal programmatic decisions	None known; possibly in French internal programmatic decisions	Factored into DOE/NE's AFCI programmatic decisions in the early 2000s	None known	No evident use by country-specific decision makers Used in DOE documents concerning programmatic decisions
Examples of predefined framework assessments performed using the methodology:	Initial development (NERAC 2001) used method to identify R&D needs. Separate comparison of proliferation resistance of 10 fuel cycles (Hassberger 2001). Unclear whether this factored into any decisions.	Two trial applications in the early 2000s.	Eight case studies were considered in (Greneche 2007): four for theft by an effort sponsored by a non-host state, four for host state diversion	Used by AFCI via NERAC to compare a number of fuel cycles (Waltar and Omberg 2004) Used by Metcalf (thesis) to evaluate uranium and thorium fuel cycles for fast reactors (Metcalf 2009) Used by TAMU to assess fast reactors with closed fuel cycles (Chirayath 2010). Unclear whether this factored into any decisions.	None known	Used in the draft GNEP Non-Proliferation Assessment [NNSA 2008] supporting the draft GNEP PEIS [DOE 2008]. A series of assessments was performed on various reprocessing technologies (Bari et al. 2007, 2008b, BNL 2009) Assessments were performed on an example sodium-cooled fast reactor, grid-appropriate (small modular), and the six GEN-IV reactor designs (DOE 2009, DOE 2011b, Bari 2008a) AECL assessed safeguards-by-design for an advanced CANDU reactor (Whitlock 2010) Belgium assessed the proliferation resistance of a proposed spallation device (Van der Meer 2010)

Appendix C: Statement of Task

An ad hoc committee will conduct a study and prepare a report for the Department of Energy (DOE) regarding potential research and development (R&D) directions for improving the assessment of the host state proliferation risk of nuclear fuel cycle facilities. The study will:

1. Identify key proliferation policy questions capable of being answered by a technical assessment of the host-state proliferation risk posed by a given nuclear fuel cycle, and discuss the utility of these questions for informing international nonproliferation policy decisions;
2. Assess the utility for decision makers of existing and historical methodologies and metrics used by DOE and others (such as the International Atomic Energy Agency) for assessing proliferation risk, both for considering the deployment of these facilities domestically as well as the implications of deployment outside the United States;
3. Assess the potential for adapting risk assessment methodologies developed in other contexts (such as safety and security) to host-state proliferation risk assessments—including both qualitative and quantitative approaches—their benefits, limitations, and the challenges associated with adapting these methodologies to proliferation risk assessment;
4. Identify R&D and other opportunities for improving the utility for decision - makers of current and potential new approaches to the assessment of proliferation risk; and
5. Identify and assess options for effectively communicating proliferation risk information to government and industry decision makers, as well as the public and the NGO community both within the United States and internationally.

This study will not address the risk associated with the physical security of the facility or materials against attack, theft, or diversion of nuclear materials. The study may examine policy options but will not make specific policy recommendations.

Appendix D: Presentations and Committee Meetings

Washington, DC, January 16-17, 2012

- *Proliferation Risk Assessments: A Policy-Maker's Observations*, Dunbar Lockwood, National Nuclear Security Administration, DOE, Office of Nonproliferation and International Security, NA-24
- *DOE/NE Perspectives on the National Academies Proliferation Risk Assessment Project*, Andrew Griffith, Office of Nuclear Energy, DOE
- *Phase One Workshop Overview: Policy-Side Perspective,* Sharon Squassoni, Center for Strategic and International Studies
- *Phase One Workshop Overview: Technical Perspective,* William Charlton, Texas A&M University
- *Overview of Proliferation Risk Methodologies,* William Charlton, Texas A&M University
- *Assessing Proliferation Risk: Approaches from Quantitative Political Science*, Jeff Kaplow, University of California, San Diego

Washington, DC, March 26-27, 2012

- *Recent Nonproliferation Policy Decisions,* Joyce Connery, Nuclear Energy Office of International Economics, National Security Council
- *Progress and Application of Proliferation Risk Reduction to the Design of a Reprocessing Facility*, John Herzceg, Office of Fuel Cycle Technologies, Office of Nuclear Energy
- *Nonproliferation Decision-Making Within Congress*, Mary Beth Nikitin, Congressional Research Service
- *Government Agencies Outside of DOS and DOE Using Proliferation Risk Assessments***,** Ray Richardson, U.S. Central Intelligence Agency

Stanford, CA, May 11, 2012

- *Host State Intentions: Political Science Perspectives*, Christopher Way, Cornell University
- *Determinants of Nuclear Proliferation*, Erik Gartzke, Department of Political Science, University California, San Diego
- *Thoughts on Proliferation Risk Assessment*, Chris Whipple, ENVIRON
- *Proliferation Analysis: Methodologies, Assessments, and Warning Indicators*, Lisa Owens Davis, Lawrence Livermore National Laboratory

Livermore, CA, May 22-23, 2012

- *TAMU's TPRA [Technical Proliferation Resistance Assessments]Methodology and TPRAs State of the Art***,** William Charlton, Texas A&M University
- *Proliferation Resistance Assessment: GIF, INPRO, and IAEA Safeguards*, Jon R. Phillips, Pacific Northwest National Laboratory
- *Gen IV Working Group PR&PP Methodology***,** Robert Bari, Brookhaven National Laboratory
- *Nuclear Energy Materials Applied to Nuclear Weapons,* Vladimir Georgevich, Lawrence Livermore National Laboratory
- *LLNL Z-Division Proliferation Events***,** Mary Beth Ward, Lawrence Livermore National Laboratory
- *LLNL Z-Division Host State Assessments for Government Decisions*, Lisa Owens Davis, Lawrence Livermore National Laboratory

Albuquerque, NM, July 9-10, 2012

- *Technical Assessments of Proliferation Risk and the Nuclear Supplier's Group Review of Dual Use Technology List*, Jeff Bedell, Los Alamos National Laboratory
- *Probabilistic Effectiveness Methodology (PEM) for the Domestic Nuclear Detection Office (DNDO), A Transportation Pathways Risk Assessment*, James Smith, Los Alamos National Laboratory
- *DNDO's Global Nuclear Detection Architecture Adversary Risk Model*, Steven Streetman, Domestic Nuclear Detection Office, Department of Homeland Security
- *Probabilistic Risk Analysis Background and Applications*, David Johnson, ABS Consulting
- *Threat Assessments for Cyber-Security*, Rafail Ostrovsky, University of California, Los Angeles

Washington, DC, September 12-13, 2012

- *Utilization of Prioritization Methodologies by Policymakers*, Phillip Dolliff, Office of Cooperative Threat Reduction, Department of State
- *International Aspects of the Tasking and Safeguards*, Kory Budlong-Sylvester, Los Alamos National Laboratory
- *Improving the Assessment of Proliferation Risk of Nuclear Fuel Cycles*, Michael Rosenthal, past member of International Atomic Energy Agency's Standing Advisory Group on Safeguards Implementation
- *SILEX Risk Assessment Panel with Global Laser Enrichment Evaluation Team*, Donald M. Kerr, George Mason University; Susan Koch, independent consultant; and Gordon Oehler, Potomac Institute for Policy Studies
- *How to Develop Complex Nuclear Risk Messages for the Public*, Hank Jenkins-Smith, Oklahoma State University
- *Models on Countries' Intent*, Brian Lessenberry

Appendix E: Glossary and Acronyms

GLOSSARY OF KEY TERMS

The terms are defined in this glossary for the purpose of usage in this particular report.

Adaptive adversary	An opponent that reacts to actions and protective measures by constantly adapting or inventing new pathways to do harm
Best practice	An approach or method that has consistently proven to be exceptionally effective and is used as a standard against which other approaches are gauged
Case-by-case assessments	A systematic analysis of a problem using multidisciplinary teams of subject matter experts assembled to address a specific problem
Decision maker	Programmatic decision maker within the U.S. government
Extrinsic attributes	Properties of a nuclear fuel cycle dependent on implementation of safeguards, operations, and facility details
Intrinsic attributes	Properties inherent to a nuclear fuel cycle, usually related to materials and processes
Predefined framework	A structured analysis used to assess the proliferation resistance of a fuel cycle, which contains predetermined lists of detailed attributes of the fuel cycle and a predetermined approach for scoring and combining these attributes to determine the cycle's overall proliferation resistance
Policy maker	A person within the U.S. government who is making policy decisions or is responsible for enacting policies
Political science	A social science concerned primarily with the structure, behavior, and interactions of states, governments, and other political institutions
Probabilistic risk assessment	A method of analyzing risks associated with complex, interrelated systems by assessing what can go wrong, how likely it is to occur, and what the consequences are if it does happen (Kaplan and Garrick 1981)

Proliferation	The development of and/or acquisition of a nuclear weapon by a non–nuclear weapon state
Proliferation resistance	"The characteristics of a nuclear energy system that impede the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices" (IAEA 2002)
Proliferation resistant	Used to describe nuclear fuel cycles or components of a fuel cycle to indicate an increased barrier to proliferation, often misunderstood or misinterpreted as "proliferation proof"
Proliferation risk	The committee purposefully did not define this term but suggests its definition be determined by analysts and users of the assessments. One definition introduced to the committee was, "The probability that a host-state will choose to proliferate along a particular or multiple pathways (L), the probability of success along that path (P), and the consequences of proliferation (C)." This definition is used throughout the report but should not be interpreted as endorsement by the committee
Social science	An academic area of study that examines the behavior and development of human society and the interaction of individuals to and in society

ACRONYMS

CANDU	CANada Deuterium Uranium reactor
DOE	U.S. Department of Energy
DOE-NE	DOE Office of Nuclear Energy
DOE-NNSA	DOE National Nuclear Security Administration
DUPIC	direct use of pressurized water reactor spent fuel in CANDU
E&R	enrichment and reprocessing
EPA	U.S. Environmental Protection Agency
FOM	Figure of Merit
GEN III	Generation III; current nuclear fuel cycles
GEN IIIa	Generation III; advanced light water reactors
GEN IV	Generation IV; future nuclear fuel cycles
GIF	Generation IV International Forum
GNEP	Global Energy Nuclear Partnership
IAEA	International Atomic Energy Agency
INFCIRFC	IAEA Information Circular
INPRO	International Project on Innovative Reactors and Nuclear Fuel Cycles
JAEA	Japan Atomic Energy Agency

MYRRHA	a flexible fast spectrum research reactor at the Belgian Nuclear Research Centre in Mol
NAS	National Academy of Sciences
NCA	Nuclear Cooperation Agreement
NNWS	non-nuclear weapons state
NPAS	Nonproliferation Assessment Statement
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	National Research Council
NSG	Nuclear Suppliers Group
OUO	official use only
PEIS	programmatic environmental impact statement
PR&PP	Proliferation Resistance and Physical Protection
PRA	probabilistic risk assessments
RIPA	Risk-Informed Probabilistic Analysis
SAPRA	Simplified Approach for Proliferation Resistance Assessment
SNM	special nuclear material
TAMU MAUA	Texas A&M University Multi-Attribute Utility Analysis
USNRC	U.S. Nuclear Regulatory Commission
TOPS	Technical Opportunities to Increase Proliferation Resistance of Global Civilian Nuclear Power Systems