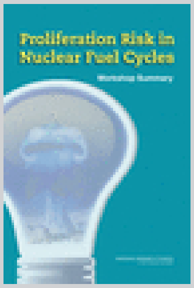

Proliferation Risk in Nuclear Fuel Cycles: Workshop Summary

Sarah C. Case, Rapporteur; National Research Council

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Proliferation Risk in Nuclear Fuel Cycles

Workshop Summary

Sarah C. Case, *Rapporteur*

Nuclear and Radiation Studies Board

Division on Earth and Life Studies

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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 (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the NRC 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
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Michael Zentner, Pacific Northwest National Laboratory

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the contents of this report, nor did they see the final draft of the report before its release. The review of this report was overseen by James H. Johnson, Jr., Howard University. Appointed by the National Research Council, he was 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 author and the institution.

Contents

Overview

The worldwide expansion of nuclear energy has been accompanied by concerns about nuclear weapons proliferation. If sited in states that do not possess nuclear weapons technology, some civilian nuclear technologies could provide a route for states or other organizations to acquire nuclear weapons. Metrics for assessing the resistance of a nuclear technology to diversion for non-peaceful uses—proliferation resistance—have been developed, but at present there is no clear consensus on whether and how these metrics are useful to policy decision makers.

In 2011, the U.S. Department of Energy asked the National Academies to convene a public workshop addressing the capability of current and potential methodologies for assessing host state proliferation risk and resistance to meet the needs of decision makers. This report is a summary of presentations and discussions that transpired at the workshop—held on August 1-2, 2011—prepared by a designated rapporteur following the workshop.[1] It does not provide findings and recommendations or represent a consensus reached by the symposium participants or the workshop planning committee. However, several themes that emerged from the workshop discussions are outlined in the following paragraphs.

Nonproliferation and new technologies. Several speakers noted that for decades, advanced nuclear fuel cycles have received little attention in

[1] Many facts were reiterated at the workshop, and no attempt has been made to attribute these statements in the summary.

the United States beyond research and development, and that the potential for a worldwide nuclear renaissance may mean that such attention is now overdue. Some participants also noted that non-proliferation policy has not kept pace with new technology developments. For example, one participant stated that relatively new technologies such as laser enrichment can present challenges for policy makers. Moreover, advancing technologies from other fields—such as carbon fiber technology—are breaking down the barriers that have previously separated fuel cycle technologies from other industrial technologies.

Separate policy and technical cultures. Many participants noted the existence of two cultures within the nuclear nonproliferation community, one highly technical and the other policy-focused. Several examples of poor communication between these two cultures were cited, including: poor communication of policy needs to the technical community; a lack of clear definitions common to both the technical and policy communities for proliferation risk and resistance; and technical results that do not focus on the needs of policy makers. Some participants also noted that the communication difficulties are heightened by the reality that policy makers' decisions related to nuclear fuel cycle technologies—domestically or internationally—are not solely motivated by proliferation concerns, but are interwoven with other concerns, such as geopolitics, economics, energy, or radioactive waste management requirements.

Value of proliferation resistance analysis. Many workshop participants disagreed regarding the value of proliferation resistance or risk analysis itself, particularly if quantification is involved. Several participants judged that technical and quantifiable assessments might be able to provide useful input on some issues, including:

- Managing risk when making international policy decisions;
- Determining the relative proliferation risk of two fuel cycles;
- Deciding where to provide money for further R&D analyses; and
- Deciding which countries to cooperate with on nuclear technology, and how.

Furthermore, some participants judged that quantifiable (or at least, highly technical) conclusions could be helpful to policy makers, due to their potential for rigor.

On the other hand, other participants judged that technical and quantifiable assessments are unlikely to be useful to address many policymaker concerns. Moreover, some participants judged that quantification might be counterproductive, particularly if underlying assumptions and uncertainties in the methodology were not made clear to the policy makers. In addition, some participants raised concerns that identifying the most (and least) proliferation-resistant technologies could assist potential proliferators in determining where to focus their efforts.

Usefulness of social science approaches. Finally, participants discussed the possibilities for further analyzing why countries might choose to use nuclear fuel cycle technology to produce nuclear weapons material, using examples from social science and historical analysis. For example, one participant suggested that there could be stark differences in approaches if the country of interest were a "closed" versus an "open" society.

1

Background

A worldwide resurgence in interest in nuclear power plant construction has recently been underway. According to the International Atomic Energy Agency (IAEA) in 2010:

> In recent years, in every region of the globe, many countries have expressed a new or renewed interest in nuclear power. In the context of growing energy demands to fuel economic growth and development, climate change concerns, and volatile fossil fuel prices, as well as improved safety and performance records, some 65 countries are expressing interest in, considering, or actively planning for nuclear power (IAEA, 2010a).

If a resurgence of nuclear power does occur,[1] fuel will be required for new power plants. In this situation, many countries—particularly new entrants—may need assurance that fuel for these power plants will be cost effective and available. Thus, unless an alternative solution to producing or recycling nuclear fuel domestically is proposed and universally accepted, some nations may be interested in constructing nuclear fuel cycle facilities, including enrichment or reprocessing facilities.

Nuclear power plants themselves are often considered a lesser proliferation[2] risk than other nuclear fuel cycle facilities, particularly those that

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[1] The global economic crisis and the recent events at the Fukushima nuclear power plants in Japan may change or delay these plans.

[2] Defining the point at which a state is considered to have proliferated is complicated. For example, is a nation a proliferator if it produces highly enriched uranium or plutonium, or

are used to produce or recycle nuclear fuel. These facilities are considered to have a significant potential to increase the risk of host state proliferation[3] if sited in states that do not currently possess nuclear weapons technology (NRC, 2009).[4] This is because these facilities in many cases are or can be easily converted to dual use; potentially, they can be used to produce weapons-usable material and to spread nuclear weapons technology as well as fuel for nuclear reactors.

There exist both technical and policy efforts aimed at managing and reducing the proliferation risks associated with nuclear fuel cycle facilities. In particular, a range of technical methodologies are currently being developed to assess some of the proliferation risks associated with these facilities. For the most part (as discussed in more detail later in this report) these methodologies remain immature (TAMU, 2010).

The current report is a summary of a workshop on improving the assessment of proliferation risk associated with nuclear fuel cycles. The workshop was held on August 1-2, 2011 by the National Research Council (NRC) of the U.S. National Academies at the National Academies' Keck Center in Washington, DC.

The workshop was organized as part of a larger project undertaken by the NRC, the next phase of which (following the workshop) will be a consensus study on improving the assessment of proliferation risks associated with nuclear fuel cycles.[5] This study will culminate in a report prepared by a committee of experts with expertise in risk assessment and communication, proliferation metrics and research, nuclear fuel cycle facility design and engineering, international nuclear nonproliferation and national security policy, and nuclear weapons design. This report is planned for completion in the spring of 2013.

The overall project was originated in response to a 2011 joint request from the U.S. Department of Energy (DOE) National Nuclear Security Administration's Office of Nonproliferation and International Security and the DOE Office of Nuclear Energy. DOE asked that the workshop feature discussions about key nonproliferation policy questions capable

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is it necessary to begin other efforts to construct a weapon? There is no standard that the workshop briefings summarized in this report are necessarily adhering to in the discussions of the subject.

[3] Throughout this workshop, participants discussed "host-state" proliferation, or actions taken by the government of the state in which the facility is located to use the facility to illicitly produce nuclear materials for non-peaceful uses.

[4] Throughout this report, the risk associated with the physical security of the facility or materials against attack, theft, or diversion of nuclear materials (security risk) is considered to be separate from host state proliferation risk. Security risk is explicitly not intended to be considered by the current study.

[5] The task statement for the full study can be found in Appendix A.

of being answered by a technical assessment of the host state proliferation risk and the utility of these questions for informing nonproliferation policy decisions. The statement of task for the workshop is included as Appendix B.

DOE and NRC agreed that the workshop would not result in consensus findings or conclusions among the participants, but would instead focus on encouraging discussion on the topics in the statement of task. For this reason, the current report does not feature findings, conclusions, or recommendations, but instead serves as a summary record of the briefings and discussions that occurred during the symposium. Many of these themes will be expanded upon in the consensus study.

The workshop was organized by a four-member committee with extensive expertise in nonproliferation policy, proliferation resistance assessment, nuclear weapons policy and technology, and nuclear fuel cycle technology. Biographical sketches of the committee members and staff are provided in Appendix C. The committee met twice over the course of the project: first, in May 2011, to plan the workshop; and second, in August 2011, to hold the workshop. The workshop agenda is provided as Appendix D, and the list of workshop participants is provided as Appendix E. Appendix F contains biographical sketches of the workshop speakers.

The workshop featured a range of expert briefings on proliferation and the nuclear fuel cycle as well as extensive audience participation in the form of breakout and discussion sessions. The workshop was organized into three sessions, reflected in chapters 2, 3, and 4 of this report: (1) key policy issues associated with proliferation and the nuclear fuel cycle; (2) methods and methodologies to assess the proliferation resistance of fuel cycle facilities; and (3) summary and future directions for the assessment of proliferation resistance.

The remainder of the chapter is based on a white paper distributed to the workshop participants (Case and Ferriss, 2011) and is intended to provide the reader with background information regarding proliferation and nuclear energy, the nuclear fuel cycle, and some basic concepts associated with assessing the proliferation resistance of nuclear fuel cycle facilities.

NUCLEAR FUEL CYCLES

Uranium nuclear fuel cycles consist of three stages: (1) the front end, in which uranium is mined, milled, enriched,[6] and fabricated into fuel; (2) power generation; and (3) the back end, in which spent fuel is either

[6] Enrichment is not a part of all fuel cycles; for example, the CANada Deuterium Uranium (CANDU) reactor design can operate using natural (i.e., unenriched) uranium.

disposed of (open fuel cycles) or processed to produce new fuel (closed or partially closed fuel cycles).[7]

The power generation (second) stage is often considered to pose a lesser risk than facilities associated with the front end and the back end of the fuel cycle.[8] As stated in the 2009 National Research Council report on America's Energy Future, "Nuclear power plants themselves are not a proliferation risk, but nuclear fuel cycle technologies such as enrichment and reprocessing introduce the risk that weapons-usable material could be produced" (NRC, 2009, p. 491). This risk is discussed in the following two sections: (1) the front end, or enrichment; and (2) the back end, or recycling (reprocessing) or disposal.

Front-End Facilities: Enrichment

Nuclear fission reactions—in which a neutron is used to split an atom, releasing energy that becomes the power plant's heat—are sustained in materials that are "fissile," such as certain isotopes of uranium (e.g., uranium-235) and plutonium (e.g., plutonium-239).

More than 99 percent of natural uranium is uranium-238, rather than uranium-235, the uranium isotope whose fission is used to power most nuclear reactors. Typically, in uranium fuel produced for power generation (or material for use in a nuclear weapon), the concentration of uranium-235 is increased from natural concentration, i.e., enriched. The first working technologies to enrich uranium—thermal diffusion and electromagnetic isotope separation—were developed for the Manhattan Project, the United States' massive effort in the 1940s to develop a nuclear weapon. However, these technologies are both expensive and time-intensive, and were eventually dropped from the U.S. program in favor of a technology known as gaseous diffusion enrichment. However, gaseous diffusion enrichment is very energy-intensive, and in the decades since, more efficient gas centrifuge enrichment technology has been developed and deployed around the world. Either technology can be used to produce power reactor fuel or nuclear weapon-usable material, by using a different number of enrichment stages.

Both gaseous diffusion and gas centrifuge enrichment processes rely on the slight difference in mass between uranium-238 and uranium-235. In gaseous diffusion enrichment, uranium hexafluoride gas (UF_6) is forced through a series of semi-permeable membranes. Because lighter mol-

[7] This is a simplification; DOE, for example, has research underway on modified open fuel cycles.

[8] While reactors alone may present little risk, a clandestine reprocessing capability (or a possible breakout scenario) can significantly increase this risk.

ecules pass through the membrane more easily than heavier molecules, at each membrane stage slightly more uranium-235 passes through the membrane than uranium-238. After many repetitions, the UF_6 gains a higher proportion of uranium-235 until it is enriched to the desired level.

Gas centrifuge enrichment uses a cascade of centrifuges (rapidly rotating containers) to gain a slightly higher percentage of uranium-235 at each stage. Uranium-238, being slightly heavier, is driven farther in the radial direction from the center of the centrifuge. The lighter molecules of uranium-235 remain closer to the center of the centrifuge, and are drawn out and then input into the next stage of the centrifuge.

Other technologies that have been proposed to produce nuclear material include laser isotope separation, in which the uranium isotopes are separated using laser light to excite the molecules. There are currently no operating commercial-scale laser separation facilities in the world; however, General Electric-Hitachi plans to build a laser separation facility in Wilmington, North Carolina.[9]

As of 2010, three new commercial enrichment facilities, all using centrifuges, were planned: George Besse II in France, as well as the American Centrifuge Plant and the National Enrichment Facility in the United States. The U.S. Nuclear Regulatory Commission is currently reviewing plans for an additional centrifuge facility in Idaho and the previously mentioned laser enrichment facility in North Carolina (IAEA, 2010b).

Back End Facilities: Reprocessing

After highly radioactive spent nuclear fuel (SNF) has been removed from a power reactor it must either be stored for eventual disposal or reprocessed to recycle the remaining fissionable material. These options are referred to as a once-through or open fuel cycle and a closed or partially-closed fuel cycle, respectively. The United States is currently using a once-through fuel cycle; however, the Obama administration's recent decision to cancel the planned repository program at Yucca Mountain in Nevada has resulted in no clear path for the disposal of U.S. spent fuel, most of which is currently being stored on-site at the power plants (BRC, 2011; NRC, 2008). Over the past few years, the complicated U.S. situation with respect to spent fuel and high-level radioactive waste disposal has led to a renewed interest in closed fuel cycles for waste management. This interest is due in part to their potential to reduce the long-lived radioactive waste burden (USDOE, 2007; USDOE, 2010). Russia, India, Japan, France, and the U.K. maintain (at least in part) a closed fuel cycle for civilian SNF (IAEA, 2011).

[9] See: http://www.starnewsonline.com/article/20100415/ARTICLES/100419797

Reprocessing (also called recycling) spent fuel requires several steps, notably including a chemical or electrochemical process to separate and recover fissile components of the fuel. Most proliferation and security discussions focus on this step, because it is at this point that a stream of material that could be used in weapons (or easily treated to be usable in weapons) is produced.

The most common and best understood method used for separating fissile components is a variant of the PUREX (Plutonium and URanium EXtraction) process, which was initially used in the 1950s. This process results in a separated, pure stream of plutonium as well as uranium. Alternatives to PUREX currently under investigation (e.g., advanced Uranium Reduction and EXtraction [UREX+]; CO-Extraction of uranium and plutonium [COEX]; and electrochemical separations) include both evolutionary modifications of PUREX and entirely different separations technologies.

In many cases, alternatives to PUREX are intended to avoid the generation of the pure stream of plutonium that PUREX produces, and so reduce proliferation and theft risk. However, the reduction in risk is not always robust if minor changes are made to the process. For example, a modified version of PUREX has been suggested to provide increased proliferation resistance, but in 2008, the NRC reported that small adjustments could convert this process to PUREX (NRC, 2008).

ASSESSING PROLIFERATION RISK AND PROLIFERATION RESISTANCE OF NUCLEAR FUEL CYCLE FACILITIES

Whether or not proliferation occurs is based on individual and group decisions. These decisions can be reversed, modified, paused, or substantially altered as the potential proliferator's political and economic environment changes and new technical options and opportunities emerge. However, there are some technical tools that have been proposed to evaluate and manage the risk of proliferation as well as the resistance of nuclear facilities to proliferation attempts.

Managing any risk—whether proliferation risk, safety risk, or security risk—involves three interacting elements: risk assessment (understanding the risk), risk communication (informing decision makers about the risks), and risk control (arriving at and implementing decisions to manage the risk) (NRC, 2011). In the following section, some background is provided for the reader on proliferation risk and resistance as connected to the nuclear fuel cycle. When discussing the probability of a nuclear facility being used to produce material for weapons, two terms are frequently used: proliferation resistance and proliferation risk. Throughout the report, a distinction has been made between these two concepts.

Proliferation resistance assessment focuses on how difficult it is to divert a particular dual use technology for non-peaceful uses.[10] On the other hand, proliferation risk assessment recognizes and attempts to quantify the likelihood of threats, the barriers that must be overcome (proliferation resistance) and the consequences resulting from a potential threat (IAEA, 2002; Charlton, 2011). Proliferation risk and resistance are discussed in more detail in Chapter 3 of this report.

The proliferation resistance associated with a fuel cycle system or facility is frequently described in terms of extrinsic and intrinsic barriers to proliferation. A 2001 report from Lawrence Livermore National Laboratory (Hassberger et al., 2001) defines intrinsic barriers as "those features fundamental to the nuclear fuel cycle that deter or inhibit the use of materials, technologies or facilities for potential weapons purposes." The same report states that extrinsic barriers "depend on implementation details and compensate for weaknesses in the intrinsic barriers. Safeguards, material control and accountability are examples of these extrinsic barriers, often referred to as the institutional barriers."

The two most commonly used approaches to assessing the proliferation resistance of a nuclear fuel cycle are attribute-based and scenario-based analyses. Attribute-based analyses, such as the approach developed by the Texas A&M University's Multi Attribute Utility Analysis (MAUA), attempt to identify and quantify both intrinsic and extrinsic barriers and then aggregate them. Scenario-based analyses model specific proliferation scenarios[11] in their entirety rather than individual attributes of a particular system[12] (TAMU, 2010). The Proliferation Resistance and Physical Protection (PR&PP) Working Group within the Generation IV Initiative Forum (GIF) has developed a scenario-based approach (TAMU, 2010).

Extrinsic barriers have been established by a number of diplomatic efforts, such as international treaties. They include the Nuclear Non-Proliferation Treaty (NPT)—which opened for signature in 1968 and entered into force in 1970—and the IAEA, founded in 1957. As of November 2010, the IAEA, which facilitates the peaceful use of nuclear material and facili-

[10] This definition of proliferation resistance draws on the International Atomic Energy Agency definition used by William Charlton in his Chapter 3 discussion of proliferation resistance. However, other definitions of proliferation resistance are used, for example, the Generation IV International Forum's Proliferation Resistance and Physical Protection methodology uses a definition based on six measures of proliferation resistance (http://www.gen-4.org/Technology/horizontal/proliferation.htm).

[11] Scenarios describe the sequence of events of an attempt to proliferate, beginning with the initial efforts and continuing through each stage (and associated barriers) to the final objective.

[12] In this context, a "system" refers to the technological system being modeled, i.e., the fuel cycle or the facility.

ties, had 151 member states willing to comply with various inspections and safeguards.[13] One hundred ninety nations are parties to the NPT,[14] with the notable exceptions of Israel, Pakistan, and India. North Korea signed the treaty in 1985 but withdrew in 2003 (UN, 2011). Another example of an extrinsic barrier might be the adoption by the Nuclear Suppliers Group of criteria for sales of sensitive fuel cycle technologies.

Other, related, extrinsic barriers—specifically, safeguards measures[15]—can be highly technical, and require technical assessments to understand, improve, and maintain their efficacy. Nuclear safeguards measures are applied primarily to non-weapons states and require nuclear facility operators to maintain and declare detailed accounting records of all movements and transactions involving nuclear material. These records are verified through official in-person inspections by the IAEA as well as surveillance cameras and other instrumentation.[16]

The remainder of the report discusses the key questions for non-proliferation policy and the potential for technical assessments to provide valuable input to these questions.

[13] See: http://www.iaea.org/About/Policy/MemberStates/

[14] See: http://disarmament.un.org/TreatyStatus.nsf/

[15] The IAEA defines "safeguards measures" as "activities by which the IAEA can verify that a State is living up to its international commitments not to use nuclear programmes for nuclear-weapons purposes." (http://www.iaea.org/Publications/Factsheets/English/sg_overview.html)

[16] See: http://www.iaea.org/OurWork/SV/Safeguards/what.html

2

Policy Makers' Perspectives on Key Nonproliferation Issues Associated with the Nuclear Fuel Cycle

One of the tasks of this National Academies workshop (see Appendixes A and B) was to solicit input from policy makers. Several policy makers were invited and asked to comment on two topics: (1) the key questions involved in U.S. nonproliferation policy; and (2) the potential for technical assessments of fuel cycle facilities' proliferation resistance to inform real-world decision-making.

The workshop's first day began with three briefings by U.S. Department of Energy (DOE) policy makers. First, in the workshop's keynote speech, U.S. Deputy Secretary of Energy Daniel Poneman provided background and insights on the past, present, and potential future of U.S. nonproliferation policy. Following Mr. Poneman's briefing, Edward McGinnis, Deputy Assistant Secretary in DOE's Office of Nuclear Energy, and Mark Whitney, Assistant Deputy Administrator for Nonproliferation and International Security in DOE's National Nuclear Security Administration's (NNSA) Office of Defense Nuclear Nonproliferation, provided briefings on the applicability of and potential role for technical assessments of proliferation resistance as well as potential questions and goals for the workshop.

Following these briefings, a panel discussion was convened including panelists from three agencies responsible for formulating and executing U.S. nonproliferation and nuclear security policy:

- Dunbar Lockwood, Team Leader for International Safeguards Policy, NNSA Office of Nuclear Safeguards and Security;

- John Harvey, Principal Deputy Assistant to the Secretary of Defense for Nuclear and Chemical and Biological Defense Programs at the U.S. Department of Defense (DoD); and
- Richard Stratford, Director of the Office of Nuclear Energy, Safety, and Security (NESS) in the Bureau of International Security and Nonproliferation at the U.S. Department of State.

This panel discussion was moderated by Sharon Squassoni, director and senior fellow in the nonproliferation program at the Center for Strategic and International Studies and workshop committee member.

This chapter provides summaries of the key points made by each of these individuals and by participants in the subsequent discussion sessions. These statements reflect the viewpoints of the individual speakers, not the consensus views of the workshop participants or of the National Academies.

IS STOPPING NUCLEAR PROLIFERATION A HUMAN PROBLEM, A TECHNICAL PROBLEM, OR SOMETHING ELSE?

Daniel Poneman

U.S. nuclear arms control policy began directly following World War II with the Baruch Plan. Since that time, the pendulum of U.S. policy has swung from a highly positive view of civilian nuclear energy worldwide (in the 1970s) to a more negative view of nuclear energy, discouraging nuclear fuel cycle facilities abroad and abandoning some projects (e.g., breeder and reprocessing projects) domestically due to proliferation concerns. In many ways, the pendulum now appears to be swinging back again to a greater international interest in nuclear energy.

For a generation, U.S. nuclear energy policy was a product of President Eisenhower's 1953 Atoms for Peace speech to the United Nations.[1] In this speech, he encouraged the peaceful uses of atomic energy—as opposed to the military uses—and proposed the establishment of the International Atomic Energy Agency (IAEA):

> The governments principally involved, to the extent permitted by elementary prudence, should begin now and continue to make joint contributions from their stockpiles of normal uranium and fissionable materials to an international atomic energy agency. . . . The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peace-

[1] Available on the Internet at: http://www.iaea.org/About/history_speech.html

> ful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world. Thus the contributing Powers would be dedicating some of their strength to serve the needs rather than the fears of mankind. (Eisenhower, 1953)

In 1974, however, India's test of a "peaceful nuclear explosive" challenged the previous assumption that civilian nuclear fuel cycle technology could be safely shared. This view reflected concern that Canadian and U.S. peaceful nuclear assistance was used in the project to facilitate India's development of an explosive device.

Following these tests, both the U.S. executive branch and Congress changed their approach to nuclear nonproliferation policy. Notably, on April 7, 1977, the Carter administration banned domestic reprocessing of civilian used nuclear fuel and sought to persuade other nations to shortly follow the U.S. example. While the United States abandoned the effort to close the nuclear fuel cycle, however, other nations, such as France, Japan, Russia, and the United Kingdom, persisted.

At the same time, the effect of the tests in India—combined with the political impact of the 1979 partial meltdown of a nuclear reactor at Three Mile Island in Pennsylvania and the 1983 Washington Public Power System municipal bond system failure[2]—resulted in a shift in the U.S. consensus on the value of nuclear energy. This shift lasted for more than a decade.

By the late 1990s, nuclear energy again began to rise in prominence in the United States. This rise was due in large part to two factors: first, recognition of the potential role of nuclear energy in addressing concerns over carbon dioxide emissions and climate change; and second, significant regulatory improvements that had taken place over the previous decade. Beginning in the mid-2000s, a relatively robust consensus emerged that nuclear energy has a place in a low-carbon future. Nuclear energy continues to enjoy support in the United States today.

Nuclear power is currently expanding around the world. In many cases, nations that have not previously had nuclear power programs are considering constructing reactors. It is important that the United States is engaged globally in ensuring that nuclear power is expanded safely and securely and that an increase in nuclear power worldwide does not lead to further nuclear weapons proliferation.

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[2] In 1983, the Washington Public Power System declared in the late summer of 1983 that it could not repay $2.25 billion in bonds used to finance partial construction of two now-abandoned nuclear power plants in Washington State. More information available on the Internet at: http://www.time.com/time/magazine/article/0,9171,955183,00.html

Nuclear security concerns have preoccupied President Obama since before taking office. As an Illinois senator in 2006, he worked with Senator Richard Lugar on a bill seeking to secure nuclear weapons,[3] and he traveled to Russia to discuss issues of nuclear security. He believes that it is in the interest of the United States to pursue a vision of a world free of nuclear weapons in a vigorous manner.

The administration, however, also recognizes the importance of the peaceful uses of nuclear energy to building a low-carbon future. In order to help countries to benefit from nuclear energy in a safe and secure manner, President Obama recommended the establishment of a new framework for international civilian nuclear cooperation in his April 2009 speech in Prague:

> …we should build a new framework for civil nuclear cooperation, including an international fuel bank, so that countries can access peaceful power without increasing the risks of proliferation. That must be the right of every nation that renounces nuclear weapons, especially developing countries embarking on peaceful programs.[4]

One proposal for such cooperation would involve seeking commercial consortia offering to provide fuel cycle services to countries looking to initiate or expand nuclear energy programs, so that there is no need for them to develop fuel cycle services domestically.

Many, if not most, nations currently pursuing nuclear power are genuinely seeking a source of electricity, not a back door to obtain nuclear weapons. But in order to succeed, the reliability of any offer must be established to the satisfaction of the reactor operators and their host governments. If these nations received an assurance that fresh fuel would be reliably provided and used fuel reliably managed, reasons for pursuing fuel cycle facilities—with their concomitant proliferation risks—would be reduced. This arrangement would allow countries to freely pursue peaceful nuclear aspiration without increasing proliferation risks.

One possibility is some form of layered guarantees for fuel assurance. Commercial entities could provide assurances for execution of contracted fuel services, which then could be reinforced by national governmental, and finally multilateral, guarantees. In addition to safeguarding any facilities involved in the fuel assurances, the IAEA could support this framework both by hosting fuel banks and other potential fuel assurance mechanisms and by determining when a member state had violated its nonproliferation commitments. Of course, a Nuclear Non-Proliferation

[3] Available on the Internet at: thomas.loc.gov/cgi-bin/bdquery/z?d109:s.02566:
[4] Available on the Internet at: www.whitehouse.gov/video/The-President-in-Prague

Treaty violator would not be entitled to continue to enjoy the benefits of the contracted fuel assurances.

In July 2011, DOE held a workshop to consider future directions in nuclear separations technology.[5] This workshop brought together individuals working in NNSA, the Office of Applied Science, the Office of Nuclear Energy (NE), and the Office of Science to discuss fuel assurance, and other approaches for controlling proliferation, particularly modified fuel cycles and the use of small modular reactors (SMR). Several points are clear following this workshop: first, none of the participants thought they knew the answer to preventing proliferation; second, analytical rigor is important in considering how to prevent proliferation; and third, this analytic rigor will need to be integrated with the many governmental and political issues involved in preventing proliferation.

Summary of Question and Answer Session

Working with international partners. Workshop chair C. Paul Robinson (Director Emeritus of Sandia National Laboratories), asked Deputy Secretary Poneman to elaborate on the melding of technical solutions to proliferation with political solutions. In response, Deputy Secretary Poneman noted that the budget environment has changed over the last year, and that less funding is projected to be available at DOE than in previous years. The effects of reduced funding will need to be considered in any effort. However, DOE's nuclear complex has a great deal of scientific expertise, and effective international partnerships can optimize the usefulness of this expertise. For example, continuing close interactions with nations such as France, with its many experts in fuel cycle technologies, and Russia, with its current work on a test bed for advanced fuel cycle technologies, are likely to be fruitful. Of course, this kind of collaboration will be easier with countries for which the United States already has 123 Agreements[6] in place, but in other cases, other agreements may be in place to allow for a convening purpose.

Business opportunities and the back end of the fuel cycle. Workshop committee member Sharon Squassoni (Center for Strategic and International Security) observed that fuel assurances might be easier to manage on the front end of the fuel cycle than on the back end of the fuel cycle,

[5] The workshop agenda can be accessed on the Internet at: http://events.energetics.com/NuclearSeparationsTechnologyWorkshop/agenda.html

[6] "123 Agreements" refer to Section 123 of the United States Atomic Energy Act of 1954, which establish an agreement for cooperation as a prerequisite for nuclear deals between the United States and any other nation.

particularly given the recent fate of the proposed spent fuel repository at Yucca Mountain in Nevada. She then asked Deputy Secretary Poneman to comment on the recent findings on this topic contained in the interim report of the President's Blue Ribbon Commission on America's Nuclear Future (BRC, 2011).

Deputy Secretary Poneman agreed that it is likely to be easier to cooperate internationally on the front end of the fuel cycle. However, there are also potential opportunities to be considered on the back end. For example, he suggested that an entity able to effectively close the back end of the fuel cycle would have the ability to provide a full package of fuel cycle services to nations that want to start a nuclear energy program.

However, as noted previously, a reactor operator will need to have sufficient confidence that the entity managing such fuel cycle services will continue to function, and that used fuel will not return to the operator either physically, legally, or financially. This may require governments to make a backstopping statement that they have some residual responsibility for the fuel.

Finally, the BRC's recent findings may provide a useful basis for people in the business community, non-governmental organizations, and Congress to tackle this national challenge.

U.S. DEPARTMENT OF ENERGY'S OFFICE OF NUCLEAR ENERGY'S PERSPECTIVE ON PROLIFERATION RISK AND NUCLEAR FUEL CYCLES

Edward McGinnis

There is a grand challenge facing the world right now: Ensuring that a global expansion of nuclear power does not increase the proliferation risk associated with nuclear weapons technology. An expansion of nuclear power could carry both benefits and risks. Although some fuel cycle facilities associated with nuclear power have the potential to be misused for non-peaceful purposes, nuclear power can also provide a low-carbon energy source as well as significant economic benefit, including jobs. Because of this dual nature of nuclear power, effective nuclear security is important, as is effective nuclear safety.

To maximize the contribution of nuclear power to the world's future energy mix, it will be important to use and expand nuclear technology in the safest and most secure way possible. However, proven and well-known designs are sometimes preferred by new entrant countries over next generation designs that may offer enhanced safety and perhaps security features. This is because the technical, cost, and schedule risks are perceived to be reduced when a proven nuclear power plant design is deployed. Therefore, the nuclear authorities in an emerging market country may simply believe they cannot afford the risks associated with building a first-of-a-kind plant.

However, another risk associated with successfully deploying a nuclear plant in many nations relates to limited national electric grids. As a general technical rule, any single power source should not exceed approximately 10 percent of the national electric grid. Thus, a country seeking to deploy a 1,000 megawatt (MW) reactor should have a grid supporting at minimum 10 gigawatts (GW) of electric generation. However, a number of emerging market countries have smaller grids. A proven small modular reactor design could serve an important role in meeting electricity needs in these countries, because the vast majority of proven and commonly-deployed nuclear power plant designs are 1,000 MW plants or larger. The potential cost, safety, and proliferation resistance improvements that SMRs could offer could be beneficial in an expanding global market.

The present workshop was convened to consider options for assessing and minimizing the risks of nuclear proliferation associated with the nuclear fuel cycle. Along with other organizations, DOE-NE is grappling with these issues. DOE-NE is particularly interested in innovative ideas related to implementing effective risk assessment and risk management approaches in a world where access to nuclear energy is expanding. Understanding and minimizing the risk of proliferation is an integral part of DOE-NE's research and development (R&D) roadmap (DOE, 2010).

DOE-NE's R&D roadmap focuses on four key research objectives aimed at the safe and secure use of nuclear energy, including minimizing proliferation: (1) innovative technologies and intrinsic design features; (2) next-generation materials protection and accounting control systems; (3) international frameworks and institutions; and (4) proliferation risk assessment and risk management. Although all of these areas are interrelated, the focus of this briefing is on the fourth topic.

Risk assessment as a discipline is not new; however, applications to proliferation resistance of fuel cycle facilities remain immature. Probabilistic risk assessment (PRA) has been used in the context of nuclear safety for decades, beginning with the seminal 1975 WASH-1400 reactor safety study (USNRC, 1975). However, WASH-1400 did not address proliferation or terrorism. While substantial work has been done since WASH-1400 to advance the state-of-the art for applications of PRA to proliferation and terrorism, significant difficulties remain, and further research remains to be done. These difficulties include understanding and analyzing an intelligent, adaptive, and determined adversary using a structured methodology such as PRA, as noted in two recent National Research Council reports (NRC, 2010; NRC, 2011).

Experts are still debating how best to analyze and understand the proliferation risks associated with nuclear fuel cycles, including the appropriate role of quantification. The appropriate balance of quantitative and qualitative assessments will need to be well-understood to avoid misunderstanding and misinterpretation. There is an important role for the quantification of certain aspects of risk, but quantification must be performed in combination with other qualitative and related factors and not used as the only approach.

There are both strengths and limitations associated with using the output of proliferation risk (or resistance) assessments to inform policy decisions, whether using PRA or another method. At its best, such an assessment has the potential to:

- Encourage a disciplined approach and a clear display of important information, including uncertainties;
- Present information in an understandable form so that interested people can scrutinize and challenge the data and assumptions;
- Provide qualitative insights about the structure and performance of complex systems;
- Enable a deeper understanding of dependencies and interactions among different subsystems and components of the fuel cycle system; and
- Give fresh, comparative perspectives on the relative advantages and disadvantages of various opportunities to reduce and control risks.

On the other hand, such assessments have limitations, including:

- The involvement of complex phenomena, including an intelligent, adaptive, and determined adversary;
- Sparse data;
- Limited models;
- Large uncertainties;
- Challenges associated with effective risk communication; and
- Dangers associated with misinterpretation or misuse of results.

DOE-NE is considering many potential future research directions for proliferation risk assessment, such as:

- Leveraging university-based innovative research in the field of risk assessment, through Nuclear Energy University Programs (NEUP);

- Utilizing cross-disciplinary teams (e.g., political scientists, social scientists, mathematicians, engineers, and communications specialists in laboratories, industry, and academia);
- Focusing on a cross-section of key topics and approaches;
- Establishing standardized "benchmark problems" for consistent comparisons of different methods;
- Performing prototypic evaluation studies of proliferation risks, focusing on a range of nuclear energy systems of interest to DOE; and
- Providing guidance on metrics that can be used by systems analysts to evaluate a multitude of fuel cycle options (along with other parameters such as economics, safety, and waste management).

High-quality proliferation risk information is important to DOE-NE's mission, whether it is quantitative, qualitative, or a mix of both. In performing analyses relevant to proliferation risk, it is important to distinguish clearly between *risk assessment*, which seeks to understand and identify the risks, and *risk management*, which seeks to minimize risks subject to a range of factors, and is typically the domain of policy decisions. Quantitative measures have the potential to be valuable in risk assessment but must be used judiciously in risk management. Finally, strong coordination and dialogue among stakeholders will prove to be vital, whatever methods are used for risk assessment and risk management.

Summary of Question and Answer Session

Management vs. reduction of proliferation risk. Workshop committee member William Charlton (Texas A&M University) noted that if nuclear power increases worldwide, it is possible that proliferation risk would increase. He asked Mr. McGinnis for his opinion regarding (1) whether it is possible to increase nuclear power worldwide while decreasing proliferation risk; and (2) if proliferation risk is likely to increase, then whether nuclear energy's other benefits (e.g., climate change and economic benefits) are significant enough to justify managing these risks. In response, Mr. McGinnis stated that he thinks it is possible that innovative concepts and ideas might reduce the incentive to proliferate. For example, if used fuel removal becomes commercially available, many nations would likely avail themselves of this service, particularly those with only a few reactors. They would be likely to see a used fuel-removal service as a far superior economic and business opportunity compared with building their own long-term storage and repository sites, particularly given politically burdensome siting and public acceptance processes.

As Deputy Secretary Poneman also observed, this could reduce the incentive to construct domestic fuel cycle facilities.

The potential role of government in fuel management services. William Charlton also asked Mr. McGinnis for a summary of DOE-NE's position on whether a government entity might provide a fuel management service, as the amount of risk involved is substantial for a commercial entity. In response, Mr. McGinnis stated that there is no assumption that such an entity should be entirely government operated or entirely commercially operated; however, he stated that some roles by government are necessary and inevitable, whether it involves third-country transfer approvals for nuclear materials or regulatory oversight. He further noted that in 20 years, he had never seen a better opportunity for alignment between commercial success involving commercial used fuel removal and long-term disposal and nonproliferation success related to supporting expanded access while minimizing proliferation risks. However, how such a fuel management service might work will need to be developed on a case-by-case basis for specific customer needs and supplier capabilities, so it is hard to predict what the specific details of the final arrangement might be.

U.S. NATIONAL NUCLEAR SECURITY ADMINISTRATION'S OFFICE OF NONPROLIFERATION AND INTERNATIONAL SECURITY'S PERSPECTIVE ON PROLIFERATION RISK AND NUCLEAR FUEL CYCLES

Mark Whitney

DOE-NNSA's Office of Nonproliferation and International Security (NIS) focuses primarily on host state proliferation, as does the current National Academies' project and workshop. This is important because there are significant differences between the risk—and risk mitigation measures—associated with assessing and managing host state proliferation compared to a sub-national threat. Host states are typically capable of a larger and more sustained technical proliferation effort than sub-national groups (such as terrorists). Moreover, the ultimate proliferation goals of host states and sub-national groups are often very different.

The most obvious example of a host-state proliferation concern is the diversion of nuclear materials. However, NNSA's concerns are broader than this; they are also concerned with the use of a particular nuclear fuel cycle technology in the context of a breakout scenario. Examples include misusing declared facilities and using existing or newly developed technical capabilities to support clandestine facilities.

The decision to proliferate requires both technical skill and political will. For this reason, managing proliferation requires both technical and political understanding. More often than not, decisions about whether or not to proliferate are based on specific and often dynamic political situations. While there is value in examining nuclear fuel cycle technologies for characteristics that could make proliferation more difficult for a host state, work to date has shown that there is no technology that can completely eliminate the risk of proliferation by host states, although many technologies may have a significant impact against sub-national threats. As a result, nuclear supplier guidelines and other institutional arrangements are the pillars of the current nonproliferation regime and will continue to be for the foreseeable future.

Several methodological questions were proposed as important considerations for discussing proliferation resistance and risk, both for the current workshop and for the follow-on consensus study. These questions include the following:

- Is it possible to evaluate proliferation risk effectively, and is it valuable to do so?
- Does the value of performing such an assessment outweigh the risks of performing it, particularly for a quantitative assessment?
- If there is no silver bullet to eliminate proliferation concerns from nuclear facilities, how can technology best be used to minimize proliferation concerns?
- If the time frames of concern for proliferation are measured in decades, what is the present-day utility of probabilistic risk assessment?
- Is it possible to determine the risk of proliferation based on technological considerations alone, and, if so, how can the conclusion be trusted when so many of the key factors involved in proliferation are non-technical in nature?
- How do we best understand the national and regional dynamics that might affect the misuse of technology?
- Can analytical results be produced that are actionable?

These questions relate to many currently pressing issues for NNSA. NNSA launched the Next Generation Safeguards Initiative (NGSI) to develop the policies, concepts, technologies, expertise, and infrastructure necessary to sustain the international safeguards system over the coming decades. NGSI is a very complicated undertaking, and NNSA hopes that the workshop and the follow-on National Academies study will articulate a serious set of questions for NNSA to consider in this project. Such a list would be of interest to DOE as well as to a broader set of international participants.

Summary of Question and Answer Session

Interactions between NNSA (NIS) and DOE-NE. John Ahearne (Sigma Xi) asked Mr. Whitney to clarify the interactions between NNSA and DOE-NE. In response, Mr. Whitney stated that NNSA works very closely with DOE-NE, largely as a result of initiatives started by former Assistant Secretary of Nuclear Energy Warren Miller. Major decisions are now made with the benefit of the other offices' input. However, NNSA, particularly NIS, focuses primarily on the international components of nonproliferation, such as international nonproliferation policy, developing and implementing programs internationally, and nuclear security. DOE-NE focuses on domestic technology R&D efforts, and with respect to nonproliferation, is largely interested in how proliferation can be incorporated into R&D efforts. The work of the two offices is complementary.

Proliferation resistance as a system. Mark Goodman (U.S. Department of State) asked Mr. Whitney if he judged that proliferation resistance assessments should examine all elements of a nuclear energy system, including the entire fuel cycle and its implementation. Mr. Whitney replied that it is essential to look at proliferation as a system, and clarified that technology is not the only issue that should be addressed in such a system. Geopolitical issues, the intent of the host nation, cost and other factors are also involved. There have been attempts to consider proliferation resistance as a system like this for many years, but so far no good solution has been found.

What NNSA would like to learn. Page Stoutland (Nuclear Threat Initiative) asked what NNSA expects to learn from proliferation risk (or resistance) assessment, and whether Mr. Whitney believes that a useful assessment could be performed that could meet these expectations. In response, Mr. Whitney stated that, for host-state proliferation, NNSA is most interested in learning more about the ability to detect, deter, and prevent diversion via safeguards. In addition, different fuel cycles and product streams that would make proliferation harder would be of interest. For example, this might include measures that would increase costs or change the application of safeguards.

Management vs. reduction of proliferation risk. Sharon Squassoni asked Mr. Whitney if he agreed with Mr. McGinnis' previous statement that nuclear power can be expanded while managing or even reducing the overall proliferation risk. Mr. Whitney replied that he, like Mr. McGinnis, also hopes that proliferation risk can be managed under a worldwide expansion of nuclear power. Current U.S. policy is to work to prevent enrichment and reprocessing technologies from spreading beyond the states that currently have them. An expansion of nuclear power could increase the possibility that fuel cycle technology could move to states that do not presently have such technology, raising the proliferation risk. Without further context, it is hard to say whether the risk is likely to remain the same.

PANEL DISCUSSION: KEY ISSUES FOR NONPROLIFERATION POLICY

A panel discussion was held involving representatives from DOE, DoD, and the State Department. The three panelists were asked to provide insight on the following issues:

- Identify the key questions associated with proliferation policy, in your office's view;
- Discuss how the proliferation risk of fuel cycle/reactor choices is measured;
- Identify other considerations taken into account in decision-making;
- Discuss analytical tools that are not currently used but could prove useful; and
- Compare the importance of fuel cycle/reactor choices vs. other government actions (e.g., government controls) that can be taken.

Short summaries of the panelists' comments are provided in the following sections, along with a short summary of the panel's comments during the question and answer period.

Insights from the U.S. National Nuclear Security Administration

Dunbar Lockwood

NNSA, and particularly NIS, is deeply involved in many U.S. funding and policy decisions related to increasing the proliferation resistance of nuclear fuel cycle facilities. NIS has prepared numerous nonproliferation impact assessments for proposed government actions and is regularly involved in major nonproliferation policy decisions. These decisions include international nuclear cooperation agreements; nonproliferation aspects of international fuel cycle policy and siting determinations; and enrichment, reprocessing and fuel cycle technology export determinations. Here the primary concern is nation-state proliferation rather than terrorism (security) threats. These threats must be clearly separated when discussing proliferation, as the methods used to understand and to guard against these two threats are necessarily very different.

When proliferation and fuel cycle facilities are discussed, the terms "proliferation risk" and "proliferation resistance" are often used.[7] Proliferation resistance, rather than a quantity to be measured, can be considered as a goal of U.S. nonproliferation policy: Specifically, to make proliferation technically more difficult, time consuming, and detectable. However, experience shows that the term "proliferation resistant" is too often misinterpreted as "proliferation-proof."

To support the nonproliferation policy tasks listed above, NNSA has supported several efforts to increase understanding of proliferation resistance in the nuclear fuel cycle, and particularly to support proliferation resistance assessment methodology development. These efforts include:

1. Funding the Non-Proliferation Assessment Methodology (NPAM) working group;
2. Co-sponsoring U.S. participation in the ongoing Generation IV project Proliferation Resistance and Physical Protection working group (Gen IV PR-PP WG);
3. Performing internal proliferation resistance studies on proliferation characteristics of advanced reprocessing technologies, small reactors, and reactors considered in DOE's Global Nuclear Energy Partnership (GNEP) Programmatic Environmental Impact Statement (PEIS); and
4. Funding ongoing nuclear material attractiveness studies.

Drawing on this experience (both with methodologies and decision-making), several key considerations have been identified that should underlie a good quantitative or qualitative proliferation resistance analysis.

First, no fuel cycle is completely proliferation-proof. There may be small distinctions in proliferation resistance between advanced reprocessing methods, but NIS has so far encountered no significant differences that should change U.S. policy on the importance of facility locations or current requirements for high levels of safeguards and security. Most states can acquire the technical knowledge needed to overcome technical barriers. For example, all advanced reprocessing methods, using some approachable level of technology, produce products usable in nuclear weapons and nuclear explosive devices.

[7] These terms are defined in Chapter 1 of this report.

For this reason among others, fuel cycle technology choice should be recognized as only one factor affecting proliferation resistance. Nontechnical factors carry a great deal of weight; these include political motivations, strategic/security considerations, and changing political and other international dynamics. Thus, safeguards, security, and location are critical factors in the proliferation resistance of a nuclear facility. A recurring policy concern related to technical assessments of proliferation resistance is whether researchers are spending a disproportionate amount of effort examining nuclear material attributes at the expense of safeguardability—the ease at which safeguards can be introduced into a system—and location.

However, a good analysis of proliferation resistance could be useful if it is performed as part of a broader systems analysis also involving cost, resource base, and other factors. In this way, tradeoffs can be identified and it can be determined whether or not the tradeoffs are worthwhile. It could also be useful to consider the breakout risk associated with the transfer of nuclear technology and know-how as part of the analysis.

The results of proliferation risk analyses also need to be both useful and understandable to policy makers charged with risk management. Several key questions ("food for thought") that NNSA would like to better understand prior to considering integrating proliferation resistance assessment methods into nonproliferation policy decision-making include the following:

- How will proliferation risk analyses help to inform NNSA's often country-, region-, and situation-specific nonproliferation policy decisions?
- Would quantifying small differences in risk help or confuse decision-making?
- What additional precision over qualitative analysis will be gained through more probabilistic (or quantitative) analysis, and how will that make a difference to decisions?
- Are the analyses and the results of proliferation risk models useful, usable, and understandable to decision makers?
- What is the empirical basis for probabilistic assessments and how will they be validated?
- How can the risk of extremely rare events be quantified, and will the public understand or believe the results? How should policymakers use the results of such an analysis of rare events?
- Is an initiating event (i.e., a decision to proliferate) assumed to occur, or is its likelihood of occurrence assessed? What is the public confidence in an analysis based on the latter?

- What is "acceptable" risk? How is it defined? By whom? How is it expressed?
- If technology is not considered to be the primary driver of proliferation risks, how far can you go in making technology choices based on risk studies?

A U.S. Department of Defense (DoD) Perspective on the Nuclear Fuel Cycle and Related Proliferation Risks

John Harvey

As noted in several of the previous discussions, the goal of strengthening nonproliferation is at the top of the President's agenda, as is preventing terrorism related to weapons of mass destruction (WMD). Through the efforts of the U.S. government, warheads have been dismantled in the United States and in Russia, fissile material has been secured around the world, and nuclear security has been bolstered. In addition, peaceful uses of nuclear energy have been supported and have increased.

Limiting proliferation and preventing WMD terrorism are complex problems, and multiple U.S. government agencies are involved in efforts to address them. DOE leads U.S. government efforts to reduce the proliferation risk associated with nuclear facilities, but the contributions from DoD, the Department of Homeland Security, the State Department, the Federal Bureau of Investigation, and others are essential.

The DoD is not as deeply involved in nonproliferation policy as DOE or the State Department. DoD's work in nuclear security focuses more on weapons of mass destruction and threat reduction, particularly the retrieval of special nuclear material that is no longer under (national or international) regulatory or military control. DoD is primarily involved in situations that would occur after safeguards have failed and with situations that involve protecting U.S. military interests. However, DoD does have several interests related to safeguards, proliferation, and civilian nuclear energy.

First, IAEA safeguards and inspections have implications for DoD.[8] The IAEA Additional Protocol[9] allows access by inspection to all aspects of the fuel cycle: mining, fuel fabrication, waste storage, and other

[8] Although participation in IAEA safeguards are voluntary for the United States, it participates to bolster the IAEA's goal of preventing proliferation in non-weapons states.

[9] The Additional Protocol is a legal document granting the IAEA complementary inspection authority to that provided in underlying safeguards agreements. A principal aim is to enable the IAEA inspectorate to provide assurance about both declared and possible undeclared activities. Under the Protocol, the IAEA is granted expanded rights of access to information and sites. (http://www.iaea.org)

facilities where nuclear material is present. It is essential to balance the transparency required by IAEA safeguards with the costs of real security challenges: Specifically, to ensure sufficient transparency and access to sensitive facilities while (1) protecting against loss of economic and proprietary information that could undermine U.S. competitiveness; (2) protecting sensitive information; and (3) controlling the overall costs of transparency and access.

Although DoD recognizes that safeguards are important, it is important to understand how safeguards impact DoD equities. The U.S. national security exclusion to the Additional Protocol (Article 1b) states:

> The United States shall apply, and permit the [International Atomic Energy] Agency to apply, this Protocol, excluding only instances where its application would result in access by the Agency to activities with direct national security significance to the United States or to locations or information associated with such activities.

Thus, the IAEA is not permitted to hold safeguards inspections at DoD facilities. However, there are other facilities that may also need protection, and it is important to vet the list of facilities subject to IAEA inspection prior to the annual submission of this list to Congress.[10] This is in part because other, non-nuclear technology or information may be sampled when an inspection team is present in a sensitive facility, which could be of concern.

Second, recently DoD has been interested in understanding the feasibility of using nuclear power at U.S. military installations. Small reactors could easily support a brigade and would need refueling yearly or even less often, which could provide numerous benefits. For example, using small reactors in remote and hostile locations could reduce security requirements by limiting supply runs and the need to divert forces to guard fossil fuel convoys. Building nuclear power plants at military installations also has the potential to reduce the reliance on fossil fuels and reduce greenhouse gas emissions. Previous government experience and knowledge of next generation nuclear plant designs will be helpful in developing a nuclear plant that could meet these needs and, in particular, could enable the development of a compact and safe design with good security and reliability characteristics.

[10] This list is required to be submitted to Congress under 22 USC Sec 8172, which states that: Not later than 60 days before submitting to the IAEA any revisions to the United States declaration submitted under the Additional Protocol, the President shall submit to Congress a list of any sites, locations, facilities, or activities in the United States that the President intends to add to or remove from the declaration, and a report thereon. (See Additional Protocol Implementation: http://uscode.house.gov/download/pls/22C88.txt)

Proliferation risk analysis will play an important role in bringing these power plants overseas—for example, nuclear power plants installed in hostile areas will require the best in safeguards, security, and proliferation resistance. Instead of trying to retrofit the plants, these safeguards and security elements can be incorporated during the design phase. In addition, it is possible that better understanding of proliferation risk can help to better address the unique challenges associated with placing small reactors in a military situation prior to fielding.

In the future, the United States will need an unencumbered source of low-enriched uranium to use in the Tennessee Valley Authority's nuclear reactors to make tritium for nuclear warheads.[11] In addition, although it is not immediate, the United States will eventually run out of highly enriched uranium (HEU). At this time, the United States will need to have modern domestic enrichment processes ready for use to fuel naval reactors.

As a final comment on the overall topics of the workshop, quantitative risk assessment has barriers to overcome before it can be constructively applied to physical security and terrorism, as noted by two recent NRC reports (NRC, 2010; NRC, 2011). It is likely that many of the same shortcomings—including an intelligent adversary and human unpredictability in protecting facilities—will also apply to the application of quantitative risk assessment to proliferation problems. However, the critiques are typically not whether to use risk assessment, but how best to use the results of risk assessment as part of the policy process. A comparative study of different options might be the best use of quantitative risk assessment in proliferation and security.

Insights from the U.S. Department of State

Richard Stratford

For the State Department, the technical aspects of proliferation resistance are not the key issue, but rather, the bottom line involves questions of international politics. The State Department—and the Office of Nuclear Energy, Safety, and Security in the Bureau of International Security and Nonproliferation in particular—works to determine how to keep proliferation risk as low as possible while still doing what is necessary to sustain the nuclear fuel cycle.

The essential message of U.S. nonproliferation policy is that it is important to prevent the *unnecessary* spread of sensitive nuclear technologies. This does not mean that sensitive technologies should not be

[11] Because tritium has a half-life of 12 years, new supplies must be continuously generated.

used—many would argue that some use of sensitive nuclear technologies by those who have a need for them is acceptable. For example, enrichment has a use unless all nations choose to use CANDU reactors in the future. In this briefing, a sequence of examples are provided, both outlining the history of U.S. nonproliferation policy related to the nuclear fuel cycle and illustrating the types of day-to-day issues that policy makers face in this area.

The history of U.S. nonproliferation policy associated with the nuclear fuel cycle has not been straightforward. Some believe that the history of U.S. nonproliferation policy began with President Carter's decision to place a moratorium on reprocessing in the United States. However, prior to Carter's decision, President Ford stated that the United States would need to decide whether it was going to reprocess used fuel. Carter stated that replacements for reprocessing would need to be found.

At the time, a reprocessing facility was under construction in Barnwell, South Carolina, that was about to be licensed by the U.S. Nuclear Regulatory Commission (USNRC). The USNRC was told that the presidential policy was to avoid reprocessing, so the licensing process was stopped. Subsequently, the USNRC was sued for this decision, but the courts upheld the USNRC decision not to take the application.

The Carter administration, along with its position toward domestic reprocessing, began to impose roadblocks related to Japanese and European fuel cycle facilities. Upon taking office, the Reagan administration devised an alternative solution to preserve the United States' Japanese and European relations on this topic. At the time, Congress was insisting that the administration renegotiate all its international agreements related to peaceful nuclear cooperation to include a long list of requirements. The Reagan administration worked out new agreements for these countries, including all the Congressional controls and giving the U.S. consent rights over reprocessing of U.S. origin fuel. In return, the United States agreed to give consent to nuclear fuel reprocessing and plutonium storage for the life of the agreements. For new facilities that could not be foreseen at the time, an automatic process was agreed on. In addition, these agreements were written in a way that assured foreign governments that the agreement could not shift completely when U.S. policy changed. This way of handling the difficult diplomatic issue worked both for Japan and for Europe.

More recently, President George W. Bush recommended that the Nuclear Suppliers' Group (NSG) ban the transfer of reprocessing and enrichment technologies to all countries without currently operating facilities. However, the NSG was unwilling to accommodate such a ban. As a result, a criteria-based approach was developed. For export of nuclear fuel cycle technology to a country, a number of criteria regarding safety and security had to be met. Beyond this, three additional criteria apply: (1) the supplier can consider other criteria beyond those specified; (2) the supplier must reacquire an IAEA Additional Protocol complementing the safeguards agreements;[12] and (3) for enrichment, the technology must operate as a "black box."

The next big issue to emerge was the Indian nuclear cooperation agreement. India has three reprocessing facilities and wanted consent from the United States regarding these facilities. The Bush Administration agreed to give consent with two conditions:

1. India was asked to build an all-new state-of-the-art reprocessing facility permanently dedicated to safeguarded reprocessing; and
2. India was not to reprocess until a second agreement was put in place setting out terms and procedures relevant to reprocessing.

The negotiations with India began not long after conclusion of the agreement, and the final draft was sent to Congress as a subsequent agreement. However, it was challenging to determine how to set terms and conditions for the agreement.

NESS solved this difficulty by asking DOE and the U.S. National Laboratories to provide a page-long document describing state-of-the-art safeguards. This description was crafted into an agreement for India.

These negotiations not only involved technical expertise, but also common sense. For example, India asked for consent on two reprocessing facilities, rather than the one that was in the original agreement. The State Department recommended this request be accommodated, because the first facility was located far north on the subcontinent, while the second facility was located in the south. Having two facilities would prevent India from needing to move used fuel across the entire subcontinent, reducing the possibility that a shipment of fresh or used fuel would be diverted.

Once the India negotiations were complete, the next challenge was negotiation of a nuclear cooperation agreement with the United Arab Emirates (UAE). The Obama Administration determined that, in order to approve a nuclear cooperation agreement with the UAE, there would need to be a legally binding commitment to not have enrichment or reprocessing plants on UAE soil even if the plant in question did not use

[12] An Additional Protocol is "a legal document complementing comprehensive safeguards agreements. The measures enable the IAEA not only to verify the non-diversion of declared nuclear material but also to provide assurances as to the absence of undeclared nuclear material and activities in a State" (IAEA, 2011). See http://www.iaea.org/Publications/Factsheets/English/sg_overview.html

technology exported from the United States, and thus was not subject to U.S. consent. The UAE voiced concerns about their options for managing spent fuel in that situation. The United States responded that the spent fuel could be sent to the U.K. or to France for reprocessing; however, no MOX fuel or plutonium would be returned to the UAE. The UAE accepted this agreement.

However, following the UAE agreement, some in Congress decided that this same solution should be applied to any new nation that negotiates a nuclear cooperation agreement with the United States. However, each agreement needs to be managed on a case-by-case basis, and a blanket requirement could create difficulties in successful negotiations. It should be recognized that other suppliers of nuclear technologies will not make the same concessions, and it is certain that if the United States is not willing to engage with a particular nation, others will be.

Currently, several new technologies are posing challenges, particularly pyroprocessing and uranium enrichment using lasers to separate the isotopes (Separation of Isotopes by Laser Excitation, also known as SILEX). Initially, pyroprocessing was thought to provide good opportunities for reprocessing without easy access to weapons-usable material, but that no longer appears to be the case. SILEX appears to have the capacity to make enriching uranium much cheaper, which could be good for the U.S. economy, but it may also pose proliferation risks. There are a number of potentially dangerous technologies, both nuclear and non-nuclear (e.g., nanotech, biotech). However, the solution for non-nuclear technologies is not typically to stop using the technology; this is not a reasonable solution for nuclear technology, either.

Summary of Question and Answer Session

The briefings from the policy panelists were followed by a lively Q&A session. In the section to follow, some key comments, questions, and responses that were brought up during this session are summarized.

Policy questions for DOE-NE. Warren (Pete) Miller (Texas A&M University) noted that DOE's Office of Nuclear Energy is the lead program on the back end of the fuel cycle and is charged with developing the right back-end technology for the United States to deploy domestically. The attributes that will be used to make these decisions include: uranium availability, cost, technical maturity, physical security impacts, environmental impacts, repository availability, and also, proliferation risk impacts. He stated that it is important to be cautious regarding the proliferation risk impacts of domestically-deployed technologies for two key reasons. First, if such a technology is deployed, this could have an impact as to whether other nations choose to deploy it. Second, whoever deploys the technology is likely to want to export it commercially. These factors are both a part of DOE-NE's R&D decision-making. It would be useful if the overall National Academies project on proliferation risk (not simply the workshop) is able to help DOE-NE to determine how to use proliferation risk to inform its decisions on technology choices. There is significant disagreement about the proliferation resistance of different technologies, and some additional clarity would be valuable.

The essential role of safeguards. Corey Hinderstein (Nuclear Threat Initiative) noted that there was a great deal of conversation about safeguards in the preceding briefings. However, safeguards do not prevent proliferation, with the potential exception of deterrence, but instead allow the international community to know about proliferation activities. Both Mr. Lockwood and Dr. Harvey agreed with the observation. Mr. Lockwood noted that the stated objective of safeguards was not to prevent proliferation, but rather to "detect" diversion of a significant quantity of nuclear material in a timely manner and to deter such diversion by increasing the risk of early detection. Both Mr. Lockwood and Dr. Harvey underlined the importance of safeguards as one part of a greater strategy to intercept and prevent the diversion of nuclear materials. Mr. Lockwood emphasized the importance of considering the safeguardability of new designs to complicate a proliferator's task, promote early detection, and provide time for other measures to intervene. Similarly, Dr. Harvey emphasized the importance of safeguards as an early-warning system: "If something bad is about to happen, we need to know… if safeguards tell you you've lost ten kilograms of HEU weeks later, that is much less manageable than days or hours later."

The value of standardization. Jon Phillips (Pacific Northwest National Laboratory) observed that much of the discussion during the panel was about quantification, but that in his view, it would be more valuable to—in whatever way necessary—standardize the approach to assessing proliferation risk among different agencies and among different problems. It would be useful to agree upon certain factors as requirements for the assessment, and agree on a scope (e.g., a state-specific analysis is required). Mr. Lockwood replied that although at first this seems reasonable, in his view, standardization is in fact very difficult to handle in practice. The world situation is dynamic, a lot of different and often unique factors need to be taken into account, and state behavior can often change dramatically in a short period of time.

U.S. leadership in the fuel cycle. Steven Skutnik (North Carolina State University) asked how the United States would be able to take on a leadership role in integrated fuel cycle services in the absence of a U.S. plan for the back end of its fuel cycle. In response, Mr. Stratford commented that spent fuel management is difficult due to politics. There are some areas in which the United States cannot lead, and others where it may. An example of the latter is future fuel cycles involving reprocessing; however, without a clear end state for the nuclear waste, reprocessing could also eventually encounter difficulties. Mr. Lockwood added that in the coming decades, we may find some transformational science and technology that will solve the problem, but the back end of the fuel cycle is a very vexing challenge right now.

Plutonium and current reactors. Emory Collins (Oak Ridge National Laboratory) asked why the United States and the international community are not concerned with the production of plutonium in their efforts to safeguard nuclear technology, in a situation where nuclear reactors themselves—not just the fuel cycle facilities—are producing plutonium all around the world. Mr. Stratford responded that this is a very different problem, and that to his knowledge, no plutonium from commercial light water reactors has ever gone into explosive use. Nations that have pursued weapons programs have done so with indigenous or illegally acquired materials. In addition, beyond concerns about nonproliferation, there are other concerns that must be balanced. For example, it must be considered whether it would be better to have a nation with significant energy needs—such as India or China—build 50 new nuclear plants, or instead, 50 new coal plants with their attendant greenhouse gases.

Innovative approaches for proliferation risk assessment. Mark Mullen (Los Alamos National Laboratory), referring to Dr. Harvey's briefing, commented that the Department of Defense performs extensive assessments as part of its planning and evaluation processes. Because of the nature of DoD's mission, these assessments must take account of the challenge of understanding and analyzing intelligent, adaptive, and determined adversaries. Since that type of adversary must also be analyzed in proliferation risk assessments, Mr. Mullen asked Dr. Harvey if there are novel or innovative methods that the DoD uses that might be transferred or adapted to proliferation risk assessments.

Dr. Harvey noted that a recent National Academies report addressing security in the DOE nuclear weapons complex (NRC, 2011) included extensive discussion of the challenges posed by intelligent, adaptive, and determined adversaries, and he suggested that some of the methods described in that report, such as red team/blue team analysis,[13] might be applicable to proliferation risk assessments. Dr. Harvey responded that he is uncertain if such approaches are currently in use, but that the dynamic part of the risk assessment process is important. When proliferation risk or resistance is discussed, one must consider the likelihood that a terrorist team or a host state actor might go down a particular proliferation route as opposed to other routes. The value of quantitative analysis is that it is structured, and the assumptions can be transparent. If this type of analysis is combined with a red team analysis, this could be very helpful.

Mr. Mullen agreed that red team/blue team analysis is indeed a good approach. He said he was familiar with DoD applications where it had been used to good effect, and he suggested that it be applied more widely in proliferation risk assessments, as one part of a more comprehensive, multifaceted analysis.

[13] A red team activity involves an unannounced assessment of security and readiness by an unfamiliar team of operators with no awareness or support from the assessed target. The goal of a red team is to try to think like the adversary and use information, incentives, and capabilities that he or she would have to the maximum extent possible.

Box
The Genie is out of the Bottle: Low-Cost Centrifuge Enrichment

Olli Heinonen, Harvard University Kennedy School of Government
Belfer Center for Science and International Affairs

For nuclear weapons proliferation, a mastery of technology beyond that required to build nuclear power plants is necessary. This can take the form of either back-end fuel cycle technology (reprocessing) or front-end fuel cycle technology (enrichment). However, this discussion will focus on the front end of the nuclear fuel cycle, more specifically, on low-cost uranium centrifuge enrichment.

There are four questions to be asked with respect to the proliferation threat from low-cost centrifuge enrichment:

- What information is out there?
- Who has the information?
- What can someone do with it?
- What can be done about this?

First, it is known that a complete set of information on type P-1 and P-2[1] centrifuges is available on the black market, as well as information on at least three nuclear weapon designs and the conversion of enriched uranium hexafluoride gas (UF_6, the typical output of centrifuge enrichment) to metal components, all thanks to A.Q. Khan. Other players connected to the A.Q. Khan network have made available additional centrifuge designs from the 1980s using composite rotor materials and magnetic bearings as well as information on UF_6 production processes, feed, and withdrawal systems. Second, it is known that Libya, Iran, and North Korea have received some part of this information, and that the information was offered to Iraq, Syria, and potentially others.

With this information, it is possible for a state to build centrifuges, enrich UF_6 gas to HEU, convert the UF_6 to uranium metal, and ultimately, construct a nuclear weapon. A scenario for producing HEU using this technology is as follows. A state might use as the original feed 2,400 kg of UF_6 gas enriched to 4 percent uranium-235, a typical enrichment for nuclear power plant fuel. Then it would be possible to proceed stepwise using the centrifuge designs supplied by A.Q. Khan, enriching from 4 percent to 20 percent, then 20 percent to 60 percent, then 60 percent to 90 percent, until weapons-grade HEU is produced. The UF_6 could then be converted to metal using the information from A.Q. Khan.

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[1] Pakistan developed the P-1 and P-2 centrifuge designs based on the Soviet Zippe-type design.

[2] The IR-2M is an Iranian centrifuge design that was reportedly installed at Iran's Natanz enrichment facility in July 2011. See http://isis-online.org/isis-reports/detail/iran-reportedly-installing-advanced-centrifuges/.

continued

Box Continued

This entire process could take under a year. Using 2095 type IR-2m centrifuges,[2] step 1 (4 to 20 percent enrichment) would require 10 cascades of 131 centrifuges each and approximately 2 months. Step 2 (20 to 60 percent enrichment) would require 3 cascades of 179 centrifuges each and about 0.9 months. Step 3 (60 to 90 percent enrichment) would require 2 cascades of 124 centrifuges and only 0.4 months. Preparing the metal components would only require one additional month. In total, the time from completion of the centrifuges to availability of uranium metal components would be about 4.3 months for the first batch. A second batch could be produced 2 months following the first batch, and a third batch 2 months following the second batch, culminating in the production of 69.5 kgs of 90 percent enriched uranium metal components in only 9 months total.

The final question, then, is what can be done about this situation? Detecting such a program requires an all-source information analysis coupled with substantial international cooperation. The International Atomic Energy Agency (IAEA) will need to use all of its authorities to meet its objectives and maintain a highly robust verification scheme. The international community will need to use all means to enforce the IAEA and United Nations Security Council efforts. Finally, it is possible that embarking on nuclear cooperation could change the narrative of future nuclear discourse.

3

Technical Assessment of Proliferation Resistance

In addition to soliciting input from policy makers, a second task of the National Academies workshop was to seek input from technical experts in proliferation risk and resistance assessment and implementation. Several technical experts were asked to comment on the potential applicability of proliferation resistance assessment methodologies and measures to policy makers' concerns, as well as the current maturity level of those methodologies.

Five technical experts presented briefings at the workshop:

- William Charlton, director of the Nuclear Security Science and Policy Institute (NSSPI) at Texas A&M University, associate professor of nuclear engineering, and workshop committee member;
- Christopher Way, associate professor of government at Cornell University;
- Robert Bari, senior physicist at Brookhaven National Laboratory;
- Bartley Ebbinghaus, staff scientist at Lawrence Livermore National Laboratory; and
- Olli Heinonen, senior fellow at Harvard University Kennedy School of Government Belfer Center for Science and International Affairs.

This panel discussion was moderated by William Charlton.

This chapter provides summaries of the key points made by each of these individuals and by participants in the subsequent discussion sessions. These statements reflect the viewpoints of the individual speakers, not the consensus views of the workshop participants or of the National Academies.

OVERVIEW AND BACKGROUND: TECHNICAL EFFORTS ON PROLIFERATION RISK

William Charlton

The first technical assessments of proliferation resistance and risk associated with nuclear facilities date back to the early 1970s. Since then, significant progress has been made in using technical analyses to inform nuclear safety, but less progress has been made in assessing security and nonproliferation.

In discussions of technical assessments of the vulnerability of nuclear fuel cycle facilities to proliferation, two related terms are often used: proliferation *resistance* and proliferation *risk*. These concepts do not refer to the same idea, as discussed in Chapter 1. The definition of proliferation resistance is relatively well-agreed upon 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 (IAEA, 2002).

It should be noted that this definition of proliferation resistance limits the concept only to state actors, not non-state actors.

On the other hand, proliferation risk is not nearly as well defined in the international community. There are several factors, both technical and non-technical, that influence proliferation risk, including:

- Characteristics of the proliferator (e.g., motivation, goals, resources, and technical capabilities);
- Intrinsic features of the nuclear energy system (i.e., technology and design features);
- Extrinsic measures (e.g., domestic institutional measures and international safeguards); and
- Consequences of proliferation success (e.g., increased military capacity, changes in the geopolitical situation and regional stability).

By comparison, only intrinsic features[1] of the nuclear energy system and extrinsic measures[2] are considered in an assessment of proliferation resistance.[3]

One possible definition for proliferation risk—a perturbation of the more general definition of risk—can be expressed mathematically as:

$$R = \sum_{n=1}^{N} L^n P^n C^n$$

Where L^n is the probability per unit time that an adversary might attempt to proliferate along path n; P^n is the probability that an adversary will be successful at proliferation without timely detection, given that he has chosen to proliferate along path n (most closely related to proliferation resistance); and C^n is the consequence of adversary proliferation without detection along path n (Charlton, 2011).[4] Most current attempts at understanding proliferation risk focus on P^n; C^n and L^n are very difficult to understand and to estimate.

Since the 1970s, progress has been made in assessing the proliferation resistance of nuclear facilities, and several methods have become fairly well-developed. On the other hand, studies of proliferation risk remain immature. For this reason, the remainder of this discussion will focus on methodologies for assessing proliferation resistance.

There are a number of proliferation resistance assessment methodologies being developed around the world. These methods can be categorized by several key characteristics: the method of analysis; whether a qualitative or quantitative judgment is produced; or by the figure of merit produced.

A range of methods can be used to analyze the proliferation resistance of fuel cycle facilities. For example, the Technology Opportunities for Proliferation Resistance (TOPS)—developed by an international team funded by the Nuclear Energy Research Advisory Committee—and the

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[1] As noted in Chapter 1, intrinsic barriers are the technical aspects of the system that contribute to proliferation resistance, and include considerations such as type of special nuclear material (SNM) used (e.g., low enriched uranium vs. highly enriched uranium), technical difficulty of proliferation, and difficulty of detection (IAEA, 2002). (Difficulty of detection also has extrinsic aspects.)

[2] As noted in Chapter 1, extrinsic barriers are usually fundamentally non-technical, and include measures such as international treaties and safeguards measures (IAEA, 2002).

[3] Some proliferation resistance methods do attempt to incorporate adversary characteristics into the analysis. For example, the Generation IV Initiative Forum's Proliferation Resistance and Physical Protection approach (discussed elsewhere in this chapter) incorporates a "threat description" describing a proliferator's capabilities, objectives, and strategy. However, this threat description is not used in a predictive fashion.

[4] This definition indicates that proliferation risk is time-dependent.

Japan Atomic Energy Agency's (JAEA) methods rely primarily on expert judgment. On the other hand, probabilistic risk assessment is used by the Generation IV Initiative Forum's Proliferation Resistance and Physical Protection (PR&PP)[5] analysis and Sandia National Laboratory's Risk-Informed Probabilistic Analysis (RIPA). Other approaches use different methods (see Ford, 2010 for more detail).

In addition, while all methods require subjective inputs, some methods are intended to produce a qualitative assessment of a facility's proliferation resistance (e.g., TOPS and JAEA), whereas others attempt to quantify the proliferation resistance of a facility (e.g., PR&PP, Texas A&M University's Multi-Attribute Utility Analysis [MAUA], North Carolina State University's Fuzzy Logic method, and RIPA). The primary difference between quantitative and qualitative methods is whether a number is provided as the output. In some cases, a quantitative output can be somewhat misleading, as subjective judgments inevitably are hidden within that output.

Different methods may also produce different figures of merit.[6] For example, PR&PP produces six different figures of merit for proliferation resistance,[7] while many other methods attempt to aggregate the information produced into a single figure of merit or may even produce none at all. A single figure of merit has both benefits and costs—the decision-maker is provided with a single value, which is clearer; however, some fidelity and information content is lost by merging the various elements of proliferation risk into a single number.

Even though a range of proliferation resistance assessment methods are currently under investigation, none of them are likely to be easily used to answer many of the questions that were discussed by the policy makers in Panel 1 of the workshop (see Chapter 2). This is in large part because many of the methodologies were designed to better understand nuclear energy systems rather than to answer the questions a policymaker might be interested in. Difficulties likely to be encountered in attempting to apply these methodologies to answer policy makers' questions include the following:

[5] PR&PP can also be considered to be a framework rather than just a methodology. In this case, it is relatively easy to take out the mathematical model and substitute another. However, as currently implemented, PR&PP uses pathway analysis, which is akin to a PRA methodology used for safety assessments.

[6] A "figure of merit" is a single—typically quantitative—value that summarizes a range of information about the proliferation resistance of a fuel cycle system.

[7] PR&PP produces figures of merit related to technical difficulty, proliferation cost, proliferation time, fissile material type, detection probability, and detection resource efficiency.

- Most proliferation resistance methodologies have generally ignored the characteristics of the adversary, aside from the adversary's technical capability—however, geopolitical information and creativity in proliferation decision-making (pathway choices) are essential features of real-world proliferation;[8]
- Many methods require a pathway determination which is rarely complete;
- Many methodologies are static rather than dynamic;
- Not all methods lend themselves well to uncertainty analysis;
- Comparisons between methods have been rarely reported, presenting difficulties in achieving transparency;
- All methodologies have some degree of subjectivity;
- Effectively presenting the results from these methods to decision makers is challenging;
- Consequences of proliferation attempts are typically only handled in a cursory fashion; and
- Most methods have not been used to understand the impact of technology transfers to states.

However, each methodology was developed originally to answer a specific question, either policy-related or technical. It will be essential to establish whether these original questions are relevant to nonproliferation decisions, and whether, ultimately, the methodology is able to provide answers to the original question.

In closing, there is likely to be no truly proliferation-proof nuclear energy system or nuclear fuel cycle, and these methods cannot be expected to identify such a system. A state *can* eventually proliferate—it's a question of how much time is required. The methods discussed here are also not predictive tools, and even generating good probability estimates is complex because proliferation is a rare event. Ultimately, a realistic goal is to seek ways to use technical proliferation resistance and risk assessment methods to help inform decisions and manage risks.

METRICS AND METHODOLOGIES FOR ASSESSMENT OF PROLIFERATION RISK

Robert Bari

Technical assessments have the capability to inform a number of nonproliferation policy questions. For example, technical assessments can inform decisions related to: (1) the relative nonproliferation advantages of

[8] One notable exception is the PR&PP methodology.

nuclear energy systems applicable to energy generation, material production, waste treatment, and research; (2) tradeoffs between international arrangements and national programs; and (3) broader tradeoffs between nonproliferation and energy, the environment, economics, security, and safety.

Several steps are involved in preparing a good evaluation of the proliferation risk or resistance of a nuclear fuel cycle facility. First, one must determine how to characterize and measure proliferation resistance or risk, and, second, one must evaluate the risk or resistance. Most research on proliferation resistance and risk has focused on these steps. However, it remains important to keep in mind that proliferation involves both non-technical (motivation, intent) and technical (capability) aspects. For this reason, a good proliferation risk evaluation would consider (1) the host-state context, including the host state's objectives, capabilities, and strategies, and (2) the fuel cycle facility design features, including the requirements for safeguards and security measures.

Once the evaluation has been completed, it is important to determine how to use the results and how to communicate them to the various stakeholders involved. Some ways in which a proliferation risk or resistance analysis could be used to inform policy makers include:

- Performing absolute or relative assessments on a specific facility;
- Evaluating system risk reduction and informing risk management;
- Informing the design of alternative systems to reduce risk; and
- Constructing a global nuclear architecture.

With the use in mind, the results then must be communicated in an understandable way to each of a broad range of specific users, including policy makers, nuclear fuel cycle facility designers, and other stakeholders, not all of whom will appreciate a highly technical response.

In addition, for a proliferation risk or resistance analysis to be effectively used, it would be useful to have clearly structured interactions between the technical experts performing the analysis and the policy makers who would use the results of the analysis. Ideally, policy concerns should inform the statement of the question to be addressed by the analysis. Once the question is stated, technical analyses can be performed to provide clear statements of alternatives. Finally, policy can be used to choose among the alternatives presented in the technical results.

The remainder of this briefing focuses on the PR&PP methodology for evaluating proliferation resistance. DOE-NE and NNSA co-sponsor the U.S. participation in the international working group for PR&PP under the Generation IV International Forum (GIF).

The technology goal for PR&PP is to determine how to design Generation IV nuclear energy systems in a way that will increase the assurance that they are not a desirable route for diversion or theft of weapons-usable materials and will provide increased physical protection against acts of terrorism. Key objectives for PR&PP as part of GIF include:

- Facilitating the introduction of PR&PP features into the design process at the earliest possible stage of concept development; and
- Assuring that PR&PP results are an aid to informing decisions by policy makers involving safety, economics, sustainability, and related institutional and legal issues.

PR&PP is a methodology based on the types of PRA methodologies that have been highly successful in evaluating the safety of nuclear facilities. Modern efforts on PRA can be dated back to the 1975 publication of the definitive reference for risk assessment in a nuclear safety context, the WASH-1400 study, which departed from and added to the previous deterministic and prescriptive perspective on nuclear safety regulation (USNRC, 1975). In the years since, PRA has been highly successful when used to understand nuclear safety. Current work on methodologies such as PR&PP seeks to determine whether it is possible to risk-inform nonproliferation measures in a similar way, and also whether the success in the safety arena holds lessons for proliferation risk assessment.

The overall PR&PP framework involves three steps: challenges, system responses, and outcomes, shown in Figure 3-1. For a proliferation risk scenario occurring at a nuclear facility, "challenges" are threats to the nuclear facility, such as diversion, misuse, breakout, or the establishment of a clandestine facility. System responses to the challenge are then evaluated, for example, whether there are physical and technical design features that would combat or slow this particular attempt or safeguards in place that would alert the international community. Finally, the possible outcomes resulting from the challenge and the system response are evaluated. These steps are repeated for many potential challenges and system response variations.

The PR&PP analysis of the system response occurs in three stages. First, the nuclear system is decomposed into system elements to permit a pathway analysis. This involves identifying elements such as the materials, facilities, processes, and transportation links that an adversary could exploit to accomplish his or her goals. Second, the location of operations and materials, their accessibility, and characteristics are identified. In addition, any extrinsic measures and the locations where they are applied are noted, such as material balance areas and locations of safeguards and physical protection systems. Finally, interfaces with other systems that are

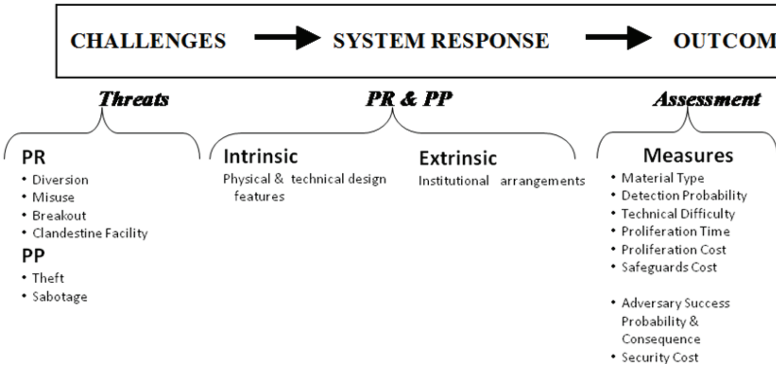

FIGURE 3-1 The PR&PP Methodology Framework. The overall framework involves three stages: challenges; system response; and outcomes. Challenges are evaluated by generating a threat list. The system response is evaluated using PR&PP's PRA methodology. The outcomes are assessed using a number of metrics, listed in the figure. SOURCE: Bari (2011).

not part of the analysis (i.e., links to clandestine facilities) are evaluated to identify any additional potential vulnerabilities.

A number of knowledge gaps remain that are associated with PR&PP and with proliferation resistance assessment more generally. These include:

- Scenario completeness;
- Human performance;
- Combination of different types of information to create the final evaluation;
- Harmonizing design understanding with potential safeguards and protection possibilities; and
- Conveying and displaying results, particularly, what we know and what we do not know.

Further work is needed to fill these gaps.

However, progress is being made. Studies[9] performed for GIF and others have shown that system studies of proliferation resistance can be performed on a comparative basis (e.g., studying reprocessing alternatives to PUREX). These studies have also shown that there are no simple

[9] See, for example, the study of "Reprocessing Alternatives to PUREX" (Bari et al., 2009) and the study "Advanced Reactor Alternatives to ALWR" (Zentner et al., 2010).

answers regarding proliferation resistance. There are many potential pathways to proliferation, and adversary success is highly dependent on pathway choice and creativity. In addition, the results and applicability of an analysis are dependent on a number of assumptions about adversary capabilities and objectives. These uncertainties make it difficult to effectively collapse the proliferation resistance of a facility into a single value denoting overall proliferation resistance. However, one key conclusion has emerged from the work performed to date for PR&PP: Safeguardability is a very important consideration.

In closing, the overall framework used for PR&PP—quantitative evaluation methods aside—provides a holistic view of the energy system with respect to nonproliferation that has the potential to provide worthwhile insights. Even a qualitative analysis can provide information that is helpful to better understand the system being evaluated. For example, a qualitative analysis is useful for informing decision makers on which threat scenarios are associated with particular nuclear process characteristics.

The benefits of a risk assessment-type approach can go beyond the "final answer," because the insights gained from the performance of a highly structured analysis can be valuable in themselves. This process is not simply a checklist exercise, but a process that must be repeated throughout the life-cycle of the facility with new potential to provide insights at each iteration.

POLITICAL SCIENCE APPROACHES AND FUEL CYCLE CHOICES

Christopher Way

At present, there is no significant political science research agenda on proliferation risk and the nuclear fuel cycle. There has been considerable work done on drivers and intent for proliferation, but not much on the narrow focus of the workshop (i.e., the relationship of fuel cycle choices to proliferation). Therefore, this briefing will draw attention to three research areas that might be developed further to provide insight into this workshop's key topics.

Two major patterns can be pulled from the history of nuclear weapons. Although it is not clear that historical patterns indicate future patterns, in the absence of experimental data, history is the primary source of information on proliferation.

First, the motivation to proliferate is very important. No matter what the United States chooses to do with fuel cycle technology, a nation will find a way to acquire a nuclear weapon or a nuclear program if the desire to do so is strong enough. There are several situations that have been shown to drive the desire to proliferate, at least in part. Evidence is quite clear that the security environment of a state is important in influencing the government's decision to proliferate. In addition, in recent decades, personalistic[10] regimes appear to be more willing and able to proliferate. Finally, a desire for prestige is a known motivator to proliferate.

Second, there are patterns to be drawn from the historical fuel cycle choices of proliferators. Prior to 1970, the back end of the fuel cycle (reprocessing and plutonium production) was favored by proliferators. Six out of seven state attempts at proliferation followed the back-end approach—using the plutonium uranium extraction (PUREX) process—and six succeeded. After 1970, the front-end approach—using enrichment technology to produce highly enriched uranium (HEU)—began to be favored. Seven out of nine state attempts at proliferation after 1970 selected the front end approach; only three succeeded.

Possible reasons for this shift from using reprocessing technologies to using enrichment technologies include the tightening of extrinsic barriers and the attractiveness of new technologies. By the 1970s, previous successful attempts at proliferation led toward a tightening of extrinsic barriers to proliferation. Reprocessing facilities, heavy water, and other sensitive nuclear technologies became harder to acquire, and it became harder to conceal reprocessing facilities. At the same time, centrifuge enrichment technology displaced gaseous diffusion technology as the enrichment method of choice. Compared to gaseous diffusion, centrifuge enrichment was much easier to conceal and the components and information needed were available to potential proliferators, particularly through the A.Q. Khan network.

Although, as noted previously, little political science research has focused directly on the issue of proliferation risk and the nuclear fuel cycle, other political science research exists that could be helpful in analyzing these issues. This research has been conducted in three areas: assessing the risk of the host state's desire to proliferate; assessing the likely consequences of technology diversion; and assessing the patterns of potential technology and knowledge sharing.

Estimates of how likely a host state is to decide to proliferate have been calibrated using the past 50 years of experience with nuclear proliferation. Nevertheless, these estimates have a great deal of uncertainty associated with them. Fortunately, there have been few instances of proliferation, but with such rare events it is inevitable that huge errors in estimation will be generated. In addition, there is political uncertainty involved in assessing proliferation risks—today's policymaker may not

[10] In a 2011 paper, C. Way and J. Weeks define personalistic regimes as those in which "a paramount leader enjoys an enormous amount of personal discretion over government decisions, to an extent unseen even in other dictatorships" (Way and Weeks, 2011).

be tomorrow's policymaker. Over decades and even months political situations can change dramatically.

Work has been done to assess the likely consequences of technology diversion. This includes, for example, determining the ability to convert reprocessing technologies and processes to separate plutonium. It can be very difficult for a host state to use information provided to them or otherwise acquired without a great deal of tacit knowledge, so a high technical capacity should not be assumed.

A large amount of literature exists tracking the patterns of legal and illegal sharing of nuclear weapons-related technology and knowledge. This research could help in assessing the patterns of potential technology/knowledge sharing in the context of the nuclear fuel cycle. Although research has not addressed fuel cycle choices directly, it could be used to do so. Game theoretical tools might be able to be adapted and combined with red teaming to provide additional insights about the patterns of legal and illegal sharing of knowledge and technology.

In summary, political science research has not to this point addressed fuel cycle choices directly, but research exists that could provide a platform to begin such work. Some additional research on extrinsic barriers and likely compliance with treaties and restrictions could be of value for this purpose.

HOW MATERIALS ATTRACTIVENESS ESTIMATES ARE DONE AND HOW THEY CAN BE USED AS PART OF A PROLIFERATION RISK ASSESSMENT

Bartley Ebbinghaus

The overall goal of estimating materials attractiveness[11] is to communicate clearly about how attractive different nuclear materials are for use in a nuclear weapon. Accurate estimates have four key benefits. First, it is possible to correct false or misleading publicly-available statements on material attractiveness that could lead to inappropriate security or proliferation decisions for some materials or processes, such as the claimed proliferation resistance of reactor-grade plutonium[12] or uranium-233 containing parts per million (ppm) levels of uranium-232. Second, material attractiveness estimates could be used to prevent inappropriate reductions in existing safeguards and security requirements for nuclear materi-

[11] Material attractiveness is defined as the relative utility of nuclear material for an adversary in assembling a nuclear explosive device.

[12] Reactor-grade plutonium is defined as plutonium that contains over 18 percent plutonium-240.

Figure of Merit (FOM)	Weapons Utility	Materials Attractiveness Level [a]	Designation on Plots
2-3	Preferred	~B	H
1-2	Potentially Usable	~C	M
0-	Impractical	~D	L
<0	Very Impractical	~E	O

[a] "Nuclear Material Control and Accountability," U.S. Department of Energy manual DOE M 470.4-6 Chg 1 (August 14, 2006), http://www.directives.doe.gov.

FIGURE 3-2 Theoretical figure of merit (FOM) for the attractiveness of different nuclear materials. For example, a highly attractive nuclear material would have a FOM of 2-3, a preferred weapons utility, and would have a materials attractiveness level of B. SOURCE: Ebbinghaus (2011).

als. Third, the attractiveness of the materials used in various nuclear fuel cycles (e.g., PUREX vs. UREX or open vs. closed cycles) can be assessed to better understand some aspects of the relative proliferation risks associated with these fuel cycles. Fourth, good materials attractiveness estimates can quantify the relative attractiveness of existing nuclear materials.

Materials attractiveness can be communicated in several different ways, with increasing granularity. Official government standards (for example, on the utility of reactor-grade plutonium) are the most general, followed by safeguards and security regulations, such as graded safeguards tables. Most specific are nuclear material attractiveness metrics, such as a "figure of merit of material attractiveness"[13] (figure of merit) for a specific nuclear material, discussed below. This last, most granular, approach to discussing materials attractiveness is most useful in considering the proliferation potential associated with nuclear fuel cycles.

A materials attractiveness figure of merit is used to quantify the utility of nuclear material to an adversary. It is a grade relative to established standards that is supported by weapons design and materials processing considerations, and is generally equated with nuclear material attractive-

[13] A figure of merit of material attractiveness is a quantified measure of material attractiveness.

ness in safeguards and security applications. For example, as shown in Figure 3-2, an individual material might be graded on a three- or four-step scale. For a host state, the assumption is made that the element can be purified; however, for a substate, it is considered possible that they cannot.

This figure of merit can be used to quantify one proliferation resistance measure: specifically, fissile material type. Other proliferation measures, such as proliferation technical difficulty, proliferation cost, proliferation time, and detection probability, are also important, but cannot be quantified using a material attractiveness metric.

There are four primary physical factors that affect the utility of a material for weapons use:

- Bare critical mass (size factor), which affects the size of the nuclear device constructed from the material, and, necessarily, the difficulty in hiding and moving it;
- Internal heat generation (stability of the device), which affects the difficulty in keeping the device assembled and operable;
- Intrinsic neutron rate (yield factor), which affects the reliability of some nuclear devices; and
- Radiation dose rate (acquisition factor), which affects the difficulty in collecting the materials and assembling the device.

All these factors are used for the material attractiveness metric shown in Figure 3-2, with the exception of the intrinsic neutron rate. The availability (or material quantity) is treated as a separate parameter, aside from the attractiveness of the material.

Figure 3-3 shows that the figure of merit ranks materials consistently with their known utility in a nuclear device. On the other hand, some information that is not common knowledge is also shown by the calculation used to produce this chart—for example, that pure americium-241 is not attractive.

The figure of merit can also be used to show how the material utility changes as a function of different parameters of interest to technical experts or policy makers. For example, it is possible to plot the attractiveness of a material as a function of burnup, as shown in Figure 3-4.

When using material attractiveness metrics, it is important to keep several key points in mind. Material attractiveness is just one of several important measures of proliferation risk, as mentioned previously. In addition, material attractiveness to the adversary is subjective—the choice to proliferate and the determination of how attractive a material would need to be for it to be usable depends strongly on the adversary's goals.

Element	Isotopic Composition	Radiation	Concentration	Form	Figure of Merit (FOM)
Pu	94% 239	Unirradiated	N/A	N/A	2.72
U	100% 233	Unirradiated	N/A	N/A	2.69
U	93% 235	Unirradiated	N/A	N/A	2.18
Pu	24% 240	Unirradiated	N/A	N/A	2.09
Np	100% 237	Unirradiated	N/A	N/A	2.05
Pu	83% 238	Unirradiated	N/A	N/A	1.03
U	20% 235	Unirradiated	N/A	N/A	1.01
Am	100% 241	Unirradiated	N/A	N/A	0.82

FIGURE 3-3 Materials attractiveness estimates for various nuclear materials. The first column shows the element; the second column shows the isotopic composition of the element, i.e., 94% 239 in row 1 means that the material in question is 94 percent plutonium 239. The third column denotes whether the element was irradiated, the fourth and fifth columns show its concentration and form; and the final column shows the figure of merit calculated for that particular element. SOURCE: Ebbinghaus (2011).

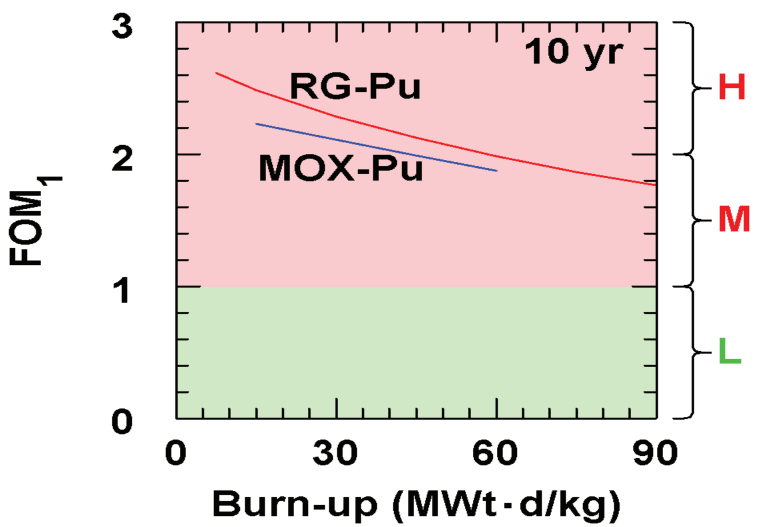

FIGURE 3-4 Materials attractiveness, expressed as FOM, as a function of fuel burn-up, expressed as megawatt-thermal-days per kilogram of uranium. This figure shows that reactor-grade plutonium (RG-Pu) and MOX fuel become somewhat less attractive with increasing burn-up. SOURCE: Ebbinghaus (2011).

For this reason, all materials that have utility to a potential adversary should be safeguarded.

On the other hand, material attractiveness is a useful measure because it uses the undisputable physical properties of the material to assess its risk. This estimate is reproducible, unlike many other measures of proliferation risk. Finally, the concepts and calculations involved in materials attractiveness can be expanded to include additional factors that are more relevant to terrorist than host-state threats.

HOW CAN SAFEGUARDS EFFECTIVENESS BE IMPROVED?

Olli Heinonen

International Atomic Energy Agency (IAEA) safeguards are implemented according to facility-specific criteria in a range of facility categories, such as light water reactors, enrichment plants, and reprocessing plants. These safeguards are applied to all facilities in all countries. However, the exact application of the safeguards criteria varies depending on the facility and the material in use. For example, to ensure that a significant quantity[14] of the material is not diverted, the safeguards criteria state that plutonium must be verified monthly, and LEU must be verified annually.

A great deal of work will be involved if there is a desire to increase safeguards effectiveness and if these significant quantity criteria are maintained at the current level. In addition, even more work will be added if more nuclear facilities are built around the world. At present, IAEA conducts 800 inspections annually on 900 facilities, largely focused on non-weapons states. Virtually no inspections are performed in the United States, Russia, the U.K., China, or France, with some exceptions involving agreements that have been made with Japan for enriched uranium and plutonium that is sent from Japan to Europe for reprocessing.

A significant global expansion of nuclear power is not unrealistic. Post-Fukushima, it appears that few nuclear programs around the world are changing course from their previous plans to increase nuclear power. At the same time, the proliferators are progressively gaining new capabilities: for example, they are now able to use cyber technology—including Internet hacking and surveillance—to advance their goals.

However, the current world situation needs to be kept in mind when

[14] A significant quantity is defined by the IAEA as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear device cannot be excluded. For plutonium, 8 kg is considered a significant quantity, while 75 kg of uranium-235 contained in LEU is a significant quantity.

considering how the international safeguards system can develop and grow to meet these challenges. The worldwide economic situation, for example, suggests that it will be difficult to simply devote more money to improving safeguards and other anti-proliferation measures, and that the additional work associated with the new facilities will need to be managed using fewer resources. In addition, it is unlikely to be fruitful to simply expand current measures; the challenges of the 21st century (e.g., cyber and information challenges) can only be met with the tools of the 21st century.

The key to increasing the effectiveness of safeguards lies in increasing the amount of information available to the IAEA. The Agency's strengths include access to information, sites, people, and cooperation. In reality, only one of these strengths can be expanded significantly to increase the effectiveness of nuclear safeguards: access to information. The number of sites, number of people, and amount of cooperation will not increase.

In seeking increased access to information, it is necessary to carefully determine what kind of information is needed, and to keep the purpose of gathering the information in mind. James Montier, the Chief Global Security Strategist at SG Securities in London stated: "Too much time is spent trying to find out more and more about less and less, until we know everything about nothing. Rarely, if ever, do we stop and ask what we really need to know" (Heinonen, 2011b). Intelligent information use would do several things: focus; prioritize; use all tools, authorities, expertise, and in-house and other information; and assess the weaknesses and strengths of the conclusions reached. One solution is the smart use of in-field efforts combined with all-source analyses.

The smart use of in-field efforts might combine unannounced inspections with remote inspection techniques, enhance design information verification, use information analysis to direct in-field inspection activities, and make the best possible use of risk assessment to understand the proliferation risk and the likelihood of detecting the proliferation attempt. For example, if inspectors appear at sites unexpectedly, proliferators are likely to become nervous and stop using declared material for proliferation purposes. When this occurs, the IAEA must analyze available information and return to look for undeclared material.

Current information use at the IAEA focuses on state-level evaluation and approaches. Once a year, the information is combined to make an estimate of all material currently declared. The IAEA analyzes both the state-level and world information to maintain bottom-line safeguards implementation criteria.

IAEA's information analysis is collaborative and continuous, using all in-house expertise as needed. The analysis used to be mechanistic, but no longer is; IAEA now uses a template and a pathway analysis based on a mathematical model. Finally, the results of the analysis are red-teamed as a final verification.

However, a number of obstacles make effective information analysis difficult:

- Overlap between the equipment, knowledge, and materials required to develop nuclear weapons and to conduct civilian nuclear research;
- Overlap between defensive and offensive nuclear military activities;
- Nations' use of secrecy to protect commercial, proliferation-sensitive, and national security related information;
- The limited number of signatures indicating a military program; and
- The complexity of assessing a nation's intentions and the possibility of making mistakes.

Intelligence information provides another source of increased information; however, there is a cultural divide within the IAEA regarding whether intelligence information should be used. One side favors the use of intelligence, as exemplified in a statement by Hans Blix: "We cannot inspect every nook and cranny in a large country." The other side objects to the use of intelligence information as part of IAEA's work, as exemplified in a statement by Mohamed ElBaradei:

> It isn't realistic for an international organization to have an intelligence branch … Having our own spies going around the world is contrary to our nature. We do our work above ground; we don't work underground. So I continue to preach transparency.

Unfortunately, transparency loses in the real world. Once a clandestine program realizes that IAEA inspectors are aware of its existence, it will immediately retreat deeper underground.

However, if intelligence information is used, it needs to be used intelligently. Intelligence information is not evidence itself; however, it can be used to direct inspectors to the needed evidence. Intelligence information, to provide reliable information, needs to be corroborated.

In summary, access to as much information as possible is essential for the safeguards regime to be effective. Ultimately, the IAEA is as effective as its member states want it to be. To be truly effective, the IAEA Secretariat needs to use all its authorities, including special inspections, to gather information, and the IAEA needs to be provided with up-to-date tools and adequate resources. Finally, member states need to provide support to the IAEA in reinforcing non-compliance cases using all provisions of the IAEA statute.

SUMMARY OF QUESTION AND ANSWER SESSION

As with the policy panelists in the previous chapter, the briefings from the technology panelists were also followed by a lively Q&A session. In the section to follow, some key points that were brought up related to this session are summarized.

Proliferant choice of front- or back-end paths. William Dunlop (Lawrence Livermore National Laboratory) asked Dr. Way to comment further on his discussion of the path (front- or back-end approaches) selected by the largest number of successful proliferators. Dr. Dunlop suggested that most countries pursued both options early on, but now it simply appears to be more inexpensive to get into the enrichment business. Dr. Way agreed that both front- and back-end approaches were typically pursued by most proliferating states prior to the 1970s, but added that in many cases the back end seemed to receive more effort. Drs. Heinonen and Charlton agreed as well and noted that this is also true for current proliferating states such as Iran. Dr. Charlton commented that although the effort may be focused on either the front end or back end, programs typically develop both options, perhaps as insurance. The path chosen is the one that is most easily available and most successful.

Utility of proliferation risk tools and unannounced IAEA inspections. Mark Mullen (Los Alamos National Laboratory) asked Dr. Heinonen, first, what role proliferation risk assessment tools play in the IAEA's efforts to strengthen safeguards, and, second, whether he believes that there are truly surprise IAEA inspections. Regarding the first question, Dr. Heinonen replied that he was personally hesitant to recommend adopting too many tools at the IAEA, and stated that the first question that needs to be settled is how information will be used and how expertise will be acquired. As to the surprise inspections, Dr. Heinonen stated that in some ways surprise inspections work, but in others they do not—for example, in China, an unannounced inspection is likely to be impossible because the inspection team would be very conspicuous. On the other hand, because IAEA representatives are posted in Iran all the time, their unannounced inspections are far less conspicuous.

Fuel cycle facilities and hedging by states. Sharon Squassoni (Center for Strategic and International Security) noted that in many cases, a state might not make a specific decision to proliferate but, rather, might make a decision to hedge its bets by acquiring fuel cycle technology. Thus, the concern may ultimately be about preventing unnecessary transfers of technology to other countries. She asked the panelists if they believe that the United States and other countries concerned about proliferation have been complacent about the capabilities of safeguards in bulk-handling facilities such as enrichment plants.

Dr. Heinonen replied that he is very comfortable with the declared facilities. However, there are ways of misusing facilities, for example, if more material is passed through the facility than is declared. If this occurs, undeclared material can be transported to another location for processing. Another possibility is if an enrichment facility design is changed to create HEU. He stated that the IAEA, within a month's time, should be able to identify a change in facility design, but undeclared enrichment or diversion of plutonium from a reprocessing plant is more difficult to detect. However, over time, the detection probability will become higher.

Dr. Way added that he agrees that hedging is a concern—because it is impossible to know the future, it makes sense to many governments to be several steps ahead in the event that a nuclear capability might be desired. In the best of all possible worlds, you restrict the information spread of many aspects of enrichment and reprocessing, but in reality, this might not be possible.

4

Summary Discussions

The workshop's discussions were summarized in three ways. First, the workshop participants were divided into three breakout groups of about 20-25 participants each to discuss the workshop briefings; the highlights of the breakout sessions were reviewed in front of the full workshop. Second, following the breakout session discussions, a panel of experts was convened and charged with summing up the workshop's major messages. Finally, the floor was opened for free discussion by the participants.

In this chapter, the major issues presented from the breakout group discussions, each of the panelists' briefings, and the key points made during the free discussion period following the panel briefings are summarized. These statements in this chapter reflect the viewpoints of the individual speakers, not the consensus views of the workshop participants or of the National Academies.

BREAKOUT GROUP SESSIONS SUMMARY

As noted above, during the workshop, the participants were divided into three breakout groups. Each of these breakout groups was charged with:

- Identifying the key nonproliferation policy questions that are important to decision makers, drawing on the briefings and discussions;

- Discussing the overlap between these questions and the issues that proliferation resistance and risk assessment methods can address; and
- Discussing ways to increase this overlap.

Following the breakout group discussions, the workshop participants reconvened to review and discuss the major issues brought up during the breakout group sessions. The breakout group chairs, workshop committee members Sharon Squassoni (Center for Strategic and International Security), William Charlton (Texas A&M University), and Charles Forsberg (Massachusetts Institute of Technology) gave short presentations summarizing the key points made during each of the breakout sessions. These presentations and discussions are summarized in this section.

Minimizing the proliferation risk associated with maintaining nuclear fuel cycle facilities around the world involves using both technical and nontechnical approaches. Due to this technical/non-technical dichotomy, two cultures have developed in the nonproliferation community:

- A highly technical culture, focused on maximizing proliferation resistance by considering the design and operation of facilities; and
- A non-technical public policy/political science culture, focused on discouraging and slowing proliferation attempts using domestic and international policy measures.

While policy makers—such as those at NNSA or the State Department—do not typically use highly technical quantitative analyses to inform their policymaking decisions, such input would be possible and would not be unique. In other endeavors, such as Treasury Department activities, technical analysis is used to help formulate and drive policy. However, multiple workshop participants, particularly those working in policy, stated that such analyses would be more useful if the technical analysts working on nonproliferation problem were aware of and considering the types of questions that are important to policy makers. Participants in one breakout group suggested that helpful questions for the technical community to consider would include: (1) who the policy makers are; (2) what questions they are asking; (3) which of those questions are amenable to technical analysis; and (4) how policy makers are putting technical information to use.

A good assessment also needs to account for a broad range of ways in which information could be acquired. It was noted several times in the course of the discussions that nuclear fuel cycle technologies are currently lagging behind many other commercial technologies. This means that commercial technologies developed for other purposes have the potential to influence proliferation risk associated with fuel cycle facilities. One example cited by participants is carbon fiber technology for airplanes and sporting goods. The widespread knowledge of carbon fiber design and fabrication technology could enable nations to build centrifuges with reasonable output that may be simpler to design and debug than the technologies already made available by A.Q. Khan. A second example mentioned is laser technology, where advances in lasers could make laser enrichment more viable for more countries.

With this in mind, the following summary of the key points articulated by the workshop's breakout groups is presented in two sections: first, key nonproliferation policy concerns and opportunities for technical methodologies to assist in decision-making; and second, the utility of current technological assessments and potential paths for improvement. No attempt has been made to identify which breakout group or individual is responsible for specific statements in the following summary. It has also been noted where significant disagreement occurred during the discussion over specific points.

POLICY CONCERNS AND OPPORTUNITIES FOR TECHNICAL METHODOLOGIES

One breakout group listed four overarching policy issues for nonproliferation that emerged from its breakout group discussions:

1. Managing risk when making international policy decisions;
2. Determining the relative proliferation risk of two fuel cycles;
3. Deciding where to provide money for further research and development (R&D); and
4. Deciding which countries to cooperate with and how.

In many cases, these policy issues involve technology; however, some participants noted that the full range of nonproliferation-related concerns is much broader than purely technical. For example, some key considerations regarding cooperation with a new nuclear power program might include understanding the potential motivations of the technology supplier (e.g., Russia, France, or China); the full set of conditions and arrangements for the sale; the recipient national government's level of corruption; and the recipient national government's stability.

Beyond this, some participants noted that policy decisions regarding nuclear fuel cycle technologies—whether domestic or overseas—may not be solely motivated by proliferation, making proliferation resistance and risk measures inadequate as sole discriminators for policy decisions.

Other factors, including national goals, economics, and nuclear waste management, are likely to factor into decision making.

A participant in one breakout group expressed his view of the central issue for policy makers very clearly: fundamentally, what policy makers want to know is how many ways they can get into trouble, even if the chances of trouble are remote. For example, from a policymaker's perspective, if a policy goal is to encourage nuclear energy, where might trouble appear (e.g., what materials, facilities, or locations could create problems)? In many cases, probabilistic or highly technical answers to these types of problems are not desired. Top-level decision makers simply want to know if other nations are likely to acquire nuclear weapons.

Unfortunately, there is no tool available that will answer this question, but there may be a range of tools that can answer other important questions. A common understanding of what policy makers' key questions are could be useful in determining the right tools. In other words, a simpler and clearer question to consider is: What information needs to be obtained to improve policy efforts to minimize proliferation?

As a starting point, one breakout group listed a number of specific questions that a policymaker might productively ask of a technical assessment:

- If the United States is entering into a nuclear cooperation agreement with another country, what technologies would be appropriate to share with that country?
- If a technology is transferred, how could it be used to proliferate in a specific country, and what latent capability would then exist in the country?
- Which fuel cycle technology should the United States devote resources to developing, assuming that this technology may be eventually exported by a commercial entity to another country?
- What characteristics of a country affect its desire to use a nuclear fuel cycle technology to proliferate?
- Does the design and operation of a specific nuclear energy system provide information or develop skills that are likely to result in a breakout scenario?
- How can the International Atomic Energy Agency (IAEA) apply its limited inspection resources to better block particular paths to proliferation in countries of concern?

Applicability and Usefulness of Technical Assessments

Several workshop participants observed that technical and quantifiable assessments of proliferation resistance might not be the ideal tool to use to advise policy makers on many of their highest-priority concerns. Two major reasons were provided for this observation. First, there exists a mismatch between the concrete day-to-day issues described by policy makers (see Chapter 2) and the more abstracted, technical issues described by the panel of technical experts in proliferation resistance analysis (see Chapter 3). Second, some concerns that are of greatest interest to policy makers—for example, a nation's motivation to proliferate—cannot easily be addressed with a purely technical analysis.

However, others observed that technical assessments have the potential to be very useful if directed toward addressing certain appropriate questions and concerns. Specifically, one participant noted that there are no purely technical solutions to purely political problems, but there are often technical solutions that can assist in managing some part of a political problem. One example is the use of technical methods to assess the safeguardability of fuel cycle facilities, thereby improving the implementation of a political solution (such as the nuclear nonproliferation treaty).

One breakout group provided four suggestions that could serve as a starting point for a subset of issues that policy makers would be interested in and that are amenable—at least in part—to technical analysis:

- Preventing or providing proof of proliferation, in concert with the IAEA safeguards regime;
- Identifying particular nuclear materials, facilities, locations, or portions of the fuel cycles as of particular concern;
- Helping to determine policy decisions on technology choices (from the nonproliferation point of view); and
- Helping develop or adjust strategies for negotiating agreements, for example, on technology transfer of specific technologies.

Both benefits and drawbacks associated with the use of proliferation resistance assessments in policy decision-making were discussed. Some participants suggested that careful and disciplined assessments of a facility's proliferation resistance could be useful to sharpen the debate on the role of civilian nuclear fuel cycles in proliferation and clarify the underpinnings of decisions taken as a result. On the other hand, others noted that there is a danger of misuse of a comparative risk assessment by foreign nations with an interest in proliferation, as it would allow them to identify the most productive fuel cycle with which to begin their proliferation efforts.[1]

[1] The use and protection of sensitive or classified information is often involved in analysis efforts, and capabilities are often needed to manage and control this information. For example, in Proliferation Resistance and Physical Protection assessments of Generation IV nuclear energy systems, some detailed pathway descriptions may include sensitive information.

The value of a "single number" quantification of proliferation risk (a figure of merit) was also debated by the workshop participants. Some were concerned about the potential for misuse by those with vested interests (i.e., foreign nations interested in proliferation or politicians with specific agendas) who choose to neglect the underlying uncertainties and assumptions. Others suggested that such a number would have value for communicating with policy makers about the results of technical assessments, because of its simplicity and clarity.

The time horizon (i.e., the length of time) that an analysis needs to be applicable to is likely to vary depending on the policy question under consideration. There was some disagreement among workshop participants about whether different tools would be needed to acquire answers over time horizons of decades, years, or weeks. Some participants judged that different tools would be needed in each case, whereas others judged that it should be possible to converge on a single tool that would be usable for either short- or long-term decision-making.

Several key issues related to proliferation risk and resistance assessments were mentioned over the course of the discussion that were loosely connected to one another and to the previous discussion. These issues included the following:

- Some participants stated that simple judgments, such as one fuel cycle is "good" while another is "bad," are unlikely to be found, and suggested that policy makers and others should avoid seeking to identify winners and losers among fuel cycle technologies. Rather than asking "Does this technical change result in a more or less proliferation-resistant fuel cycle?" one might ask, "In the context of this situation, what changes would improve or degrade the proliferation risk?"
- The response to the idea of quantifying proliferation resistance was mixed. Some participants suggested that technical assessments might better inform policy makers' management of proliferation risk by focusing on tradeoffs and scenarios more rather than quantification, and they underlined the importance of clarifying and communicating the uncertainties in the methodologies. Another workshop participant stated that a mix of quantifiable and non-quantifiable assessment is valuable, noting the importance of both technical rigor and well-thought-out opinions.
- Some participants stated that good assessments of proliferation resistance should be situation-specific, but they noted that implementing such specificity can be difficult. All national situations are not identical, and a method that treats all country contexts as identical is not necessarily helpful in making policy decisions.

However, it is very difficult to validate a model that looks at a specific state. One suggested solution was to look at related problems where analyses were performed with no ability to validate the models, for example, stockpile stewardship. Another suggested solution was to carry out analyses with different tools and compare the answers; the final conclusion communicated to a policymaker might be based on either multiple answers or the worst-case estimate. Multiple participants thought that such a situation-specific assessment would be useful.

- Some participants thought that it could be useful to analyze why a country might pursue a particular path toward proliferation. Such an analysis might take different economic environments in different countries into account. In addition, the analysis might also consider the problem of mimicking: Does U.S. selection of a fuel cycle technology encourage other countries to develop the same technology, and what is the probability that another state will follow U.S. action, for good or bad?
- Some workshop participants suggested using history to gain insight on proliferation models. For example, proliferation risk models could be evaluated by comparing their output against the actual historical outcome. However, concerns were raised with such an approach. Specifically, the answers provided by all current models are likely to be similar because the models are very similar. In addition, one is unlikely to ever have complete knowledge, even for historical cases; instances of proliferation are rare, and the few individuals with first-hand knowledge are now retiring.
- To date there has been very little consolidation or standardization of models. Some work has been done to combine INPRO[2] and Proliferation Resistance and Physical Protection (PR&PP), but as of now, there has been no work to combine or standardize other methodologies.
- Finally, some participants noted that most thinking about nuclear fuel cycles is tactical rather than strategic, and suggested that it could be valuable to take a strategic look at the nonproliferation impacts of large-scale fuel cycle changes, such as eliminating, combining, or co-locating facilities.

[2] International Project on Innovative Nuclear Reactors and Fuel Cycles.

OPPORTUNITIES FOR PROLIFERATION RISK ASSESSMENT: PANEL DISCUSSION

Following the overview of the breakout session discussions, a third and final panel was convened involving the following experts:

- William Tobey, Senior Fellow at Harvard University Kennedy School of Government Belfer Center for Science and International Affairs;
- John Ahearne, Executive Director Emeritus of Sigma Xi; and
- Joseph Pilat, Program Manager in the National Security Office of the Los Alamos National Laboratory and Senior Scholar at the Woodrow Wilson International Center for Scholars.

This session was moderated by C. Paul Robinson (Director Emeritus of Sandia National Laboratory) and chair of the workshop committee. The panel members were asked to briefly discuss their views on:

- The potential role of technical assessments of proliferation resistance in informing real-world decision-making; and
- Potential ways to make the assessments more useful, including R&D directions and suggestions.

Their briefings are summarized in the following sections.

William Tobey

Technical assessments are of course important to policy makers, but they can be improved if those who develop the assessments have a solid understanding of the context in which policy decisions are made.

However, in many cases policy makers have misconceptions about nonproliferation. There are five issues in particular where conventional policy wisdom is at variance with reality:

1. **Multinational arrangements are inherently proliferation resistant.** While such arrangements can be useful, the greatest proliferation disaster originated in a multinational arrangement (URENCO).[3]
2. **Nuclear energy programs lead to nuclear weapons programs.** In fact, the case is more often the reverse. Weapons programs can

[3] A.Q. Khan was an employee of the uranium enrichment company URENCO when he obtained access to the centrifuge designs that he later supplied to the Pakistani government and others.

often lead to nuclear energy programs, which may be used as a cover for the weapons programs.

3. **Safeguards are insufficient, but the failings are not technical.** There has been no known case where safeguarded material has been used to build a weapon; the real failings with respect to safeguards have been political.
4. **The greatest proliferation threat comes from nation-states.** A.Q. Khan and nuclear terrorists are also nuclear proliferators. The threat from states is acute, but it is limited.
5. **Technology can be kept secret.** It is unrealistic to expect that technology can be kept secret indefinitely. The primary purpose of keeping technology secret is to create a delay so that proliferation concerns can be addressed by other means.

With these comments in mind, here are three observations regarding how the United States should be thinking about technology and proliferation. First, it is important to use previous experience to inform decisions. When thinking about increasing proliferation resistance, it can be helpful to examine previous failings. For example, in all but one of eighteen cases where nuclear material has gone beyond the control of a state, it has been in bulk form.

Second, nonproliferation standards for states are no longer sufficient. Much of the current nonproliferation edifice is based on the assumption that states are the primary concern with respect to proliferation. However, this is no longer true, and non-state actors often have very different goals than state actors.

Finally, there are no lasting victories. Those working to stop proliferation are up against adversaries who can and will continue to work to proliferate, so those working to prevent proliferation must be equally determined to stop them.

John Ahearne

In Deputy Secretary Poneman's briefing to the workshop (see Chapter 2), he stated that forming a consortium of entities that offer reliable fuel services could be effective in limiting proliferation, with government and international arrangements as an overlay. Of course, the underlying problem is to determine what services could be offered that would be attractive to states, and enticing them to take advantage of these fuel services.

It is often suggested that fuel take-back would be a good approach, as it would be quite attractive to many nations. A recent National Academy of Sciences-Russian Academy of Sciences joint study committee on internationalizing the nuclear fuel cycle (NRC, 2009) met with a number of representatives from countries that are interested in expanding nuclear programs around the world. The committee asked them what would make the choice of *not* constructing fuel cycle facilities useful or interesting. A program for used fuel take-back was stated to be the main attraction. Thus, if a country decides to build a reactor, a proliferation resistance analysis is unlikely to affect that decision; however, an incentive might be offered, such as fuel take-back, to prevent that country from building other fuel cycle facilities.

The President's Blue Ribbon Commission on America's Nuclear Future (BRC) published its interim report very shortly before the workshop. The report's summary states:

> As more nations consider pursuing nuclear energy or expanding their nuclear programs, U.S. leadership is urgently needed on issues of safety, non-proliferation, and security/counter-terrorism. Many countries, especially those just embarking on commercial nuclear power development, have relatively small programs and may lack the regulatory and oversight resources available to countries with more established programs. International assistance may be required to ensure they do not create disproportionate safety, physical security, and proliferation risks. In many cases, mitigating these risks will depend less on technological interventions than on the ability to strengthen international institutions and safeguards while promoting multilateral cooperation and coordination. From the U.S. perspective, two further points are particularly important: First, with so many players in the international nuclear technology and policy arena, the United States will increasingly have to lead by engagement and by example. Second, the United States cannot exercise effective leadership on issues related to the back end of the nuclear fuel cycle so long as its own program is in disarray; effective domestic policies are needed to support America's international agenda. (BRC, 2011)

As the United States addresses how to better understand proliferation, it should also work to understand why countries want nuclear weapons. In his briefing, Dr. Way described an analysis that is consistent with my previous examinations of countries that attempted to acquire nuclear weapons. The primary reasons that a country might seek to acquire a weapon were first, security concerns in the local region, including a concern that the United States might withdraw its nuclear protection umbrella; and second, prestige, either regional or international. In addition, Mr. Tobey mentioned a more recent group of concerns in his briefing: non-nation-state terrorists. They might want to acquire a nuclear weapon as leverage, or worse, to actually use it.

To meet these challenges, the United States must guard against weakening the IAEA and, at the same time, work to strengthen it. The potential role of technical assessments of proliferation resistance in influencing real-world decision-making should rely strongly on the IAEA's work. Mr. Ed McGinnis encouraged us not to be reactive but to be proactive. As many speakers noted, there is no silver bullet to prevent proliferation. Perhaps the U.S. government should consider following the advice of a utility planner commenting on California energy problems: there is no silver bullet, but there might be some silver BBs.

Joseph Pilat

There has been little disagreement over the premise that there is proliferation risk associated with civilian nuclear energy programs. However, there have been many disagreements about whether civilian nuclear energy—or at least certain aspects of the fuel cycle—should be used at all. These disagreements have focused on whether the benefits outweigh the risks. They continue today.

Uncertainty in the security environment has led to greater concern about terrorism involving nuclear and other weapons of mass destruction than has been seen in the United States since the 1970s. The worst-case scenario, of course, involves widespread nuclear proliferation and terrorism. Such an outcome is by no means inevitable, but the risks and threats faced today are complex, and the current dynamic security environment is unlike any in the past.

The proliferation concerns that need to be considered include the following: Ways civilian nuclear power programs are linked to host-state proliferation and nuclear terrorism; differences between the risks associated with the open and closed fuel cycles; the costs of managing different risks; and balancing the cost of limiting nuclear growth against the cost of not doing so. These concerns are not well understood and are the subject of intense debate.

These issues are not new. In the 1970s, projected exponential growth curves for nuclear energy drove a great deal of conversation about proliferation and the civilian nuclear fuel cycle, as did the projected growth curves for nuclear energy prior to the events at Fukushima earlier this year. Indeed, since the Acheson-Lilienthal report in the late 1940s (Acheson and Lilienthal, 1946)[4] which divided nuclear activities into categories of "safe" and "dangerous" but stated that a number of "dangerous" activities could be rendered safe via technology, there has been a recurring interest in technical fixes for proliferation. Although scientists and

[4] The "Acheson and Lilienthal Report" commonly refers to a 1946 report written for the U.S. Department of State by a committee chaired by Dean Acheson and David Lilienthal. The report was entitled *Report on the International Control of Nuclear Energy.*

engineers understood that such technical fixes could be reversed, they judged that such a reversal would have required an effort beyond the capabilities of any non-nuclear-weapons state. However, it is now clear that the Acheson-Lilienthal report was too optimistic and that the situation has changed profoundly with the spread of nuclear capabilities around the world.

There is a real need for a systematic and rigorous analysis of the proliferation risk associated with fuel cycle facilities; a good analytical framework can inform nonproliferation policy decisions. Whichever analytical methodology is chosen, the implementation approach will need to be effective, credible, transparent, and cost-effective.

There are many hopes and expectations associated with quantitative approaches. If one believes that the most important aspects of proliferation resistance are technical, then the search for quantitative or at least technical solutions becomes critical, and the more quantitative and rigorous the methodology, the better. On the other hand, if both intrinsic and extrinsic barriers[5] to proliferation are considered to be highly important, the quantitative element may not always be necessary. This is particularly true if a strong emphasis is placed on the extrinsic barriers to proliferation.

Quantitative analysis may be desirable for addressing some key subissues associated with proliferation risk, but it may not be valuable for addressing many others. At present, there is no comprehensive theory of proliferation. The correlations between potential motivations to proliferate and actual proliferation decisions are often confused and contradictory, although it is clear that political issues are highly important both in motivating and preventing proliferation. Therefore, there are likely to be limits to what can be usefully quantified. In addition, as has been noted previously in this report, purely quantitative answers are unlikely to be responsive to policy makers' needs, and can be misinterpreted, misunderstood, or misused.

Beyond the political, many technical issues can be addressed by analysis but may not be easily quantified. Those that are readily quantifiable—such as materials attractiveness—can be important to address certain issues.

It is important to understand the uncertainties and limits associated with any analysis of proliferation risk, particularly a quantitative analysis. A quantitative analysis can be useful if the terms of reference for the analysis are sound and if the uncertainties and limitations of the analysis are well-understood. For example, a quantitative analysis could be useful for identifying vulnerabilities and improving safeguards. However, such an analysis is not likely to be useful for identifying a superior technology.

[5] See Chapter 1 for definitions of intrinsic and extrinsic barriers.

It is not clear that any particular fuel cycle technology can pose significant resistance to a determined state effort.

Scenario- or pathway-based analyses may prove helpful, particularly regarding the deployment of an advanced fuel cycle in specific states. Today, the PR&PP methodology (see Chapter 3) has wide acceptance globally, and shows promise; however, it has not been fully tested. While the PR&PP framework does have the capacity to bring in country-specific threats, to date, it has been only exercised using stylized threats.

As part of such a scenario- or pathway-based analysis, the concept of formal, structured expert elicitation is highly important. Such processes have done much to ease concerns about the reliability of and potential for misuse of expert judgment. Earlier in the workshop, John Harvey's briefing as well as the follow-up discussions mentioned the idea of red teaming to better understand proliferation risk. Other approaches to acquire qualitative information on potential proliferator strategies are also possible, such as game theory.

COMMENTS AND DISCUSSION

Throughout much of the second day, the floor was open for the workshop participants to comment on the workshop as a whole and on the future directions of proliferation risk assessment. These comments fell roughly into four categories: intent and choices to proliferate; proliferation in a changing world; addressing the disconnects between the technical and policy communities; and opportunities for proliferation risk and resistance assessment. The following sections provide brief summaries of these discussions.

Considering Intent and Choices to Proliferate

Some workshop participants observed that intent to proliferate and the concept of proliferation resistance are mutually dependent. Doug Shaw (George Washington University) commented that assuming proliferation intent to be constant because it is difficult to measure may be dangerous because it is possible that actions taken to respond to the risk of proliferation might influence intent, for example, through the bargain struck in the Non-Proliferation Treaty (NPT). Similarly, John Creasy (Y-12 National Security Complex) noted that attempting to influence a nation's actions can sometimes result in the creation of the very situation that one was trying to avoid. He added that this underlines the need to use the right tools and bring the right expert judgment to bear on specific situations.

Proliferation in a Changing World

In the 21st century, new challenges have appeared for containing the spread of new technologies, particularly the Internet and the existence of a worldwide economy. In this environment, C. Paul Robinson (Director Emeritus of Sandia National Laboratories) suggested that it could be futile to attempt to completely halt the spread of new technologies that could be associated with nuclear fuel cycle facilities. William Charlton (Texas A&M University) added that attempting to contain technology has not worked in the past and is even more unlikely to work in the future. He suggested that the goal should not be to keep a technology secret forever, but rather, to keep it under wraps until a diplomatic solution is reached, or, if necessary, a military solution is brought to bear.

On a related topic, John Creasy commented that much of the analysis to date on proliferation risk is based on nation-states and third-party actors. However, in the 21st century, massive international corporations exist that countries have no control over. He suggested that it might be worthwhile to consider these organizations' potential role in proliferation.

Addressing the Disconnects Between the Technical and Policy Communities

To better address the disconnects between the technical and policy communities, Raymond Wymer (Oak Ridge National Laboratory, retired) suggested that a clear distinction needs to be made between policy and policy implementation. The U.S. nuclear nonproliferation policy is clear: To, in every way practical, minimize the spread of nuclear weapons around the world. He stated that the problems that are being discussed at the workshop arise with the implementation of that policy, not the policy itself. Although technical assessment cannot provide input to the statement of policy, it can provide input to those who are implementing the policy in specific cases.

However, it remains unclear to some in the technical and policy communities how to most effectively provide and use technical input. Corey Hinderstein (Nuclear Threat Initiative) commented that she was struck by how far removed the workshop discussions have been from the discussions related to the fuel cycle that she has been involved in. She suggested that it could be mutually beneficial if these conversations could be better connected to the types of tools that the workshop participants have been discussing. For example, she suggested that methods that use pathway analyses or decision trees could be useful to policy makers to evaluate where technology choices can be more or less useful.

William Dunlop (Lawrence Livermore National Laboratory) noted that the disconnect between technical analysts and policy makers is not unique to this workshop or even this problem; it also has existed in other contexts, including the U.S. nuclear weapons program. He suggested that it might be helpful for the technical community, including the Department of Energy (DOE) and universities, to find a way to speak with a single voice to the extent appropriate, providing an actionable input to policy makers.

Charles Curtis (Nuclear Threat Initiative) suggested another approach for informing policy with science, engineering, and technical judgment. In his view, the basic question ought to be: What is the strategy from a policy standpoint, and how can science, engineering, and technical judgment inform that strategy? After the Cold War, the nuclear weapons complex faced the challenge of providing continued nuclear deterrence in the absence of testing. In response, the DOE brought together the "Navigators"—the weapons laboratory directors and the heads of the production complex—with the charge of determining the science and technology path required to meet this challenge. He suggested that a similar approach could be used for one possibility for managing the technical input needed to determine how to use technical nonproliferation risk assessment tools.

Overall, the many technical and nontechnical complexities associated with proliferation indicate a need for the international relations community and the technical community to actively work together. Joseph Pilat (Los Alamos National Laboratory) commented that some of the best work being done today in international relations is with case studies. Unfortunately, the associated statistical analysis is often not on par with the quality of the case study work. He suggested that it could be helpful for the technical community to work more closely with the international relations community.

Opportunities for Proliferation Risk and Resistance Assessment

Some of the comments made during the final discussion session reiterated that there is a need for tools that are useful given policy makers' constraints and interests, which go beyond the technical considerations only. Jon Phillips (Pacific Northwest National Laboratory) suggested that a possible model for proliferation resistance could be the U.S. Nuclear Regulatory Commission's (USNRC) system for siting decisions. The USNRC separates analyses into two parts when considering whether to allow a nuclear facility to be sited domestically: first, a generic application for a technology must be completed; second, a site-specific application must be completed. This system might be applicable to proliferation resistance assessment. The first stage of analysis would discuss the technology aspects of a facility generically; the second stage would be state- and situation-specific. Such a two-stage approach could allow the technical parts of the problem to be separated from the non-technical.

Warren (Pete) Miller (Texas A&M University) posed three questions that would be useful to investigate in more detail in the National Academies study that will follow this workshop, noting that the DOE is currently working on an analysis for the back end of the nuclear fuel cycle, to allow them to down-select from a myriad of potential technologies. These questions are:

- Among the many criteria that need to be considered in making this decision (e.g., cost and waste management), how important should proliferation resistance be?
- Should proliferation resistance be removed as a criterion for down-selection, given that the tools cannot currently discriminate between different options for the back end of the fuel cycle?
- How can analysis tools be improved or new ones developed to provide more effective differentiation on proliferation risk?

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Appendix A

Project Statement of Task

IMPROVING THE ASSESSMENT OF PROLIFERATION RISK OF NUCLEAR FUEL CYCLES

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 B

Workshop Statement of Task

An ad hoc committee will plan and conduct a public workshop on 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 the utility of these questions for informing international nonproliferation policy decisions. The committee will develop the workshop agenda, select and invite speakers and discussants, and moderate the discussions. An individually-authored summary of the event will be prepared by a designated rapporteur. The summary will serve as a key input to a separate and more detailed study of the subject that will be undertaken following the workshop.

Appendix C

Committee and Staff Biographical Sketches

C. Paul Robinson (Chair, National Academy of Engineering [NAE]) served as Laboratories Director and President of Sandia National Laboratories from 1995 to 2005. He currently serves as the President Emeritus of Sandia National Laboratories. From 1988 to 1990, Dr. Robinson served as an Ambassador and Chief Negotiator as Head of the U.S. Delegation to the U.S./USSR Nuclear Testing Talks in Geneva. From 1985 to 1988, Dr. Robinson served as Senior Vice President and Principal Scientist of Ebasco Services, Inc. He spent much of his early career at Los Alamos National Laboratory (LANL) from 1967 to 1985 and led its nuclear weapons and other defense programs. He serves as Chairman of Science and Technology (S&T) Council of ICx Technologies, Inc. and has been its member since February 7, 2007. He has been a member of Strategic Advisory Group for the Commander, U.S. Strategic Command since 1991. He is active on Defense Science Board studies. He also served on the Scientific Advisory Group on Effects for the Defense Nuclear Agency. Dr. Robinson received the DOE Secretary's Gold Award in October 2004; the American Physical Society Pake Prize in 2003 for outstanding leadership and research accomplishments; and the Outstanding Public Service Medal from the Joint Chiefs of Staff. Dr. Robinson holds a Bachelor's degree in Physics from Christian Brothers College, a Ph.D. in Physics from Florida State University and an Honorary Doctorate from Christian Brothers University.

Charles Forsberg is a professor at the Massachusetts Institute of Technology and the Executive Director for the MIT Nuclear Fuel Cycle Study. Before joining MIT he was a Corporate Fellow at Oak Ridge National Laboratory (ORNL). He is a Fellow of the American Nuclear Society and the American Association for the Advancement of Science. Dr. Forsberg received the 2002 American Nuclear Society Special Award for Innovative Nuclear Reactors, and in 2005 the American Institute of Chemical Engineers Robert E. Wilson Award in recognition of chemical engineering contributions to nuclear energy, including his work on reprocessing, waste management, repositories, and production of liquid fuels using nuclear energy. He holds 10 patents and has published more than 250 papers. Dr. Forsberg's current research interests include development of integrated nuclear fuel cycles, advanced high-temperature nuclear reactors using liquid-salt coolants, and development of global nuclear-renewables energy systems. The characteristics of each of these areas are the coupling of different technologies to enhance performance or create new capabilities. He is a licensed, professional engineer.

William Charlton serves as the director of the Nuclear Security Science and Policy Institute (NSSPI) at Texas A&M University and as an associate professor in the nuclear engineering department. NSSPI is a multi-disciplinary organization that coordinates research and education programs in the area of nuclear nonproliferation, nuclear security, and nuclear material safeguards. NSSPI customers include NNSA (National Nuclear Safety Administration), DOE (Department of Energy), DNDO (Domestic Nuclear Detection Office), NRC (Nuclear Regulatory Commission), and NSF (National Science Foundation). Prior to his appointment at Texas A&M University, he was an assistant professor at the University of Texas at Austin and prior to that served on the technical staff in the Nonproliferation and International Security Division at Los Alamos National Laboratory. He teaches courses which study the technical aspects of nuclear nonproliferation, safeguards, and nuclear security as well as fundamentals of nuclear engineering. Dr. Charlton is recognized as one of the leaders in the technical area of nuclear nonproliferation and has over 150 technical publications in refereed journals and conference proceedings.

Sharon Squassoni serves as director and senior fellow of the Proliferation Prevention Program at the Center for Strategic International Studies (CSIS). Prior to joining CSIS, Ms. Squassoni was a senior associate in the Nuclear Nonproliferation Program at the Carnegie Endowment for International Peace. From 2002 to 2007, Ms. Squassoni advised Congress as a senior specialist in weapons of mass destruction at the Congressional Research Service (CRS), Library of Congress. Before joining CRS, she worked briefly as a reporter in the Washington bureau of Newsweek magazine. Ms. Squassoni also served in the executive branch of government from 1992 to 2001. Her last position was Director of Policy Coordination for the Nonproliferation Bureau at the State Department. She also served as a policy planner for the Political-Military Bureau at State. She began her career in the government as a nuclear safeguards expert in the Arms Control and Disarmament Agency. She is the recipient of various service awards and has published widely. She is a frequent commentator for U.S. and international media outlets. Ms. Squassoni received her B.A. in political science from the State University of New York at Albany, a Masters in Public Management from the University of Maryland, and a Masters in National Security Strategy from the National War College.

Staff

Sarah C. Case (Study Director, Rapporteur) is a senior program officer in the Nuclear and Radiation Studies Board of the National Research Council (NRC). She manages a portfolio of consensus studies and workshops focused on technical issues related to nuclear security and non-proliferation. Her professional interests focus on nuclear nonproliferation as well as nuclear safety and security. She has directed multiple NRC Studies, including *Understanding and Managing Risk in the DOE Nuclear Weapons Complex* (2011) and *Progress, Challenges, And Opportunities for Converting U.S. and Russian Research Reactors from Highly Enriched to Low Enriched Uranium Fuel (Ongoing)*. Dr. Case's previous projects at the NRC have also addressed issues related to nuclear energy, electrical transmission and distribution, and the health effects of radiation. Dr. Case received her Ph.D. in physics from the University of Chicago and her B.A. in physics from Columbia University.

Kevin D. Crowley is the senior board director of the Nuclear and Radiation Studies Board, which advises the National Academies on the design and conduct of studies on radiation health effects, radioactive-waste management and environmental cleanup, and nuclear security and terrorism. The board also provides scientific support to the Radiation Effects Research Foundation in Hiroshima, Japan, a joint U.S.-Japanese scientific organization that investigates the health effects arising from exposures to ionizing radiation among World War II atomic-bombing survivors. Dr. Crowley's professional interests and activities focus on the safety, security, and technical efficacy of nuclear and radiation-based technologies. He has directed or codirected some 20 National Research Council (NRC) studies, including *Safety and Security of Commercial Spent Nuclear Fuel Storage* (2005); *Going the Distance: The Safe Transport of Spent Nuclear Fuel* *and High-Level Radioactive Waste in the United States* (2006); *Medical Isotope Production without Highly Enriched Uranium* (2009); and *America's Energy Future: Technology and Transformation* (2009). Before joining the NRC staff, Dr. Crowley held teaching/research positions at Miami University of Ohio, the University of Oklahoma, and the U.S. Geological Survey. He received his Ph.D. in geology from Princeton University.

Benjamin Rusek works as a program officer for the Committee on International Security and Arms Control (CISAC) at the U.S. National Academy of Sciences on projects related to nonproliferation, arms control, and the misuse of science and technology. Mr. Rusek manages CISAC's interaction with the Chinese People's Association for Peace and Disarmament in Beijing, CISAC's sub panel examining threats related to biological weapons and dual use biotechonolgy and serves as program staff on CISAC's "Track II" dialogues and CISAC-administered National Research Council studies. Outside of the NAS, Mr. Rusek is the chair of the Executive Board of International Student Young Pugwash (ISYP) and frequently works with the Nobel Peace Prize winning Pugwash Conferences on Science and World Affairs. Previously, he held various positions at the Henry L. Stimson Center, the Arms Control Association, and the National Air and Space Museum (as an Ohio State University John Glenn Institute Policy Fellow). Mr. Rusek has political science degrees from Ohio State University and Purdue University, where he was the president of Purdue University Student Pugwash.

Appendix D

Workshop Agenda

**Improving the Assessment of Proliferation
Risk of Nuclear Fuel Cycles:
A Workshop
August 1-2, 2011**

The Keck Center of the National Academies
500 Fifth Street, NW, Washington, D.C. 20001
Room 100

FINAL AGENDA

MONDAY, AUGUST 1, 2011

9:00 am	**Welcome** *C. Paul Robinson, Planning Committee Chair*
9:15 am	**Keynote Briefing: Is Stopping Nuclear Proliferation a Human Problem, a Technical Problem, or Something Else?** *Daniel Poneman, Deputy Secretary of Energy, U.S. Department of Energy (DOE)*
10:15 am	**U.S. Department of Energy Office of Nuclear Energy's perspective on Proliferation Risk and Nuclear Fuel Cycles** *Edward McGinnis, Deputy Assistant Secretary for International Nuclear Energy Policy and Cooperation, Office of Nuclear Energy, DOE*

10:30 am **U.S. Department of Energy National Nuclear Security Administration's Perspective on Proliferation Risk and Nuclear Fuel Cycles**
Mark Whitney, Asst. Deputy Administrator for Nonproliferation and International Security, National Nuclear Security Administration (NNSA), DOE

10:45–11:00 am **BREAK**

11:00 am **PANEL 1– Key Issues for Nonproliferation Policy**
Moderator: *Sharon Squassoni, Planning Committee Member*
Panelists:
Mark Whitney, Office of Nonproliferation and International Security, NNSA, DOE
John Harvey, Office of the Secretary of Defense, U.S. Department of Defense
Richard Stratford, Office of Nuclear Energy, Safety, and Security Affairs, Undersecretary for International Security and Nonproliferation, U.S. Department of State

Points for discussion:
- Identify the key questions associated with proliferation policy, in your office's view
- How is the proliferation risk of fuel cycle/reactor choices measured
- What other considerations are taken into account in decision-making
- What analytical tools are not currently used but could prove useful
- Compare the importance of fuel cycle/reactor choices vs. other government actions (e.g., government controls) that can be taken.

12:30–1:30 pm **LUNCH**

12:45 pm **Lunch Briefing: The Threat from Low-Cost Centrifuge Enrichment and A.Q. Khan: The Genie is out of the Bottle.**
Olli Heinonen, Senior Fellow, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University

1:30 pm **PANEL 2– Metrics and Methodologies for Proliferation Risk Assessment**
Moderator: *William Charlton, Planning Committee Member*

- **Overview of methodologies**
  William Charlton, Texas A&M University and Planning Committee Member
- **How well do political science approaches address fuel cycle choices**
  Christopher Way, Cornell University
- **How well do technical (intrinsic) barriers—and assessments of these barriers—influence fuel cycle choices**
  Robert Bari, Brookhaven National Laboratory
- **How can safeguards effectiveness be improved**
  Olli Heinonen, Kennedy School of Government, Harvard University
- **How materials attractiveness estimates are performed and how they can be used as part of a proliferation risk assessment**
  Bart Ebbinghaus, Lawrence Livermore National Laboratory

3:15–3:30 pm **BREAK**

3:30–5:00 pm **BREAKOUT SESSIONS: Compatibility between Key Policy Issues and Assessment Methodologies**

3:30 pm **Directions to Breakout Sessions**
C. Paul Robinson, Planning Committee Chair

3:40 pm **Participants to Move to Breakout Rooms**
See handout for assigned breakout groups:

- **Group A** will report to Room 101 *(Chair, Sharon Squassoni; Staff, Sarah Case)*
- **Group B** will report to Room 105 *(Chair, Bill Charlton; Staff, Ben Rusek)*
- **Group C** will report to Room 109 *(Chair, Charles Forsberg; Staff, Kevin Crowley)*

3:45 pm **Discussions of Compatibility between Key Policy Issues and Assessment Methodologies (In breakout groups)**

4:55 pm **Return to Room 100**

5:00 pm **Closing Comments**
C. Paul Robinson, Planning Committee Chair

5:15 pm **Adjourn**

TUESDAY, AUGUST 2, 2011

9:00 am **BREAKOUT SESSION SUMMARY**
Led by Charles Forsberg, Planning Committee Member
- Chairs and staff of previous day's breakout sessions to summarize and present conclusions

10:00– 10:15 am **BREAK**

10:15 am **PANEL DISCUSSION 3 – Opportunities and Path Forward for Proliferation Risk Assessment**
Moderator: *C. Paul Robinson, Planning Committee Chair*
Panelists:
William Tobey, Kennedy School of Government, Harvard University
John Ahearne, Sigma Xi
Joseph Pilat, Los Alamos National Laboratory

Points for discussion:
- The potential role of technical assessments of proliferation resistance in informing real-world decision-making
- Potential ways to make the assessments more useful, including R&D directions and suggestions

12:00 pm **Adjourn**

Appendix E

Workshop Participant List

Ahearne, John*
Sigma Xi

Ahmed, Diana
Utrecht University

Bari, Robert*
Brookhaven National Laboratory

Belvin, Anthony
U.S. Department of Energy, Office of Nuclear Energy

Beyninson, Alisa
U.S. Government Accountability Office

Blandford, Edward
Stanford University

Bowen, Matt
U.S. Department of Energy, National Nuclear Security Administration

Budlong-Sylvester, Kory
Los Alamos National Laboratory

Cahill, Christopher
George Washington University

Collins, Emory
Oak Ridge National Laboratory

Creasy, John
Y-12 National Security Complex

Cross, Sarah
Brookhaven National Laboratory

Crozat, Matthew
U.S. Department of Energy, Office of Nuclear Energy

Note: Speakers denoted by asterisks.

Curtis, Charles
Nuclear Threat Initiative

Daniels, Sameera
Ramsey Decision Theoretics

Dunlop, Bill
Lawrence Livermore National Laboratory

Ebbinghaus, Bart*
Lawrence Livermore National Laboratory

Eddy, Michaela
U.S. Department of Defense, Office of the Assistant to the Secretary of Defense

Frazer, Don
U.S. Department of Energy, Office of Nuclear Energy

Goodman, Mark
U.S. Department of State

Grice, Thomas
U.S. Nuclear Regulatory Commission

Habighorst, Peter
U.S. Nuclear Regulatory Commission

Hands, David
U.S. Nuclear Regulatory Commission

Harvey, John*
U.S. Department of Defense

Heinonen, Olli*
Harvard University

Henderson, Karen
U.S. Nuclear Regulatory Commission

Henderstein, Cory
Nuclear Threat Initiative

Herczeg, John
U.S. Department of Energy, Office of Nuclear Energy

Hettger, Joel
National Archives and Records Administration

Higgins, Paul
U.S. Department of Energy

Hughes, Jeffrey
U.S. Department of Energy

Hwang, Yongsoo
Center for Strategic and International Studies

Laporte, Zachary
Institute for Science and International Security

Levite, Ariel
Carnegie Endowment for International Peace

Lockwood, Dunbar
U.S. Department of Energy, National Nuclear Security Administration

Lowenthal, Micah
The National Academies

Machiels, Al
Electric Power Research Institute

Makarewicz, Phillip
Y-12 National Security Complex

Malyshev, Michael
U.S. Department of Defense

McGinnis, Edward*
U.S. Department of Energy, Office of Nuclear Energy

McIlvain, Thomas
U.S. Department of State

Mendelssohn, Kasia
U.S. Department of Energy, National Nuclear Security Administration

Miller, Warren (Pete)
Texas A&M University

Mullen, Mark
Los Alamos National Laboratory

Murphy, John
U.S. Department of Energy, National Nuclear Security Administration

Peranteau, David
U.S. Department of Energy, National Nuclear Security Administration

Phillips, Jon
Pacific Northwest National Laboratory

Pilat, Joseph*
Los Alamos National Laboratory

Poneman, Daniel*
U.S. Department of Energy, National Nuclear Security Administration

Price, Robert
U.S. Department of Energy, Office of Nuclear Energy

Redmond, Everett
Nuclear Energy Institute

Robinson, Chris
Oak Ridge National Laboratory

Rosner, Robert
University of Chicago

Schneider, Grant
U.S. Department of State

Sharma, Sheena
U.S. Department of State

Shaw, Doug
George Washington University

Skutnik, Steve
North Carolina State University

Slakey, Francis
American Physical Society

Smith-Kevern, Rebecca
U.S. Department of Energy, Office of Nuclear Energy

Sowder, Andrew
Electric Power Research Institute

Spitzer-Hobeika, Tamara
Center for Strategic and International Studies

Stainback, Joseph
Y-12 Nuclear Security Complex

Stoutland, Page
Nuclear Threat Initiative

Stratford, Richard*
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Sweeney, David
Texas A&M University

Syzmanski, John
Office of Science and Technology Policy

Taiwo, Temitope
Argonne National Laboratory

Therios, Ike
Argonne National Laboratory

Tobey, William*
Harvard University

Vega, Daniel
U.S. Department of Energy, Office of Nuclear Energy

Volpe, Tristan
George Washington University

Way, Christopher*
Cornell University

Whitney, Mark*
U.S. Department of Energy, National Nuclear Security Administration

Wigeland, Roald
Idaho National Laboratory

Williams, Sarah
Center for Strategic and International Studies

Wilson, Rodney
Sandia National Laboratory

Wonder, Ed
U.S. Department of Energy, National Nuclear Security Administration

Wymer, Ray
Nuclear and Radiation Studies Board

Zentner, Michael
Pacific Northwest National Laboratory

National Academies Staff:

Case, Sarah C.
Study Director
Senior Program Officer
Nuclear and Radiation Studies Board

Crowley, Kevin
Director
Nuclear and Radiation Studies Board

Rusek, Benjamin
Program Officer
Committee on International Security and Arms Control

Whetstone, Shaunteé
Senior Program Assistant
Nuclear and Radiation Studies Board

Appendix F

Workshop Speakers Biographical Sketches

John F. Ahearne is the executive director emeritus of the Ethics Program at Sigma Xi, The Scientific Research Society, a lecturer in public policy at Duke University, and an adjunct scholar at Resources for the Future. He has extensive expertise in nuclear and radiation engineering and risk assessment. His professional interests are in reactor safety, energy issues, resource allocation, and public policy management. Dr. Ahearne served in the U.S. Air Force from 1959 to 1970, resigning as a major. He has also served as deputy and principal deputy assistant secretary of defense (1972-1977), in the White House Energy Office (1977), as deputy assistant secretary of energy (1977-1978), and as commissioner and chairman of the U.S. Nuclear Regulatory Commission (chairman, 1979-1981). He is a fellow of the American Physical Society, the Society for Risk Analysis, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and a member of the National Academy of Engineering, Sigma Xi, and the American Nuclear Society. He has previously chaired or served as a member on committees for over 30 other NRC studies. Dr. Ahearne received a Ph.D. in physics from Princeton University.

Robert Bari is a senior physicist at Brookhaven National Laboratory. He is currently international co-chairman of the working group on proliferation resistance and physical protection of the Generation IV International Forum. He has served on the board of directors of the American Nuclear Society (ANS) and is an elected fellow of the Society. Dr. Bari was awarded the ANS Theo J. "Tommy" Thompson Award in 2003 and, in 2004, he received the Brookhaven National Laboratory Award for Outstanding Achievement in Science and Technology. Dr. Bari received his bachelor's degree in physics from Rutgers University and his doctorate in physics from Brandeis University.

William Charlton serves as the director of the Nuclear Security Science and Policy Institute (NSSPI) at Texas A&M University and as an associate professor in the nuclear engineering department. NSSPI is a multi-disciplinary organization that coordinates research and education programs in the area of nuclear nonproliferation, nuclear security, and nuclear material safeguards. NSSPI customers include NNSA (National Nuclear Safety Administration), DOE (Department of Energy), DNDO (Domestic Nuclear Detection Office), NRC (Nuclear Regulatory Commission) and the National Science Foundation (NSF). Prior to his appointment at Texas A&M, he was an assistant professor at the University of Texas at Austin and prior to that served on the technical staff in the Nonproliferation and International Security Division at Los Alamos National Laboratory. He teaches courses which study the technical aspects of nuclear nonproliferation, safeguards, and nuclear security as well as fundamentals of nuclear engineering. Dr. Charlton is recognized as one of the leaders in the technical area of nuclear nonproliferation and has over 150 technical publications in refereed journals and conference proceedings.

Bartley Ebbinghaus is staff scientist at LLNL leading or advising a number of efforts on nuclear materials attractiveness and related issues for the counterterrorism, intelligence, non-proliferation, and nuclear energy programs. He received his Ph.D. in High Temperature Chemistry from the University of California in Berkeley in 1991 and his B.S. in Chemistry from Southern Methodist University in 1986. Since joining LLNL 1991, Dr. Ebbinghuas has been involved in a number of actinide related projects. From 1991 to 1996, he led various actinide related projects including the volatility of actinides and hazardous metals in thermal processes, purification of actinides by pyrochemistry, and recovery of actinides from wastes. From 1996 to 2000, he led the ceramic form development activity for plutonium immobilization program, which resulted in two patents. From 2003 to 2006, he directed the plutonium analytical and materials characterization work in the LLNL plutonium facility. During this time he led all the materials property testing work at LLNL related to the plutonium pit lifetime assessment. From 2006 to 2009, he moved to Washington, DC, to become the technical advisor to the Nuclear Counterterrorism Program, which is responsible for understanding the implications of Improvised Nuclear Devices. During his time in DC, Dr. Ebbinghuas was instrumental in a review of the technical basis of the DOE Graded Safeguards Table. The Figure of Merit, which is used to quantify nuclear material attractiveness, originated from this study.

John Harvey has served as Principal Deputy Assistant to the Secretary of Defense for Nuclear and Chemical and Biological Defense Programs since July 2009, where he advises on plans, policy, and oversight of the U.S. nuclear weapons program, programs for combating weapons of mass destruction, chemical weapons demilitarization, treaty management, and the work of the Defense Threat Reduction Agency. From March 2001 to July 2009, Dr. Harvey served as Director, Policy Planning Staff of the National Nuclear Security Administration where he advised the NNSA Administrator on major policy and program decisions. He was responsible for studies and analyses relating to NSC-directed policy reviews, the work of the Nuclear Weapons Council, external advisory boards, and interagency working groups. Dr. Harvey has served on several senior advisory panels. From March 1995 to January 2001, Dr. Harvey served as Deputy Assistant Secretary of Defense for Nuclear Forces and Missile Defense Policy where he developed and oversaw implementation of U.S. policy governing strategic and theater nuclear forces and ballistic missile defense. For his service in DoD, he was awarded, in September 1985 and in January 1997, the Secretary of Defense Medal for Outstanding Public Service. Dr. Harvey received his B.A. in physics from Rutgers University and his M.S. and Ph.D. degrees in experimental elementary particle physics from the University of Rochester. He is the author or co-author of numerous scientific and technical papers.

Olli Heinonen spent 27 years at the International Atomic Energy Agency in Vienna before joining the Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, as a senior fellow. Heinonen served the last 5 years as Deputy Director General of the IAEA, and head of its Department of Safeguards. He led the Agency's efforts to identify and dismantle nuclear proliferation networks, including the one led by Pakistani scientist A.Q. Khan, and he oversaw its efforts to monitor and contain Iran's nuclear program. Heinonen led teams of international investigators to examine nuclear programs of concern around the world and inspected nuclear facilities in South Africa, Iraq, North Korea, Syria, Libya, and elsewhere, seeking to ensure that nuclear materials were not diverted for military purposes. He is considered one of the world's leading experts on Iran's nuclear program. He led the Agency's efforts in recent years to implement an analytical culture to guide and complement traditional verification activities. Prior to joining IAEA, he was a Senior Research Officer at the Technical Research Centre of Finland Reactor

Laboratory in charge of research and development related to nuclear waste solidification and disposal.

Edward McGinnis is responsible for the Department of Energy's international civilian nuclear energy activities, including international nuclear energy research, development and demonstration cooperation, international framework and partnership development, international nuclear energy policy, and other international civilian nuclear energy-related activities carried out by the Department of Energy's Office of Nuclear Energy. As part of these responsibilities, Mr. McGinnis serves as Steering Group Chairman of the International Framework for Nuclear Energy Cooperation that consists of approximately 50 participating countries and serves as the Departmental Representative to the U.S. Trade and Promotion Coordination Committee on civil nuclear energy matters. Within the Office of Nuclear Energy, Mr. McGinnis has also served as a Vice Chairman and Principal U.S. Representative to the Generation IV International Forum, and was responsible for U.S. domestic nuclear fuel assurance matters, including technical oversight activities regarding the United States Enrichment Corporation, uranium inventory management matters, as well as U.S. nuclear energy security matters.

Joseph F. Pilat is a Program Manager in the National Security Office of the Los Alamos National Laboratory and a Senior Scholar at the Woodrow Wilson International Center for Scholars where he co-directs the Nonproliferation Forum. He served as Representative of the Secretary of Defense to the Fourth Review Conference of the Nuclear Non-Proliferation Treaty (NPT), and as an adviser to the U.S. Delegation at the 1995 NPT Review and Extension Conference. Dr. Pilat also served as representative of the Secretary of Defense to the Open Skies negotiations. He has held positions in the Pentagon and the Congressional Research Service, and has taught at Cornell University, Georgetown University, and the College of William and Mary. He is the editor of *Atoms for Peace: A Future after Fifty Years?* (2007).

Daniel B. Poneman has served as Deputy Secretary of Energy since May 2009. Mr. Poneman first joined the Department of Energy in 1989 as a White House Fellow. The next year he joined the National Security Council staff as Director of Defense Policy and Arms Control. From 1993 to 1996, Mr. Poneman served as Special Assistant to the President and Senior Director for Nonproliferation and Export Controls at the National Security Council. His responsibilities included the development and implementation of U.S. policy in such areas as peaceful nuclear cooperation, missile technology, space-launch activities, sanctions determinations, chemical and biological arms control efforts, and conventional arms transfer policy. During this time, he also participated in negotiations and consultations with governments in Africa, Asia, Europe, Latin America, and the former Soviet Union. Prior to assuming his responsibilities as Deputy Secretary, Mr. Poneman served as a principal of The Scowcroft Group for 8 years, providing strategic advice to corporations on a wide variety of international projects and transactions. Between tours of government service he practiced law for 9 years in Washington, DC—first as an associate at Covington & Burling, later as a partner at Hogan & Hartson—assisting clients in regulatory, policy and transactional matters, international arbitration, commercial real estate financing, export controls, and sanctions and trade policy. Mr. Poneman received A.B. and J.D. degrees with honors from Harvard University and an M.Litt. in Politics from Oxford University. He has published widely on national security issues and is the author of *Nuclear Power in the Developing World* and *Argentina: Democracy on Trial.*

Richard J. K. Stratford is the Director of the Office of Nuclear Energy, Safety & Security in the Bureau of International Security and Nonproliferation. He is responsible for the diplomatic aspects of international nuclear energy affairs, nuclear export control policies, nuclear cooperation agreements, nuclear safety, physical protection, and international initiatives in nuclear energy technology. Mr. Stratford is a frequent U.S. delegate to the General Conference of the International Atomic Energy Agency (IAEA), where he has represented the United States in the IAEA's Committee of the Whole. He chaired the Committee in 1997 and 2005. In April 2006, Mr. Stratford was elected to be the Chairman of the Steering Committee of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency in Paris, a position he continues to hold. Mr. Stratford is the U.S. Head of Delegation to the Nuclear Suppliers Group (NSG) and to the NPT Exporters Committee (Zangger Committee). He was the chief negotiator of the "123" nuclear cooperation agreements with Russia and India, as well as the U.S./India reprocessing agreement completed in 2010. Mr. Stratford was the 2010 recipient of the Henry DeWolf Smyth Nuclear Statesman Award, presented jointly by the American Nuclear Society and the Nuclear Energy Institute. He is a career member of the Senior Executive Service.

William Tobey was most recently 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 counter-proliferation positions. He has participated in international negotiations ranging from the START talks with the Soviet Union, to the Six Party Talks with North Korea. He also has extensive experience in investment banking and venture capital.

Christopher Way is an Associate Professor of Government at Cornell University. He teaches in both the fields of international relations and comparative politics, with his research covering both security studies and political economy. His research on the politics of macroeconomic policy has covered central bank independence, partisan theories of the macroeconomy, labor organization, and inequality in the OECD countries. Professor Way's recent research focuses on the proliferation of weapons of mass destruction, and on the non-proliferation regime. He is currently completing projects on the link between personalistic regime types and WMD proliferation, and on the origins and effectiveness of the Nuclear Non-Proliferation Treaty. He received his Ph.D. from Stanford University.

Mark Whitney is the Assistant Deputy Administrator for Nonproliferation and International Security at the Department of Energy's (DOE) National Nuclear Security Administration (NNSA). In this capacity, he is responsible for DOE's global programs on nuclear safeguards, nuclear controls, nuclear verification/transparency, and for the development of DOE-NNSA nonproliferation and arms control policy. Mr. Whitney has also served as the Executive Director of the DOE Moscow Office, where he led the Department's in-country efforts on nuclear security, nonproliferation, and energy security. Previous positions Mr. Whitney has held include: President, Global Strategies Consulting; Senior International Program Manager, Science Applications International Corporation; and Director of Russian Programs, Institute for International Cooperative Environmental Research – Florida State University.