Report of the International Workshop on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS)

March 29–30, 2000

Sponsored by
the Nuclear Energy Research Advisory Committee (NERAC)
and the Center for Global Security Research (CGSR)
at Lawrence Livermore National Laboratory

Contents

Summary of TOPS International Workshop

Purpose

The Office of Nuclear Energy, Science, and Technology (NE) has established a task force under the Nuclear Energy Research Advisory Committee (NERAC) to identify near- and long-term technical opportunities to further increase the proliferation resistance of global nuclear power systems (TOPS) and to recommend specific research areas. The TOPS Task Force (Appendix A) was asked to call upon experts and hold, as needed, a series of workshops to analyze technologies and research issues. Accordingly, a TOPS International Workshop was held on March 29–30, 2000 in Washington, D.C. to help identify the:

- Key factors or attributes to evaluate technology R&D opportunities,
- Most important opportunities for relevant near- and long-term research, and
- Areas where international collaboration can be most productive.

This report contains the results of that workshop.

Terms of Reference

Since successful proliferation resistance has been, and will continue to be, an international endeavor, the workshop included experts from nations around the world experienced in the deployment of nuclear power. The workshop was convened under the following terms of reference.

Nuclear power continues to be a major factor in producing abundant and affordable energy in many parts of the world. The choice of nuclear power systems leading to acceptable growth in nuclear power among many countries must take into account a number of factors including economic competitiveness, acceptable safety standards, acceptable waste-disposal options, and acceptable risks of proliferation of nuclear weapons from such nuclear power systems. This workshop addressed primarily the last of these criteria and helped identify the research and development (R&D) directions that should be taken to support that objective. The development and application of new technology that increases the barriers to proliferation, and a clear and compelling rationale for its deployment, could contribute to international security.

Technology can contribute to the proliferation resistance of current and future nuclear power by:

- Reducing the attractiveness, and/or quantity of materials usable for nuclear weapons,
- Decreasing the potential for misuse of facilities, technologies, knowledge, and infrastructures, and
- Enhancing the capabilities of the international system of safeguards and inspection.

The technologies considered included improvements for existing reactors and fuel-cycle facilities, as well as new reactor designs, new fuel cycles, and storage and disposition facilities. Institutional improvements require technologies that can enhance the effectiveness of institutional controls rather than simply revising institutional arrangements. The expected application times of the results of the recommended R&D were grouped into two time frames: within the next decade and within the following two decades.

Format of the Workshop

The workshop agenda (Appendix B) consisted of two parts:

> (1) A plenary session was held in which overall perspectives were given by DOE officials, U.S. State Department and International Atomic Energy Agency representatives, and U.S. experts involved in proliferation-resistance work. A special address on the security aspects of advanced information technology was given (Appendix C), and

(2) Four working groups were established to focus on individual review areas and were asked to answer specific questions leading to the identification of appropriate R&D that should be pursued. The working groups and their focus areas are given below. The questions posed to them are listed in Appendix D. The working group participants are listed in Appendix E.

Working Group 1: Intrinsic barriers to proliferation (material and technical)
Chair: Tom Isaacs, Lawrence Livermore National Laboratory
Working Group 2: Extrinsic barriers to proliferation (safeguards, security, MPC&A)
Chair: Myron Kratzer, Consultant
Working Group 3: Economics, safety, environmental, and other factors that may be affected by proliferation-resistant approaches
Chair: George Davis, ABB-CE
Working Group 4: Evaluation methodologies applied to proposed systems
Chair: Wolfgang Panofsky, Stanford University

Summary of Results

The workshop produced a rich set of results that will provide essential input to the TOPS Task Force effort. Although the participants differed on some issues, the unanimity of opinion on many matters was most encouraging and greater than expected. The contribution of the international participants was key.

Overall, it was concluded that comparative proliferation-resistant assessments, primarily qualitative, can define potentially fruitful R&D. A systems approach was recommended to identify R&D that meets strategic, institutional goals. Recognizing that there are no proliferation-proof systems, the results of the assessment of intrinsic proliferation attributes should be considered as input to establishing the needs for improving extrinsic or institutional measures. A substantial agenda of R&D needs, given below, calls for a major increase in U.S. and international efforts on proliferation resistance in the context of a strong initiative on the strategic development of nuclear power for the future.

Assessment Methodology

The need for an assessment methodology as a necessary—although not sufficient—means of addressing proliferation in global civilian nuclear energy systems was strongly endorsed. Much additional work is recommended to further the development of this methodology: all of the working groups made constructive suggestions for improvement in the content as well as in the conceptual approach. Among these are the needs to:

- Better integrate intrinsic barriers with extrinsic barriers where the intrinsic barriers and their postulated threats establish the requirements for the extrinsic barriers;
- Reflect continuing changes with time in systems, barriers, and threats; and
- Maintain awareness of the potential effects of societal and political issues.

Although the methodology is not presently suitable for quantification, work in that direction is recommended for the longer term. A systems approach is favored, with the scope of evaluation both narrow and broad: narrow to characterize the barriers or threats in appropriate detail and broad to encompass global strategic goals for proliferation resistance. A generally acceptable methodology is difficult to develop because both quantitative and qualitative factors contribute to proliferation resistance. In addition, some factors are inherent to the particular fuel cycle and others are external, that is, institutional, in nature. While diversion and theft are indeed proliferation threats, we cannot rely on history in quantifying these risks. Rather, evaluation methodologies have to be based on conceptual assessments of risks, costs, and benefits.

R&D is recommended to address these and related issues so as to develop an objective and dependable methodology for the assessment of proliferation resistance. Among these R&D needs are:

- R&D designed to fill in the elements in the matrices that serve to characterize the proliferation-resistant barriers and the threats to them.
- R&D designed to evaluate the practicality of a fault-tree approach to quantitatively describe proliferation resistance.
- R&D designed to identify means to encourage motivation for incorporating proliferation resistance as a major objective in the choice of reactor technologies and fuel cycles.

International collaboration in this R&D is essential because the methodology must be applicable world-wide.

Institutional Measures

It was emphasized, consistent with the findings of the INFCE program, that institutional measures to address proliferation resistance are of key, if not dominant, importance. It was cited that the greatest recent progress in strengthening proliferation resistance has been in the increased ability afforded to the International Atomic Energy Agency (IAEA) to detect clandestine facilities and undeclared operations within declared facilities, including the additional legal authority provided through the “Protocol Additional” to the existing agreements covering the IAEA safeguards system. Results from a well-developed, intrinsic assessment methodology should be considered as input that defines the required institutional barriers specific to reactor and fuel-cycle systems under applicable political constraints or international standards.

The costs of implementing these institutional measures vary with specific systems. These costs will inevitably rise with new requirements and must be countered by efforts to achieve greater cost-effectiveness: not by squeezing down on requirements but by improving the methods of implementation through technology and improved management. There is a strong conviction that transparency is important in carrying out these measures—in keeping with open societies and international equity—yet a balance needs to ensure that transparency is not in itself a vehicle to proliferation through the dissemination of sensitive technology.

R&D is needed in the application of new, revolutionary developments in telecommunications, computers, information management, and satellite technologies to surveillance, accounting, and control measures, particularly in the early detection of clandestine and undeclared activities. Here again, international collaboration is essential.

Balancing Safety, Environment, Proliferation Resistance, and Economy

Keeping proliferation-resistance development in balance with safety, environmental impact, and economy was cited as essential. A significant problem exists in the motivation of suppliers and their customers to pay the additional costs incurred for improved intrinsic barriers. It is necessary to establish international goals and commitments to address this problem, with an appropriate level of flexibility in the manner by which the suppliers meet those goals. It is desirable to internalize—in realistic, cost-effective form—all the externalities of the civilian nuclear energy systems as well as their alternatives.

There is concern that well-intentioned emphasis on proliferation resistance will increase public opposition to nuclear power, much as the earlier emphasis on mitigating severe accidents had exacerbated public concern as to the safety of nuclear power. Over-dramatization of proliferation-resistance development should be avoided by recognizing that much of the application to civilian systems is directed at the future when the potential exists for widespread geographical use of advanced nuclear-energy systems. R&D is needed to develop semi-quantitative, and later more quantitative, methods to establish those goals, leading to insights on where more, as well as less, resistance measures would be cost-effective.

Strong, Strategically Oriented, Overall R&D Program

A strong overall R&D program was called for to improve proliferation resistance with the R&D initiatives framed to serve a global vision of nuclear energy in the future. The international credibility of the U.S. depends on a strong, sustained advanced nuclear-energy R&D program, enhanced by international R&D collaboration to ensure that the resulting technology is usable and acceptable on a global scale. R&D into the methodology designed to evaluate proliferation resistance is only a small part of the overall R&D required for the evolution of new modern reactor and fuel-cycle technologies. Research programs need to be established from the top down as well as from the bottom up to ensure focus on achieving institutional goals.

The R&D dedicated to future reactor and fuel cycle technologies sponsored by the U.S. government in general is woefully inadequate. Considering the highly competitive nature of the current deregulated energy-production environment and the long lead time required for the evolution of new nuclear-reactor and fuel-cycle technologies, the private sector cannot be expected to adequately finance such R&D.

The key specific R&D programs recommended are:

- Improving intrinsic barriers in the context of advanced reactor system R&D, through—
    - high-burnup fuels, including thorium and uranium,
    - non-fertile fuels,
    - regional spent-fuel repositories,
    - closed fuel cycles, and
    - human factors.

- Strengthening extrinsic barriers, through technologies that—
    - enhance MPC&A capabilities and the implementation of existing institutional measures, and
    - provide a dependable proliferation-assessment methodology integrating both intrinsic and xtrinsic barriers and the threats to them.

A minority in the workshop did not agree with all aspects of these overall R&D recommendations, particularly in pursuing improved proliferation-resistance R&D in the framework of a strategic, global nuclear-energy vision. There was unanimity, however, in support of R&D goals to reduce, make inaccessible, and make less attractive weapons-usable materials from civilian nuclear energy activities, with minimum opportunities for diversion.

Working Group 1 Report: Intrinsic Barriers to Proliferation

Summary

We believe several critical areas should be considered in the integration of intrinsic proliferation barriers into present and future-generation nuclear reactors and fuel cycles. These areas include developing and using appropriately assessment methodologies; structuring R&D around major technical themes and time frames; and increasing international collaboration focused on R&D needs in the technical theme areas.

In the near term, efforts should be undertaken to improve and, where practicable, standardize the proliferation assessment of different reactors and fuel-cycle approaches for planning future R&D programs. Assessment methodologies should also be multi-attribute and contextual in nature to be useful and relevant. These methodologies should not be considered to yield definitive, quantitative assessments; rather, they should provide a useful means of assessment during peer-review processes. However, a quantitative method is needed by which reactor designers can evaluate the relative proliferation worth of various fuels and materials to balance R&D costs with benefits.

To properly focus R&D resources, well-defined R&D themes and associated time frames should be promulgated. Suggested themes include (1) reduce the quantity of weapons-usable material; (2) make weapons-usable material highly inaccessible; (3) reduce materials attractiveness; and (4) design facilities to minimize opportunities for diversion and increase transparency. To balance the needs of present and future generations, it is suggested that R&D be focused on the theme categories within 3 suggested time frames: Short-term (0–5 years); intermediate-term (6–15 years); and long-term (16+ years).

In pursuing R&D aligned with the suggested theme areas and time frames, it is scientifically and fiscally advantageous to expand the present level of international collaboration. This will facilitate the exchanging of ideas, the sharing of scarce financial and physical resources, the building of international consensus, and the enhancing of the U.S.' leadership in nuclear sciences.

Further, techniques should be explored that might enable the recycling of nuclear materials under circumstances where this would lead to enhanced international security. Similarly, both fast- and thermal-spectrum reactor concepts and advanced fuels should be considered as possibly important contributors to the next-generation, proliferation-resistant nuclear power systems. It is felt that the viability and effectiveness of the pursuit of these approaches will depend on a very significant increase in R&D resources and on following a well-structured, systems-oriented approach designed to achieve specific objectives.

Introduction

Working Group 1 (WG-1) was tasked with addressing intrinsic barriers to proliferation. The working group was given a set of questions to help focus discussion:

1. What are the key intrinsic proliferation barriers in civilian nuclear systems? Are the barriers and the threats to them adequately defined in the "Attributes" document[1]? How does the effectiveness of the barriers differ from the kind of potentially proliferant state or sub-national group and its specific objectives?

2. What are the technology opportunity areas to increase the effectiveness of these barriers? For example, what R&D might lead to greater proliferation-resistant designs in Pu recycling? What R&D would be fruitful in the transmutation technologies? Are there any R&D initiatives from the INFCE studies that might be pursued?

3. What specific R&D programs within these areas should be initiated now to take advantage of these opportunities for application either in the near or the long term? Which of these programs would be enhanced by international cooperation in implementing the R&D?

4. What priorities should be assigned to these selections and in what time frame should the results apply?

The discussion of WG-1 spanned a broad range of topics including the assessment approach (which should be taken in analyzing proliferation threats and proliferation-resistant features), the necessity and focus of international collaboration, themes for future R&D, and several additional topics. This report summarizes the major areas of discussion and presents the recommendations of WG-1. There was lively discussion and a variety of views on most of the subjects presented here. However, in the end, there was generally a high level of consensus on the conclusions.

Assessment of Attributes and Technology Needs

Reference 1 presents a candidate assessment approach by which we could mechanistically assess the threats posed to the various elements of the nuclear fuel cycle and rate the effectiveness of mitigating approaches. WG-1 spent considerable time discussing the potential utility, relevance, and inherent difficulty of creating a mechanistic, tabular assessment tool, such as a discrete table of threats vs. barriers.

WG-1 concluded that using the proposed tabular approach with minor modifications is useful not as a definitive, quantitative assessment of a proliferation barrier or approach, but rather as a qualitative tool for more rigorous assessments and peer-review processes. The group members recognize that the effectiveness of a barrier depends strongly on the interaction of many variables including the sophistication of a proliferator, material in question, context in which the facilities are used, and more. It was felt that it would be impossible to obtain a meaningful, quantitative metric or judgment by considering single technologies. Compounding this difficulty is the fact that the effectiveness of a given barrier changes with time. Only through consideration of the total context, including political and institutional concerns, can we obtain a balanced assessment. Therefore, it is suggested that the technical community explore the development of a multi-attribute, quantitative assessment methodology as R&D programs evolve and use the proposed tabular approach as a qualitative assessment tool for limited applications.

Obviously, a major consideration in assessing the proliferation resistance of a given fuel cycle is what type of nuclear materials is present and in what quantities. Reference 1 contains a list of fissile isotopes that could potentially be used in a weapon. WG-1 recognizes that all fissile isotopes are of concern and require attention. However, it is also recognized that the proliferation worth or potential of the various isotopes is

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[1] Draft Paper, *Attributes of Proliferation Resistance for Civilian Nuclear Power Systems*, NERAC Task Force on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems, Draft 1.06, March 22, 2000 (included as Appendix E).

not equivalent on a per-gram basis. Because of this, WG-1 felt that the reactor designer should have a means to develop a quantitative assessment of the proliferation worth of various fuels and materials in order to balance R&D cost with benefit. Such an assessment tool should take into account not only the mass of material necessary for weapons, but also inherent physical characteristics that may make it less attractive, e.g. high radiation field, etc. As with the overall assessment (discussed above), the assessment of material worth should take a multi-attribute systems approach. Any quantitative scale that is developed should remain unclassified to increase its benefit to the reactor-design community and facilitate international understanding and cooperation. It was recognized that security and classification considerations make full disclosure of the relevant technical information problematic.

As with materials, WG-1 recommends that facilities should also be evaluated for proliferation resistance in context of their use and function in the overall fuel cycle. Additionally, how a facility is designed with respect to safeguards should be an important attribute in assessing proliferation risks. WG-1 suggests that future fuel-cycle facilities be designed to maximize inherent transparency of processes contained in the facilities. It is recognized that by designing processes and operations to be more observable (e.g., through remote sensing, environmental sampling, etc.), the potential for undetected proliferation is reduced.

In general, WG-1 felt that the list of threats summarized in Reference 1 was reasonably complete. However, we suggest that treaty abrogation be included as part of the threat profile. WG-1 concluded that, upon treaty abrogation by a proliferant state, the process of safeguards ends (successfully) and arms control and security considerations take over.

Research and Development Themes

In addition to identifying requirements for assessment tools, WG-1 focused much discussion on what specific technology areas should be pursued to further the design, development, and deployment of proliferation-resistant reactors and fuel cycles. WG-1 suggests R&D projects be defined and funded under major “theme categories.” WG-1 suggests that advanced concepts should be sought that advance the following goals:

- Reduce quantities of weapons-usable material,
- Make weapons-usable material highly inaccessible,
- Reduce materials attractiveness, and
- Design facilities to minimize opportunities for diversion and increase transparency.

In considering projects that address these broad issues, WG-1 strongly encourages the DOE to actively consider all possible options, including the development of advanced closed-fuel cycles. It is felt that the pursuit of advanced fuel-cycle options will advance the state of the art in proliferation-resistant technologies and allow the United States to collaborate more constructively with other countries.

Perhaps most importantly, the relative proliferation resistance of possible future *individual* fuel-cycle facilities may not mirror the most effective R&D agenda for achieving the overall goals outlined above. Facilities that could form elements of an integrated systems approach to minimizing proliferation and national security concerns may merit high R&D priority. This may not be apparent if only the proliferation resistance of individual facilities is considered.

Establishing appropriate and realistic time frames for R&D was considered very important by WG-1. Although we feel that a commitment to the longer-term development and deployment of advanced fuel cycles is critical, near-term needs should not be ignored. WG-1 suggests that R&D programs be established with three distinct time frames in terms of completion of R&D and implementation of the technologies:

- **Short term, 0–5 years.** Projects and programs in this time frame should focus on areas such as improving material protection, control, and accountability (MPC&A), operations "best practices," advanced instrumentation, etc. Development of incrementally higher burnup fuel, including supporting transient testing and fabrication infrastructure, could also be feasible in the short term. These projects and programs should be focused on solving problems existing with existing systems or infrastructure. Maintenance of a national infrastructure necessary to advance short-, intermediate-, and long-term R&D should be considered immediately.
- **Intermediate term, 6–15 years.** Projects and programs in this time frame should focus on enhancing current LWR fuel cycles through the use of high-burnup, non-fertile fuels or other major modifications including the use of uranium–thorium fuels. Dual-use (safeguards and efficient operations) advanced monitoring and analysis systems are feasible in this time frame.
- **Long term, 16+ years.** Projects and programs in this time frame should focus on research, development, and testing of advanced systems and concepts. These efforts should consider advanced light-water reactors, liquid-metal reactors, liquid-fuel reactors, and gas-cooled reactors. Reactor concepts that do not require refueling (10–15-year core life) should be investigated in context with sizes desirable for various nations and circumstances. Closed-fuel cycle options should be investigated.

Note that there may be a high level of synergy between activities in each of the three time frames. For example, advanced sensor technologies and MPC&A techniques developed for the short term should be incorporated into advanced system designs. There may also be benefit from technologies presently being advanced by needs in other industries. Such technologies include advanced information systems, robotics, and micro-sensors. Therefore, relevant state-of-the-art technology from both nuclear and non-nuclear industries should be assessed.

The issue of establishing appropriate funding mechanisms was considered. The consensus among members of WG-1 is that the present Nuclear Energy Research Initiative's (NERI) peer-review approach at establishing nuclear R&D projects is useful and could be more so if funded at a much higher level. However, it was felt that to gain significant industrial-scale advances in proliferation-resistant technology, a directed, top-down R&D program must be established with well-defined goals. WG-1 strongly suggests that such a directed R&D program be established to complement and enhance the benefits gained through the NERI program, and that such a program focus on the theme categories and time frames presented here.

International Collaborations

International collaboration in R&D is particularly important in this area of technology as a method of generating international consensus on proliferation-resistant technologies and strengthening U.S. leadership and credibility in these areas. A technology that is not accepted world-wide cannot strengthen the nonproliferation regime. International collaborations have been important aspects of successful R&D programs for many years. In nuclear energy research, collaborative projects involving scientists from North America, South America, Europe, and Asia already exist and are productive. As R&D costs continue to rise and the availability of nuclear research facilities becomes more restricted, international collaboration becomes an increasingly important means of leveraging resources and accessing unique research operations, thus reducing cost and increasing opportunity.

WG-1 suggests that collaborative R&D between international partners—focusing on the theme categories defined above—be expanded. Near-term prospects for increased collaboration include R&D related to high-burnup fuels, Th/U fuels, non-fertile fuels, and advanced fuel-cycle concepts. WG-1 also suggests that special effort be taken to strengthen technical collaborations with the IAEA.

Additional Points

The successful development and deployment of proliferation-resistant reactors and fuel cycles will not only require well-focused technical projects, but will also require collaboration in many areas with more of an institutional approach. For example, several concepts related to the international management of spent nuclear fuels are basically institutional in nature. WG-1 suggests that this and other institutional issues be considered.

The members of WG-1 discussed several issues on which there was no consensus among the group members. Among these is the question of whether or not future nuclear facilities should have universal potential siting, or whether there should be two different sets of facilities (one for developed countries and another set for developing nations). A suggestion was made to develop two separate types of plants: one for export and one for domestic use. This was thought to be problematic by some members of WG-1. WG-1 felt that the resolution of this type of issue would be an important factor in defining the focus of future R&D and suggests that it be addressed. Also, WG-1 suggests fuller consideration be given to technology transfer issues in general.

Working Group 2 Report: Extrinsic Barriers to Proliferation

Working Group Tasks

The expected products of the workshop are the identification of:

- A set of the most important factors or attributes to evaluate proliferation-resistant technology R&D opportunities,
- The most important opportunities for near- and long-term research, and
- Areas where international collaboration can be most productive.

The working group was given a set of questions to help provide a focus for discussion in the group. The questions were:

1) Is the definition affected by proliferation-resistant approaches adequate?

2) What technological opportunities would be most effective in (a) enhancing the extrinsic barriers to proliferation resistance, and (b) making it easier to effectively administer international safeguards? For example, what information technology applications could enhance monitoring capability? What advanced sensor/telemetry, et al., technologies could increase the capability to detect proliferation threats in a timely way?

3) What specific internationally cooperative R&D programs should be initiated or accelerated that would have the best potential to help the nonproliferation regime and its international safeguards system meet new challenges associated with a geographical spread and an increase in the number of facilities?

The Non-Proliferation Regime

To answer the question regarding important factors or attributes, the group spent some time defining various aspects of proliferation resistance and obtaining group consensus on definitions of the terms used in handout materials as well as in treaties and national safeguards regulations. The following list identifies the various technological and institutional attributes of that define current proliferation resistant efforts.

- Safeguards (those extrinsic technological and related institutional barriers that discourage a state from diverting weapons material),
- MPC&A (the technological and related institutional barriers that discourage theft or seizure of material from a facility by a subnational group, terrorist, or thief),
- Treaty obligation (NPT and other existing and emerging treaties; Fissionable Material Cut-off Treaty),
- Multi-lateral obligations,
- Bilateral obligations,
- Export control and supplier constraints,
- National policy and legislation,
- Societal openness and transparency,
- Intelligence,
- Nonproliferation ethic (most countries and their societies now are not interested in or oppose obtaining nuclear weapons, a change from the basic assumption 40 years ago),
- Sanctions and penalties (imposed by nations or international organizations).

The group agreed that the basic safeguards objectives are verification, deterrence, and detection. Safeguards should be looked upon as the means of sounding the alarm, not preventing diversion. It is recognized that a very substantial reporting requirement goes along with having an effective safeguards program, but that information provided by states on their own nuclear programs cannot be assumed to be correct or complete.

From this, the group was able to develop a list of the major attributes for an effective safeguards system:

- Availability and access to all relevant information
- Effective information analysis (proper identification of credible threats and then analysis of the particular facility where the safeguards are in place to determine if the safeguards protect against those threats)
- Completeness of coverage (Safeguards must provide a significant probability of detection of all credible/plausible diversion scenarios. Measuring completeness is a challenge.)
- Timeliness of detection
- Material accountability with high-quality measurements
- Reliable containment and surveillance where feasible
- Design review and verification (an important measure to be considered is how well the measures in place work)
- Detection and confirmation of undeclared activities
- Competent staff (while instrumentation has an important role in safeguards, there is no substitute for a significant involvement of human inspectors)
- Effective training and motivation
- Reliable/effective Nondestructive analysis and other equipment
- Adequate funding

Funding was identified as an important attribute because an effective safeguards program consists of a blend of detection systems capable of identifying nuances in the operations and an intelligent, motivated staff capable of observing, interpreting, and understanding the information provided. Neither is possible without adequate funding. The longstanding policy, shared by the U.S., of “zero real-growth” funding of safeguards should be abandoned.

Technical Opportunities for Safeguards

The development of safeguards technology has been greatly advanced by an active program of voluntary support by key IAEA member states. This program must be continued, and to the extent feasible, strengthened. There remains, however, areas of technical promise unlikely to be covered by the formal assistance program.

Throughout the 2-day workshop, such areas of opportunities for near- and long-term development and applications were identified. As a group, it was recognized that safeguards are not taking full advantage of cutting-edge information technology being developed for e-commerce or the safety, security, and safeguards systems being developed by this information technology industry. It was also noted that the federal institutions are not “mining” the weapons complex for technology that could be made available for wider application in safeguards and MPC&A. The areas of research opportunities identified are:

Information Technology

- Integration of sensors and data-monitoring systems in a facility's monitoring sensors.
- Systems that provide real-time video and measurements and store information, i.e., remote monitoring. System requirements include high-fidelity, real-time, high-integrity data transmissions. It is necessary to include measurements on the data streams to ensure no tampering is done to the system. It should continually monitor data and do intelligent decision making and "phone home" when a problem occurs. Continuous transmittal or acquisition and analysis of data is not necessary.
- Technologies that conduct quicker, smarter, and faster analysis of information gathered from monitoring systems.
- An information-rich management center that integrates information analysis, data mining, and computer networking.
- Methods to improve authenticating source data.
- Instrumentation that works in more universal applications. There is a need for simplicity and common safeguards inspection instrumentation to be applied in a variety of installations. The use of common safeguard systems rather than site-specific instrumentation should be encouraged to the fullest extent feasible.

System Studies

- Research in safeguards approaches that have a much more open architecture.
- Studies linking economies of scale to proliferation barrier enhancement. If some technologies are best performed at large facilities, then this could limit smaller, similar facilities within a single state. Most technologies have an economy of scale.
- Identification of information technologies, information protection, and reliability commonalties so that data management systems can be integrated.
- Human factors studies for improving information presentations and other aspects requiring human judgment. The final purpose of all information is to allow human decision making on compliance with safeguards and nonproliferation obligations.
- A series of simulated attack and analysis exercises. Results of the analysis and information learned can then be fed back into facility design to improve proliferation and identify MPC&A weaknesses.
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Wide-Area Environmental Monitoring

Wide-area monitoring can be among the most powerful safeguards tools for ensuring the absence of undeclared activities, but assessment is needed of the effectiveness of this measure in detecting such activities.

Enhanced Material-Tagging Measures

- Detecting HEU from enrichment plants.
- Tagging MOX fuel assemblies.
- Adding tracers in material to know its location without interfering with established plant operations, then "give that technology away."
- Developing technologies that remotely confirm a spent-fuel assembly is still where it is being stored and is intact. A major problem is number of existing assemblies and the operational implications. This has long-term proliferation implications.

Application of PRA methodology

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- Make the monitoring capability more robust. Concerns arise when institutions or extrinsic organization-monitoring capabilities break down.
- Develop risk-assessment capabilities to identify high-risk and high-probability proliferation pathways or redundancies in detection.

Improved, lower cost surveillance

Improved international/regional safeguards interaction

- Research to determine the most effective report avenues for violations/questions. There may be advantages for facility information to report into a multinational center. Advantages to trustworthiness. Everyone would have access to critical data.

One member of the group proposed that the group recommend the adoption of legally binding international prohibitions of sensitive fuel-cycle activities, such as reprocessing and enrichment to greater than 20% ^{235}U. The group concluded that such a recommendation is outside the chartered scope and tasks and took no position on the proposal's merits.

MPC&A Attributes

The working group developed the following major attributes for MPC&A listed in relative order of priority:

- Adequacy of administrative steps necessary to obtain access.
- Ability either to repel attack or delay intruders until offsite forces arrive on site to prevent theft or affect public health and safety.
- Ability to detect and prevent illicit insider activities.

Technical Opportunities for MPC&A

The areas of research opportunities identified are:

- Optimize human automation interface balance. Evaluation of technology available in defense programs that may be applicable and available.
- Attack simulation/analysis to feed back into design. Improve threat definition and analysis for optimization of protective measures.

Working Group 3 Report: Economics, Safety, Environmental, and Other Factors That May Be Affected By Proliferation-Resistant Approaches

Overview

Working Group 3 (WG-3) addressed the need to balance the proliferation resistance of future nuclear plants (including their fuel cycles) against the many other factors that must be considered when new nuclear plants are being sold around the world. Specifically, WG-3 was tasked to address the following questions:

(1) At least five criteria are primary considerations in the selection of advanced reactor systems: strategy (general policy, future development, energy independence, technological capabilities), economics (not only direct cost estimates, but also externalities), safety, environment, and proliferation resistance. How would you prioritize these criteria to determine R&D allocations? What would your priorities be? Will prioritization differ from one country to another and with the consideration of different scenarios (e.g., near-term, existing reactor systems; long-term, new reactor systems; fuel-cycle technologies in countries with and without an established nuclear infrastructure)?

(2) How do we address both the conflicts and synergies arising from pursuit of these individual criteria? What R&D should be undertaken now that might clarify these conflicts and maximize the synergies?

(3) Which of these selected programs would be fruitful subjects for international collaborative R&D?

To address these issues, WG-3 covered each topic in a round-table discussion format and reached general consensus on the recommendations included in this report.

Before attempting to prioritize the five considerations listed in the first question, the group first discussed the considerations, regrouped them, and then expanded on the list. It was quickly agreed that economics will, by far, be the number-one consideration in future decisions to build new nuclear plants—throughout the global marketplace. We noted that economic considerations not only include the cost of generating electricity (capital investment, operation, maintenance, and fuel), but also the consideration of risks that could affect the investment as well.

WG-3 agreed that considerations related to safety, the environment, and proliferation resistance could be grouped under a more general heading, “Public Acceptance Factors.” We avoided referring to these issues as “externalities” because many of them are considered in the decision to build nuclear plants, even if they are not internalized for other power-generation technologies. It was also agreed that the term “regulatory framework” should be added as an additional consideration under Public Acceptance Factors because safety and regulatory requirements do not always match up. Although not specifically prioritized within this overall group, we deemed the Public Acceptance Factors to be secondary to economics. It was also felt that proliferation resistance would probably be viewed as being at the bottom of the list, in terms of relative importance, by potential plant buyers. In addition, it was also noted that these Public Acceptance Factors are usually converted to economic factors and serve as input to the economic considerations in the selection of advanced reactor systems.

Also secondary to the economics criterion was the consideration of national strategy, which concerns general government policy, future national development, energy independence, and development of technological capabilities within a nation. This criterion, unlike the others, was felt by WG-3 to be much more country-dependent and based on the relationship between a particular plant buyer (e.g., a utility) and its government. For example, in a fully deregulated electric power market, national strategy might have a relatively small impact on the decision to build a new nuclear plant, compared to the economic and public acceptance factors. On the other hand, in a developing nation with few domestic energy sources and a state-owned utility, the national strategy factors could lead to the purchase of a nuclear energy plant, even if the economics were not quite as attractive as other energy options.

The group discussed how the above considerations might be prioritized. It became apparent there were two major impediments to preparing a detailed prioritization: (1) the substantial variation that occurs from one country to another in comparing nuclear energy plants to other energy alternatives, and (2) the lack of a quantitative tool for converting the criteria to a uniform metric for comparing proliferation resistance to economic factors (i.e., we are trying to compare apples and oranges). The latter point led to the first R&D recommendation of the group: the need for risk-analysis methodologies to quantify proliferation risks and the need for metrics to be used in cost–benefit analyses (as is now commonly performed for decision making on safety issues).

WG-3 then turned its attention toward identifying any factors that should be considered in evaluating potential R&D opportunities for improving the proliferation resistance of future nuclear energy plants.

Factors in Evaluating Technology R&D Opportunities

WG-3 spent considerable time identifying a set of the most important qualifying factors or attributes that should be considered in evaluating technology R&D opportunities for improving proliferation resistance—from the perspective of balancing proliferation resistance against the areas of economics, public acceptance factors, and national strategy. These are listed below, in no particular order.

- **Economic competitiveness of advanced reactor designs is a must**. In the overwhelming majority of situations, a potential plant buyer (be it government-owned or not) is looking for the least expensive, electricity-generating option available. With the electric power industry deregulating on a global scale, competitive market forces are pushing economic considerations to the top of the priority list. Within government constraints (policy or regulation), most or all other considerations are reduced to calculation of costs and risks on those costs.

- **Lack of competitiveness is the primary impediment to the future of nuclear energy.** Not only is economic competitiveness the most important criterion for selecting future electricity-generation options around the world, but it is probably the criterion most out of sync with what future buyers need to consider for the nuclear option. For example, it is generally agreed that the capital cost for future nuclear plants must be reduced by at least 35 percent from the estimates for the latest generation of nuclear plant designs, if nuclear energy is to be considered a viable alternative in the large, developed nations (e.g., the U.S. and Europe). It was noted that, even if nuclear energy is economically competitive in selected regions of the world, the long-term viability of nuclear energy as a global energy option is likely to depend upon it becoming a competitive new-plant alternative in the large, developed nations.

- **All externalities should be converted to economic factors.** Because economic competitiveness has become the primary consideration of future plant buyers, it is increasingly important that all other considerations (e.g., safety, environmental impact, proliferation resistance, etc.) be converted to a common "currency" that allows quantitative comparisons among energy options. For example, a common currency is needed to evaluate the desirability of a proliferation-resistance feature that will result in added costs, reduced safety, and/or increased environmental impact. Otherwise, how could such a decision be made objectively?

- **Proliferation-resistance concerns depend on whether they are being viewed by the buyer or seller. Proliferation resistance is primarily a seller's issue.** Although the issue is not black and white, it must be acknowledged that the buyer of a nuclear plant is not generally concerned that it (the nation or company buying the plant) will become a proliferation threat. However, it should also be acknowledged that some nations might consider the example they are setting for others, and, therefore, will give some consideration to the proliferation risk of a plant design. On the other hand, the developing nations most likely to be considered proliferation risks by the global community are not likely to be willing to pay more for a nuclear plant design with improved proliferation resistance. They will want the least expensive designs. Thus, some of the large, developed nations not likely to be considered proliferation risks may be willing to pay a small premium for improved proliferation resistance (only if the government's national strategy requires it or provides incentives), but the smaller, developing nations will not.

  On the other hand, the sellers of nuclear plants are concerned about proliferation issues. Even here, it is important to distinguish between the exporting company and its government. The company exporting the nuclear plant has little or no incentive to improve proliferation resistance because it will normally be competing against companies from other nations that may not have an equal standard of proliferation resistance. Ultimately, the company must focus on minimizing costs to be competitive. Thus, *the incentive to promote improved proliferation resistance falls upon the governments of the exporting nations because they have the most concern about the issue*.

- **An international consensus on proliferation-resistance standards among sellers is needed to prevent buyers from going to "cheaper" sellers with less proliferation resistance.** There is little benefit from developing more proliferation-resistant designs if competing sellers from other countries are allowed to offer designs that are less expensive because they do not include an equivalent level of proliferation resistance. Buyers would likely favor the less expensive design. Therefore, it would be more productive for the supplier nations to agree upon an international standard for proliferation resistance in future plants. An organization such as the international Nuclear Suppliers Group is the logical forum for agreeing to that standard; however, it also makes sense to receive input from all potential users of nuclear energy plants (including the potential buyers) through an organization such as the IAEA. Of course, it should be recognized that the international organizations could conclude that existing proliferation-resistance standards are adequate and that changes are not required. In such a case, future plant suppliers would be reluctant to add proliferation-resistance features that add to costs because this would place them at a disadvantage economically.

- **Any proliferation resistance-induced changes must not add significantly to nuclear plant costs, including fuel-cycle costs.** As noted earlier, substantial cost reductions are needed for future nuclear plants to be economically competitive in the global marketplace. It will require extraordinary efforts to achieve these cost reductions. Therefore, the addition of any proliferation-resistance features that significantly add to costs is likely to kill any chance of restoring the nuclear option. This is not to say that very small cost additions for proliferation resistance cannot be tolerated. In fact, most of the proliferation resistance features currently being deployed have a very small effect on plant costs. Stated another way, *our recommendation is that the highest priority for selecting R&D projects should go to those proliferation-resistance features that also reduce costs or are neutral to costs. Lowest priority should go to R&D projects that will significantly add to plant or fuel-cycle costs.*

- **A single standard for proliferation resistance is needed; however, varying approaches for achieving the standard should be allowed.** WG-3 discussed whether it is reasonable to expect that the large, developed nations could purchase nuclear plants that meet one proliferation resistance standard while the small, developing nations could be *required* to purchase plants that meet a more stringent proliferation-resistance standard. It was quickly agreed that such a double-standard is not workable. Under current international arrangements (e.g., the NNPT), it is not likely that a plant seller could refuse to sell a plant to a small, developing nation if that nation insists it wants the same plant design that the large, developed nations are buying. At the same time, however, it was acknowledged that there should be flexibility for different nations to meet an international standard for proliferation resistance by whatever means is most practical for its particular situation.

- **Efforts to reduce generation costs (capital, O&M, fuel) for future plants may affect the level of proliferation resistance and should be monitored.** Because substantial R&D and design programs will be required to produce new nuclear plant designs that are economically competitive, we must be vigilant in assuring that the design changes do not result in plants that are actually *less* proliferation-resistant than current plants.

- **There is a need to address disposition of spent nuclear fuel in terms of international facilities.** WG-3 felt that some of the major proliferation issues are tied to the disposition of spent nuclear fuel from future plants—especially when one considers that most of the future nuclear plants may be built in smaller, developing nations. Since it is unlikely that every nation building new nuclear plants will be capable of disposing of its spent fuel domestically, then it is important to consider alternatives for international facilities that can dispose of wastes from multiple countries.

- **Review of R&D projects against all criteria (economic, etc.) should be performed periodically, and, if necessary, the approach to meeting the proliferation-resistance standard be revised.** WG-3 noted that R&D of proliferation-resistant technologies will go through various stages: brainstorming, conceptual design, detailed design, and demonstration. In the earlier stages, it is not appropriate (and often not even possible) to expect that the conceptual designs can be realistically evaluated against criteria such as economic competitiveness. On the other hand, it is important that R&D projects are halted once it becomes clear that the resulting design will be not be viable in the marketplace. Limited R&D funds would be better spent on other, more promising projects.

- **International standardization simplifies proliferation-resistance efforts.** WG-3 noted that the standardization of nuclear plant designs is of substantial benefit in reducing nuclear plant costs and simplifying safety regulations. For example, the U.S. Nuclear Regulatory Commission promulgated 10CFR52 in 1989 to provide a regulatory review-and-approval process for standardized designs. It is commonly acknowledged that standardization greatly simplifies the efforts of safety regulators in developing new standards and reviewing compliance at each nuclear plant. Likewise, international standardization of nuclear plant designs should benefit the organizations involved in monitoring compliance with proliferation-resistance standards.

- **R&D on the proliferation resistance of the fuel cycle is likely to be more cost-effective than R&D related to the proliferation resistance of the plant design.** WG-3 felt that R&D to on changing plant designs (to substantially improve proliferation resistance) would require as much as a decade to implement, and the R&D projects are likely be quite large. At the same time, there is recognition that R&D must be done to substantially reduce the capital costs of new nuclear plants. In the meantime, it is believed that most proliferation risks stem from the fuel cycle itself and that fuel-cycle cost is not a significant impediment to nuclear plant economics. Therefore, it seems logical to focus on R&D to improve the proliferation resistance of the fuel cycle (especially for near-term implementation). This was believed by the group to be the pathway for gaining the most improvement to proliferation resistance, while having the least impact on plant economics.

- **DOE (with support of the national laboratories and industry) should organize an effort with its counterparts in other nations to develop a consensus on standard quantification methods and metrics for proliferation resistance.** As noted previously, there is a need to (1) develop methodologies and metrics for measuring proliferation resistance of future nuclear plants, and (2) establish an international consensus on a single standard of proliferation resistance for future nuclear plants. It was also noted that it is up to the governments of the exporting sellers of nuclear energy plants to encourage or require that proliferation-resistance improvements be considered in the design of new plants and fuel cycles.

The group also noted that DOE's Office of Nuclear Energy is already in the midst of organizing international collaboration in potential R&D activities to develop next-generation nuclear plant designs, referred to as Generation IV. Therefore, it seems logical that DOE's Office of Nuclear Energy should expand its efforts to include the proliferation-resistance issues described here. Because much of the nonproliferation expertise resides in the national labs, their participation in planning such an international effort is essential. Because of the extreme importance of maintaining economic competitiveness, industry participation is also felt to be necessary to ensure that the nonproliferation planning results in commercially viable products.

Recommended R&D Projects

The final effort of WG-3 was to identify potential opportunities for near-term and long-term R&D activities that might assist in addressing the need to balance proliferation resistance against the other considerations of economics, public acceptance factors, and national strategy issues. Furthermore, the group was tasked to identify which of those R&D activities would be fruitful opportunities for international collaboration. The effort resulted in identifying six potential R&D activities. The group concluded that all of them are appropriate for international collaboration:

- **Development of risk-assessment methods and metrics to quantify the various features identified for proliferation resistance by Working Groups 1 and 2.** As noted in the Overview, WG-3 felt a strong need to provide some sort of quantitative means for comparing and balancing proliferation-resistance issues against the other considerations of economics, public acceptance factors, and national strategies. It was also noted that Working Groups 1 and 2 were the groups tasked with identifying specific R&D opportunities for improving proliferation resistance, and that Working Group 3 should focus upon R&D activities needed to balance proliferation resistance against other considerations. WG-3 then discussed the success that has been achieved in applying risk-assessment methodologies to quantify safety improvements and the means that it provides for converting these improvements into economic factors that can be used in cost–benefit evaluations.

  When WASH-1400 (often referred to as the Reactor Safety Study) was published in 1975, it provided a first step toward a risk-assessment methodology that has subsequently evolved into a generally accepted tool to assess and quantify the risk to the general public of systems dealing with nuclear energy in the broadest sense—ranging from nuclear energy plants to the potential Yucca Mountain Repository.

It seems that the same general methodology is applicable to assess and quantify the risk of proliferation. The application of these risk-assessment methods to the proliferation issues should focus on a broad spectrum of issues, ranging from material processing to specific component designs to personnel-related risk items. It is recognized that the uncertainties in performing such risk assessments are substantial, considering that (1) assumptions on human actions (difficult to quantify) play a major role in establishing risks, and (2) the methodologies and databases necessary to support such risk analyses need to be developed from scratch. However, it should be noted that WASH-1400 was considered a rough attempt to quantify risks at the time. In the 25 years since, risk-assessment technology has become quite sophisticated. A similar, long-term view of risk assessment for proliferation resistance may be in order.

- **Identification and quantification of proliferation-resistance attributes that are also favorable to economics**. As noted earlier, improving the economics of future nuclear energy plants is of primary importance to restoring nuclear energy's viability in the global marketplace. Therefore, there is great value in identifying and developing proliferation-resistance technologies that have a side benefit of simultaneously reducing the costs of generating electricity. For example, reducing the need for physical-protection personnel by the introduction of automated surveillance technologies would likely provide such dual benefits.

  The surveillance and physical protection of installations and sites through the use of armed guards is also typically perceived negatively by the public. Not only is this type of physical security costly, it is also viewed as a military enforced activity. Automatic nuclear-material detectors, remote-controlled cameras, or any surveillance components networked through intelligent computer systems, such as the web cameras currently in operation at the La Hague site, enhance physical security and transparency to the system, and at the same time, reduce the number of security personnel, resulting in cost savings.

- **Research on open-cycle vs. transmutation vs. recycle, while considering issues other than proliferation resistance (e.g., economics, public acceptance factors, and national strategy issues).** It has been more than 20 years since the many options involved with the nuclear fuel cycle have been comprehensively evaluated. During that time, many of the elements proposed and evaluated in past studies have been further developed and have reached varying levels of maturity through commercial use or have been discounted. New technologies have also been introduced during the ensuing years, which should now be included in the overall evaluation, since their use could significantly effect changes to the originally derived assumptions, analyses, and conclusions.

  Therefore, it is important that we take a fresh look at the various alternatives for the fuel cycles of future plants and evaluate all potential scenarios to reach an optimal configuration for future global nuclear-fuel cycles. This research should focus on possible improvements in the various fuel-cycle steps with regard to economy, energy resources, sustainability, radiotoxicity, and proliferation resistance. More specifically, it should include an evaluation of current practices, experiences, and costs involved in both the open and closed fuel cycles, an examination of recycling and other technologies that have been developed, an exploration of the effects and value of transmutation, an analysis of radioactive waste disposal options, and an analysis of the significance of enhanced proliferation resistance. Additional research may also be needed to fully establish the attributes and parameters involved with the overall aspects of the fuel cycle. As noted earlier, this re-evaluation of potential future fuel cycles would benefit greatly from quantitative methods and metrics, so that objective tradeoffs can be made between proliferation resistance, economics, public acceptance factors, and national strategies.

- **R&D on new, more proliferation-resistant and economically competitive reactor types.** This research could build on efforts already started as part of the Nuclear Energy Research Initiative (NERI) program. Among the NERI proposals selected in the first year, three were concerned with the development of new reactor types aimed at fulfilling improved proliferation-resistance objectives. These designs—among others which could be proposed—should be reviewed for compliance with, or possible incorporation of, the recommendations forwarded by the TOPS Working Groups 1 and 2. At the end of the original three-year NERI program, the most promising concepts could be selected for sustained development. The development, design, and deployment of these new reactor types will most likely require international collaboration.

- **Development of methodology for inclusion of proliferation resistance in lifecycle-cost analyses.** New analytical tools for economic evaluation of nuclear systems are being developed. These tools (for lifecycle-cost analyses) extend the traditional economic evaluation of the nuclear plant (capital, fuel, and O&M cost) to an evaluation of the entire system. This is done by adding modules representing the economic and environmental effects of: (1) fuel mining, fabrication, and disposal; (2) decommissioning and returning to green field conditions; (3) environmental effects of power production; (4) environmental effects of supporting industries; etc. Modules quantifying the societal effect, in terms of costs, should also be included. It is recommended that modules representing the economic, environmental, and social effects of proliferation-resistance measures (both internal and external) be supported and added to the existing capability. This effort would help evaluate the total impact of such measures on the entire nuclear plant system, accounting for their complete interrelation, instead of single cost considerations conducted with current methods.

- **R&D in international spent nuclear fuel disposition capabilities, including potential for commercialization.** New reactor systems will most certainly be developed and deployed by international consortia. Recipient countries may not have the will or capability to address the disposal of spent fuel within their existing infrastructures. One potential solution is for the international vendor consortium to take back the spent fuel. This solution, however, poses both technical and institutional problems.

  On the technical side, the fuel must be stored, shipped, and disposed of in a safe and proliferation-resistant manner. For example, the issue of how the spent fuel is cooled without being partitioned into small groups of assemblies, which are easier to divert, must be resolved. On the institutional side, it is necessary to look at international framework agreements where, for example, Country A can provide the repository for fuel fabricated in Country B and used in power plants designed by Countries X-Y-Z that are located in Country C. Obviously, disposition of the spent fuel would be part of the commercial enterprise; however, an international legal framework would be necessary. Such an effort would require involvement by supra-national authorities, e.g., the IAEA.

  The concept of competitive, commercial, mined geologic repositories (such as Pangea in Australia and commercial geologic repositories in China and Russia) also requires further R&D. Consideration should be given to R&D of policy issues necessary to comply with IAEA rules that might govern canisters of vitrified fission products and of spent nuclear-reactor fuel that would be approved for storage in these repositories. Also needed is the development of safeguards for the repositories themselves.

After the workshop, one of the group participants suggested that an additional R&D topic be added to the list:

- **Research to ensure economical supplies of uranium.** The once-through fuel cycle relies upon adequate supplies of uranium to keep nuclear fuel costs low. Substantial growth in the use of nuclear energy around the world could result in market forces that would substantially raise nuclear fuel costs and create a greater need for recycling or breeder reactors. Without judging whether either of these consequences is undesirable or not, the continued availability of economical sources of uranium could prove to be a desirable option in the future. Besides the obvious path of searching for increased uranium reserves and more economical mining/processing technologies, the oceans are known to hold vast (but dilute) quantities of uranium, which cannot be economically extracted today. Research to find economical extraction methods could prove useful.

Working Group 4 Report: Evaluation Methodologies Applied to Proposed Nuclear Energy Systems

Working Group 4 evaluated methodologies that could be applied to proposed nuclear fuel cycles to assess their resistance to proliferation. Specifically, the group was charged to answer the following questions:

1) What is the potential value and application of alternate options, both past and present efforts, for integrated assessment methodologies that attempt to evaluate, at least qualitatively, the intrinsic and extrinsic barriers to proliferation as they apply to a variety of potential proliferant actors and scenarios?

2) How do you characterize and evaluate the type of potential organizations, government and non-government, that would threaten these barriers?

3) What specific international R&D programs would be appropriate for developing an assessment methodology for these purposes?

Introduction

All civilian nuclear power plants and their associated fuel cycles are examples of potential dual-use technology and therefore contribute to the risk that weapons-usable fissile materials, facilities, technology, or expertise might be diverted or stolen. Thus, "proliferation resistance" is a matter of degree, not an absolute. It is therefore important to develop a methodology that compares various existing and proposed reactor/fuel-cycle systems with respect to their proliferation resistance. However, developing a generally acceptable methodology is difficult because both quantitative and qualitative factors contribute to proliferation resistance. In addition, both types of factors are inherent to the particular fuel cycle and both are also external, that is, institutional in nature. Moreover, proliferation risk depends on the character of the threat.

While the development of methodologies defining proliferation resistance has substantial merit, societal decisions about the future of nuclear power are required that take into account economic competitiveness, acceptable safety standards, acceptable standards of environmental protection, in addition to decisions governing acceptable levels of resistance to the proliferation of nuclear weapons.

> It should be clear from the outset that no nuclear power fuel cycle can be proliferation-resistant in an absolute sense, and it is equally inappropriate to identify just one single feature of the overall nuclear power system as being the key element in respect to proliferation.[2]

When states acquired nuclear weapons in the past, they generally developed *dedicated* facilities to supply the fissile materials rather than diverting such materials from civilian nuclear power systems. Thus, while diversion and theft is indeed a proliferation threat, one cannot rely on history in quantifying this risk. Rather, evaluation methodologies have to be based on conceptual assessments of risks, costs, and benefits.

Intrinsic vs. Institutional Barriers

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[2] For instance, the recent statement by Ambassador Gallucci, that ending the use of plutonium fuel is the *sine qua non* for the future of civilian nuclear energy, is a clear over-simplification that ignores the variability and complexity of the factors which can contribute to diversion or theft of weapons-usable materials.

Barriers to proliferation can be inherent to the nature of the reactor and its associated nuclear fuel cycle, or they can be institutional, that is externally imposed to inhibit or prevent access to weapons-usable material, facilities, and technologies. Inherent barriers—including *material barriers,* defined by the physical nature of the materials involved, and *technical barriers*, defined by the characteristics of the reactor and its fuel cycle—are fundamentally different from externally imposed *institutional barriers*. The former are inherent to the nature of the nuclear systems, while the latter are imposed by political authority to meet perceived standards for proliferation resistance. In turn, such standards depend on a number of variables: the political will to prevent proliferation, the openness of the nuclear power system and the society in which it is embedded, and the relative attractiveness of diversion or theft from the civilian fuel cycle compared with the development of a dedicated nuclear-weapons complex.

The sum of the inherent barriers and the institutional barriers defines, along with the level of threat, the overall proliferation resistance. The standards—be they national or international—that overall proliferation resistance must meet are subject to political decisions. Moreover, the institutional barriers can be modified or even eliminated by political authority. Treaties or other international commitments to establish institutional barriers can be abrogated; access to externally imposed inspections can be denied. Thus, intrinsic and institutional barriers are basically distinct. The group, therefore, decided to examine the methodology used to evaluate intrinsic barriers and then to consider this evaluation as input defining the required institutional barriers under applicable political constraints or international standards. The group did not discuss the appropriate level of such constraints or standards.

The Multiple Tiers of Methodology

In principle, the option exists to transfer the statistical methods now in common use in safety analyses to evaluate the proliferation resistance of reactor and fuel-cycle systems. A recent paper available to the panel[3] examines this possibility. In essence, the method assumes that proliferation has occurred, that is diversion or theft has taken place. A fault tree is then constructed that examines alternative breeches of proliferation barriers which could have contributed to the failure of the proliferation resistance. Then, a probability is assigned to each node of the fault tree leading to that result. The problem with this method, of course, is that, due to a lack of historical perspective and lack of detailed quantitative information about such breeches, specific probabilities for each node are extremely difficult to assign. Thus, while this method has promise, its usefulness as a methodology for examining proliferation resistance remains to be established.

A second tier of characterizing proliferation resistance could be a matrix tabulating the sequence of steps within each particular fuel cycle and reactor system at which diversion or theft may occur along one axis and tabulating the material and technical barriers inherent to each fuel cycle and reactor system on the other axis. An example of such a matrix is shown in Table 1.

Note that a separate matrix has to be constructed not only for each particular fuel cycle and reactor system but also for each particular proliferant threat or actor. Such proliferant actors could be highly industrialized states, developing states, or subnational actors acting with or without external state sponsorship. Moreover, the actors in questions could attempt proliferation clandestinely, or they could carry out such activities overtly after having announced their intent, e.g., through the abrogation of treaties. Thus, under this methodology, a large number of matrices, equal to the product of the number of fuel

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[3] *Measures of Nuclear Reactor Concept/Fuel Cycle Resistance to Nuclear Weapons Proliferation,* Michael W. Golay, CGSR Workshop, Livermore, CA, 2-4 June 1999.

cycles and reactor systems under consideration times the number of potential proliferant actors, would have to be evaluated.

A further issue is how the entries into each element of the matrix are constructed. The group decided that a measure of the weight of each element in the matrix should be the burden imposed on the institutional barriers, which would result in an acceptable overall risk of proliferation. This burden could be measured by a combination of inspection requirements by an international authority (such as the IAEA), the requirements for traditional security measures (guns, gates, and guards), and the condition of openness within the states, leading to public visibility of the activities at the facilities. The group did not define the exact criteria for the entries into the matrices, but referred the definition of such entries to further study.

One component of the burden imposed on institutional barriers is the manpower required to inspect different types of reactor and fuel cycle systems. A paper introduced to TOPS by Tom Shea of the IAEA[4] tabulated the inspector manpower required for a spectrum of reactor systems. While indeed such manpower requirements are substantially different for different reactor systems, the direct financial cost of such inspections is only a minute fraction of the cost of the electricity generated by each nuclear system. The true importance of the institutional burden is thus much larger than the monetary cost of external inspections. The cost of power-plant staffing to counter sabotage, theft, and diversion are at present internalized.

A third tier of methodology could be a summary assessment of the burdens carried by institutional barriers for each of the fuel cycles and reactor systems by combining the entries of the matrices as defined above with appropriate statistical weights. This combination then defines the total “cost” of required institutional barriers to result in an acceptable level of risk for each identified threat. Such a summary assessment would reflect the net judgment that could then be applied as a factor in considering which fuel cycle and reactor system should be selected for further research and development.

Even the complex methodology enumerated above, composed of the group of matrices followed by a summary evaluation, can only partially represent the proliferation resistance of each reactor or fuel-cycle system. The panel identified other factors not directly incorporated in the above methodology. Paramount among these is the transparency of nuclear power activities to the general public. Several countries, one example being Japan, have made positive efforts in publicizing the details of their nuclear power operation while others still shroud their operations in some level of secrecy. Clearly, the maximum level of openness is desirable to inspire public confidence that proliferation is neither intended nor being carried out, thus minimizing the need for external barriers.

Lack of openness might also produce an additional risk: a terrorist group could attempt to blackmail established institutions by claiming to possess a nuclear weapon. Even if persuasive evidence that such a claim is false, the absence of transparency in nuclear power activities might give such claims a residual margin of credibility, thereby giving additional leverage to the blackmailer.

Other factors can be taken into account in evaluating the contribution of each approach to nuclear power in stemming proliferation. An example is the consumption of excess world-wide stocks of weapons-usable fissile materials. Another example is the chemical stability of spent fuel, which leaves open many options including reprocessing and storage of such fuel as opposed to chemically unstable forms that force

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[4] *Proliferation-Resistant Technologies and IAEA Safeguards*, Thomas E. Shea, IAEA, paper at this meeting (included in Appendix D).

reprocessing of the fuel. The group enumerated such additional factors but did not attempt to incorporate them into a quantitative methodology.

The above outline of the potential methodologies to evaluate proliferation resistance paints a very complex picture. In examining these methodologies, the group does not wish to imply that informed judgments on proliferation resistance cannot be made as needed without such elaborate methodologies being firmly in place.

Future R&D

The panel is fully aware that R&D into the methodology designed to evaluate proliferation resistance is only a very small part of the overall R&D required for the evolution of new reactor and fuel-cycle technologies. In fact, the group was unanimous in agreeing that the R&D dedicated to future reactor and fuel-cycle technologies sponsored by the U.S. government is woefully inadequate. Considering the highly competitive nature of the current deregulated energy production environment and the long lead time required for the evolution of new nuclear reactor and fuel-cycle technologies, the private sector cannot be expected to adequately finance such R&D.

Among future R&D needs specifically dedicated to nonproliferation-evaluation methodology, the panel identified the following:

- R&D designed to fill in the elements in the matrices as described in the preceding sections.
- R&D designed to evaluate the practicality of a fault-tree approach to quantitatively describe proliferation resistance.
- R&D designed to identify the means to motivate the incorporation of proliferation resistance as a major objective in the choice of reactor technologies and fuel cycles.

The group was particularly concerned about this last factor. Currently, nations—in particular developing nations that have strong incentives to acquire nuclear power systems—have little if any motivation to incorporate proliferation resistance into their lists of criteria affecting their choice of specific approaches. Economic considerations generally dominate. The societal requirements for safety and environmental protection already diminish the economic competitiveness of nuclear power. If requirements for nonproliferation impose additional economic burdens, nuclear power becomes even less economically competitive until such time as either environmental considerations or the scarcity of fossil fuels makes nuclear power more competitive. For this reason, WG-4 recommends an R&D effort to explore incentive structures that do not impose economic burdens, and even possibly provide international subsidies. Such steps should increase the incentive for incorporating proliferation resistance into the choice between reactor systems and fuel cycles.

Table 1

		Material Barriers				Technical Barriers				
Step	Substep	Isotopic	Radiological	Chemical	Mass/Bulk	Unattractiveness	Facility Access	Detectability	Skills	Time
Front End	Mining									
	Transportation									
	Milling									
	Transportation									
	Conversion									
	Transportation									
	Storage									
	Enrichment									
	Transportation									
	Storage									
	Fuel Fabrication									
	Storage									
	Transportation									
Reactor Operations										
	Storage									
	Fuel handling									
	Reactor irradiation									
	SF handling									
	fuel pool storage									
	handling									
	dry storage									
Back End										
	Transportation									
	Storage									
	Processing for direct disposal									
	Transportation									
	Repository emplacement									
	Reprocessing									
	Storage									
	Fuel Fabrication									
	Transportation									
	Storage									
	(return to reactor operations)									

Appendix A: TOPS Task Force Members

John J. Taylor, Chair	Electric Power Research Institute (retired)
Robert Schock, Vice Chair	Lawrence Livermore National Laboratory
John Ahearne	Sigma Xi
Edward Arthur	Los Alamos National Laboratory
Harold Bengelsdorf	Consultant
Matthew Bunn	Harvard University
Thomas Cochran	National Resources Defense Council
Michael Golay	Massachusetts Institute of Technology
David Hill	Argonne National Laboratory
Kasuaki Matsui	Institute of Applied Energy, Japan
Jean Louis Nigon	Cogema, France
W.K.H. Panofsky	Stanford University
Per Peterson	University of California, Berkeley
Mark Strauch	Lawrence Livermore National Laboratory
Masao Suzuki	JNC
James Tape	Los Alamos National Laboratory

Appendix B: Agenda

Workshop on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS)

March 29-30, 2000
Washington, DC
American Association for the Advancement of Science
1200 New York Avenue
Washington, DC

March 29, 2000:

7:30	Registration/Continental Breakfast	All
8:15	Welcome	Under Secretary of Energy, Ernest Moniz
	Goals of the Workshop	William Magwood, DOE/NE Rose Gottemoeller, DOE/NN
	Summary of June 1999 Workshop	Ronald Lehman, CGSR
	Overview of the TOPS Task Force	John Taylor, EPRI (retired)
9:15	U.S. and International Perspectives	
	U.S. Department of State	Michael Rosenthal
	IAEA	Thomas Shea
10:00	Break	
10:15	Overview of Proliferation Resistance	Wolfgang Panofsky, Stanford University
11:00	Attributes Applied to Technologies for Proliferation Resistance	Robert Schock, CGSR
11:30	Cyber Security and Technology	Mark Graff
	Information Systems	Sun Microsystems
12:00	Working Group Definition and Anticipated Product	John Taylor, EPRI
12:30	Lunch	
1:00	Breakout into Working Groups	As Assigned
	1. Intrinsic proliferation barriers (material or technical barriers) to various threats.	
	2. Extrinsic barriers to proliferation threats, including MPC&A, safeguards, and institutional barriers.	
	3. Economics, safety and other factors that impact or are impacted by proliferation-resistant approaches.	
	4. Methodologies for evaluation of specific systems.	
6:00	Reception	

March 30, 2000:

7:30	Continental Breakfast	
8:00	Working Groups Continue	
10:00	Working Groups Prepare Presentation Materials	
12:00	Lunch	
12:45	Working Group Presentations	
2:45	Break	
3:00	Chairman Summarizes and Comments	John Taylor, EPRI

Appendix C: Working Group Participants

Working Group 1: Intrinsic barriers to proliferation (material and technical)

Chair: Tom Isaacs, LLNL
Harold Bengelsdorf, Bengelsdorf, McGoldrick and Associates
Sam Bhattacharyya, ANL
Paul Brown, LLNL
Paul Chodak, LANL
Charles Forsberg, ORNL
James Hassberger, LLNL
Andrew Kadak, ANS

Facilitator/Rapporteur: Steven Aumeier, ANL
Vladimir Kagramanian, IAEA
Mujid Kazimi, MIT
Philip MacDonald, INEEL
Jean-Lous Nigon, COGEMA
Hironobu Okamoto, JNC
Mark Strauch, LLNL
Michael Todosow, BNL
Alan Waltar, Texas A&M

Working Group 2: Extrinsic barriers to proliferation (Safeguards, security, MPC&A)

Chair: Myron Kratzer, Consultant
Jeff Binder, ANL
Thomas Blejwas, SNL
Thomas Cochran, NRDC
H. de Longevialle, COGEMA
Mark Graff, Sun Microsystems
Marilyn Meigs, BNFL
Barry Mendelson, NRC

Facilitator/Rapporteur: Jim Werner, DOE
Neil Numark, Numark Inc.
Per Peterson, UC Berkeley
Thomas Shea, IAEA
Barbara Sinkule, LANL
Mark Strauch, LLNL
Ken Tomabechi, CRIEPI

Working Group 3: Economics, safety, environmental and other factors that may be affected by proliferation-resistant approaches.

Chair: George Davis, ABB CE Nuclear Systems
Mario Carelli, Westinghouse
Richard Garwin, IBM
Ira Goldman, U.S. Mission to IAEA
Andrew Klein, Oregon State University

Facilitator/Rapporteur: Marty Martinez, JUPITER
Jean-Louis Nigon, COGEMA
Takehiko Saito, Toshiba
Walter Simon, General Atomics
Leonard Weiss, Consultant

Working Group 4: Evaluation methodologies applied to proposed systems

Chair: W.K.H. Panofsky, Stanford University
Marvin Adams, Texas A&M
Tom Edmunds, LLNL
Jim Finucane, DOE-EIA
Pablo Florido, CNEA
Michael Golay, MIT
Jean-Claud Guais, COGEMA
John Ireland, LANL

Facilitator/Rapporteur: Steve Herring
Hussein Khalil, ANL
Thomas Sanders, SNL
Kenichi Sasage, Embassy of Japan
William Sutcliffe, LLNL
Masao Suzuki, JNC
Richard Wilson, Harvard University

Appendix D: Prepared Remarks, TOPS Workshop Plenary Session

Proliferation-Resistant Technologies and IAEA Safeguards[5]

Thomas E. Shea
International Atomic Energy Agency

When establishing the safeguards methods and procedures within a State, one consideration relates to the proliferation capabilities afforded by declared facilities within that State which are subject to inspection under the relevant safeguards agreement. There are other considerations, of course, involving the capabilities and motivations of a State, but the focus of these rewards is on the declared facilities.

In relation to the declared facilities, the proliferation capabilities reflect possibilities for diversion of nuclear material from declared inventories and flows, and the potential misuse of the facility as a means through which a State might produce or process plutonium or highly enriched uranium for use in nuclear weapons or other nuclear explosive devices. The ability of the IAEA to provide assurance to the international community that a State is not engaged in a program to develop nuclear weapons, and the effort required to obtain that assurance, depends in part on the extent to which the nuclear facilities in that State incorporate "proliferation-resistant" features, and features intended to facilitate the implementation of effective and efficient safeguards measures.

For a given type of facility, the ability of the IAEA to provide such assurance depends upon the features of the specific facility, the nature of the safeguards agreement between the State and the Agency and the effectiveness of the safeguards measures applied. The ability of a State to implement a program leading to the production of one or more nuclear weapons or other nuclear explosive devices will depend upon its access to talent, technology and what we refer to in IAEA safeguards parlance as "direct-use nuclear material", i.e., any plutonium except "heat-source" plutonium containing in excess of 80% ^{238}Pu, any uranium enriched to 20% or more of the isotopes ^{233}U and ^{235}U. As of last December, our board of Governors approved a reporting and "flow-sheet" monitoring regime intended to address concerns about the use of neptunium for nuclear weapons or other nuclear explosive devices, and the potential accumulation of this material to the point where more extensive measures might become prudent. Americium was also recognized as a material of potential proliferation concern.

The ability of a State to implement a program to produce nuclear weapons will depend upon what it is able to accomplish independently and what assistance it is able to acquire from other States or through other means. The extent to which it might draw upon civil nuclear operations, and in the case of imported capabilities, the existence of institutional arrangements which might at the least inhibit misuse, and at best prevent it. I believe that this area merits further consideration and I will return to it below.

The introduction of proliferation-resistant technologies should serve to raise the barriers to States seeking to produce nuclear weapons, making it more difficult to acquire or process the "direct-use nuclear material" required. The introduction of such technologies should also make the job of the IAEA easier, by reducing the effort and simplifying the means through which the IAEA could conclude that nuclear materials have not been diverted from the declared inventories or flows from facilities incorporating proliferation-resistant technologies, nor have such facilities be misused to produce or process undeclared "direct-use nuclear material".

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[5] The remarks provided are those of the author and do not necessarily reflect the views of the International Atomic Energy Agency.

The international non-proliferation regime is remarkable in its extent and its success. It wasn't mature enough to prevent the acquisition of nuclear weapons by the five States which tested before the NPT was concluded, and it was unable to stop South Africa, India and Pakistan, and presumably Israel from acquiring weapons. But through the past three decades, it has come to the point where mankind can and should state categorically, that no further proliferation is tolerable.

I would like to draw to your attention two elements of that regime that bear upon the subject of proliferation-resistant technologies. First is the matter of supplier restrictions on sensitive technologies and materials afforded through two mechanisms, the Zangger Committee and the London Suppliers Group. Both serve complementary ways to limit access to equipment and materials which could be used by a State in a program to produce nuclear weapons, and where commerce in such items is considered not to constitute a proliferation risk, to provide transparency and ensure that International Atomic Energy Agency (IAEA) safeguards are applied or that the IAEA is informed of such commerce. Whether these controls are sufficient and whether or not they are enforced sufficiently remains a matter of interest.

The second element is the IAEA safeguards system. Following the events in Iraq and the Democratic People's Republic of Korea, efforts were launched to strengthen the safeguards system especially in relation to the ability to detect clandestine facilities and undeclared operations within declared facilities. These efforts were carried out in two stages. Steps which could be implemented within the legal authority of the existing safeguards agreements were introduced first, and subsequently, a mechanism to extend the legal authority of the existing agreements was established through a Protocol Additional to the existing agreements. A model for such Protocols was approved by the IAEA Board of Governors in 1997. Safeguards agreements are generally considered to have the status of treaties, and most states must follow their constitutional requirements for adopting such Protocols. The December 1999 issue of the IAEA Bulletin, prepared with a view to the NPT Review Conference beginning on April 24th, includes articles describing the evolving safeguards system and the situation regarding implementation of the Protocols.

To strengthen the IAEA safeguards system, all States concerned should work together for universal adoption of this Protocol. I can remind you that at present, all States having any nuclear activities with the exception of Israel, India, Pakistan and Cuba, have pledged through the NPT and/or regional nuclear weapon-free zone treaties not to acquire nuclear weapons, and to accept IAEA safeguards on all nuclear materials and activities. Cuba has signed an Additional Protocol, which should provide assurance that such programs are not underway, and hopefully will ratify the Tlatelollco Treaty formally committing not to produce nuclear weapons or other nuclear explosive devices. All States concerned with the prevention of further proliferation should combine at the forthcoming NPT Review Conference to make it clear that in fulfillment of States' obligations under Article III of the NPT, an Additional Protocol is an *essential* requirement.

In approaching the topic of proliferation-resistant technologies, I believe that it is of interest to choose the technologies which are likely to make the greatest impact, and to establish a framework that will ensure that the technologies chosen and endorsed will be implemented. It is important to consider these technologies in the framework of the relevant nuclear power system which includes reactor and fuel cycle facilities front-end and back-end, including fissile materials in form of spent fuel or waste. I believe that the following "principles" might guide such an undertaking:

The first focus should be to defer access to direct-use nuclear materials as long as possible, and then, to introduce such materials for peaceful use only when programmatically justified and under institutional arrangements which make such activities transparent. I believe that here the emphasis should be on creating reliable conditions which States could count on, which would serve the purpose of encouraging such States to avoid the need to develop their own enrichment or reprocessing capabilities.

- In the case of enrichment, emphasis is needed on assurance of supply, over the predicted life-cycle of a reactor, perhaps such provisions might be included in a contract providing a reactor. Further steps might be taken to ensure that access to enrichment technology remains closed, and the operation of enrichment facilities might be through a consortium of technology holders controlling the siting and staffing of distributed operations. I believe that the peaceful use of highly enriched uranium fuels should be stopped altogether, or at least with very limited exceptions where very strong technical justifications can be made, and where the uses are clearly to the benefits of mankind.
- In the case of reprocessing, instituting fuel-return practices is a simple means to allow States to benefit from nuclear power without the need to solve spent fuel disposal on a small scale, and without the temptation to reprocess before such a step is appropriate. The spent fuel could be returned to a regional energy center, or to a nuclear weapon State, for example.
- I also believe that plutonium should not be provided to States in bulk form, and that the introduction of plutonium-bearing fresh reactor fuels should be postponed until the State has established a mature nuclear program. Consideration might then be given to an institutional arrangement which would limit the State's access to separated plutonium, perhaps through a regional energy complex or at least through multinational corporate structures with integrated staffing.

The second focus should be to defter access to enrichment and reprocessing technologies, to the maximum extent possible.

The third focus might be to introduce proliferation-resistant technologies which might be made available with little risk of misuse. Most proliferation concerns today focus on small States which remain outside the mainstream of international discourse. In the 1970s, the focus was on industrialized States, many of which had considered acquiring nuclear weapons, and some of which built facilities and continued their pursuits for quite some time. In the future, the poorer nations will hopefully see brighter prospects; concerns might arise that as development proceeds, regional relations might be threatened and nuclear weapons might be seen by some as a way to gain regional influence. The pursuit of proliferation-resistant technologies should address all future prospective concerns, recognizing that for some States, imposing constraints on access to technology could stimulate them to favor all indigenous development, or to find suppliers who are not willing to abide by such constraints.

Designing nuclear power reactors, which would inhibit access to fresh and irradiated fuels, and avoid opportunities for irradiating undeclared fertile materials would simplify the safeguards efforts required to conclude that the nuclear materials remain accounted for and committed to peaceful use, and that the reactors were not used or unreported production of plutonium or ^{233}U. There are a number of interesting ideas on the table at present, and all would seem to raise the barriers to proliferation, some more so than others.

Exports of high power research and isotope production reactors have been a concern in a number of areas, including India, Israel and Taiwan, china and most recently, in Pakistan. Designing future reactors in ways which limit their suitability for plutonium production would again simplify the IAEA safeguards measures required to ensure that such activities are not underway, and could allay regional concerns regarding the intentions of such States. Regional compacts for the production of medical and other useful isotopes, and for research making use of such reactors could provide further means to limit the opportunities available to States harboring nuclear weapon ambitions, and could provide the basis for regional confidence-building.

Given the relative simplicity of a gun-type nuclear uranium explosive device in relation any implosion-based weapon or nuclear explosive device, I am most concerned that enrichment technology does not become available. As noted, assurance of supply should reduce State's motivations for acquiring enrichment technology, but further steps are needed. I am aware that a chemical exchange proliferation-resistant enrichment technology was under investigation in France and Japan for some time, but the economics apparently ruled out actual use. Access to enrichment technology which does not require large installations or large amounts of electrical power are a concern, but even less efficient technologies have been successful. While some may view the introduction of laser or plasma enrichment technologies as attractive, from my point of view, they would be the subject of serious proliferation concern.

In pursuing the issue of proliferation-resistant technologies, I believe that the following matters need to focus future steps:

- Assuming that nuclear power reactors are developed offering proliferation-resistant features, how will they be introduced? Specifically, how will States which produce reactors not offering such features react to such steps — will they see this as a market ploy and continue to compete?
- Recognizing that a problem is best resolved by designing a system that prevents its occurrence, in some cases, such as enrichment and reprocessing, proliferation-resistant technologies may be impractical. Can the institutional framework under which proliferation-resistant technologies are provided encompass other means, such as regional energy parks undertaken by compacts of States under treaty arrangements, or multinational consortia with integrated staffing?
- And finally, how, and to what extent could proliferation-resistant technologies and institutional arrangements such as suggested be factored into IAEA safeguards? IAEA safeguards should be less extensive, less expensive and less intrusive for facilities incorporating proliferation-resistant features than for facilities not incorporation such features; what conditions might apply for institutional arrangements intended to allow States to enjoy the benefits of the peaceful uses of nuclear energy without encouraging a State's nuclear weapons ambitions. How would such technologies and arrangements be integrated into decisions regarding IAEA inspection activities and the conclusions be derived?

In relation to this latter point, it might be interesting for you to consider the inspection effort required currently at different types of facilities, which is related to some extent to the capabilities for proliferation that such facilities afford. The unit of measure is the PDI, i.e., the number of "person days of inspection" in a calendar year.

TYPE OF FACILITY	**PDIS PER YEAR**
LIGHT WATER REACTOR, NO FRESH MOX	6 - 12
CANDU REACTORS	45
LIGHT WATER REACTORS WITH MOX	15 - 45
ENRICHMENT PLANTS	70 - 150
MOX FUEL FABRICATION FACILITIES	Ca. 200
REPROCESSING PLANTS	>750

The costs for inspection equipment show a similar range, increasing from top-to-bottom.

Proliferation-resistant technologies should result in decreasing the inspection effort and the equipment costs necessary for the IAEA to conclude that a State has neither diverted nuclear material from its declared inventories and flows, nor used the facility for the unreported production of direct-use nuclear material.

In thinking about this subject, I came to think that in addition to the technical and institutional avenues identified, that it may not be appropriate to consider a legal framework which could guide the legitimate actions of suppliers and users. Here is a suggestion for consideration:

> Convention on Nuclear Power Utilization – I suggest that steps be taken to draft a Convention governing the acquisition and expansion of relevant nuclear research and nuclear power systems and related fuel cycle capabilities. The Convention should address provisions for indigenous development, and for commerce in related technologies, materials and services, and guide the actions of suppliers and recipients, establishing requirements for prudent and legitimate programs and transparency measures allowing States to realize the benefits of nuclear energy with minimal risk of proliferation. Such a Convention could provide a framework for the adoption of proliferation-resistant technologies.

In closing, I would like to recall that all States in which nuclear power might be an option are Member States of the IAEA, and that the Agency's programs reflecting nuclear applications, safety and verification provide mechanisms for the Agency to be involved in complementary ways. Following last year's TOPS Workshop, for example, an Advisory Group Meeting on "Development of a Strategic Plan for an International R&D Project on Innovative Nuclear Fuel Cycles and Power Plants" was held by the Agency to formulate a strategic plan, with the consent of the participating Member States, for an international R&D project on innovative nuclear fuel cycles and power plants. Among other recommendations, a total of nine candidate projects were identified for possible support by the Agency, including one entitled "Development of Technologies to facilitate IAEA Safeguards against nuclear proliferation", which is being proposed for extra-budgetary funding as a project to be conducted jointly by the Nuclear Energy and Safeguards Departments.

Overview of Proliferation-Resistant Attributes

Dr. Wolfgang K. H. Panofsky
Director Emeritus
Stanford Linear Accelerator Center
Stanford University

My task is to establish a context for the deliberation of this workshop. Not being an expert in reactor engineering, I will give some general perspectives. As you all know, the technology of nuclear fission is what is commonly described as dual use technology; it can serve both military and non-military purposes. This statement is general. Even a pure fusion reactor has to be safeguarded since, being a copious source of neutrons, a breeding blanket could be introduced clandestinely to produce weapons usable materials. Thus no deployment of technically more proliferation resistant nuclear power plants can obviate the need for safeguards to prevent diversion of elements of the nuclear fuel cycle to military purposes. All proliferation resistant technologies can do is to lessen the burden which safeguards have to bear to prevent diversion. There is no "silver bullet" in developing a totally proliferation resistant fuel cycle. The further development of nuclear power, notwithstanding the unquestioned increasing need for this technology during this century, has to overcome a number of hurdles: It has to be economically competitive, yet it has to achieve that competitiveness in the face of demonstrable social burdens:

- the need for safe operation meeting severe standards,
- the achievement of accepted means of waste disposal, and
- criteria preventing diversion to military purposes.

In the interest of safety and nonproliferation, nuclear energy faces both a stringent regulatory environment and governmental policy restraints which in turn directly reflect on economic performance. The development lead time for elements of the nuclear fuel cycle is very long and therefore the private sector, in particular in the current deregulated environment, cannot afford the long-range research and development to develop both safer and more proliferation resistant nuclear power systems. This therefore must remain a high priority objective of government. All elements of the nuclear fuel cycle entail proliferation risks to a varying degree. Fresh fuel must be safeguarded, depending on its weapons usable content. If that weapons usability is not present, as is the case with low enriched uranium, the enrichment process requires safeguards. Reactor operations incur diversion risks during initial fueling and refueling operations. Spent fuel must be safeguarded and reprocessing increases the diversion risk of spent fuel since it generates directly weapons usable materials. Transportation, intermediate storage, and geological or other means of final disposition also entail diversion risks.

The above statements are general but the severity of the risks within the fuel cycle and the need for safeguards depend critically on the detailed technical nature of the fuel cycle. It is extremely difficult to develop a universally applicable metric to measure proliferation resistance of each of the elements of the fuel cycle. The diversion risks depend on the nature of the potential proliferation and the proliferant. Are we talking about clandestine diversion or overt nuclear weapons programs? Are we dealing with a technically sophisticated state actor, a developing state, or even a subnational group? Thus the risks associated with the elements of the fuel cycle have to be incorporated into a matrix which tabulates that risk in accordance with the diversity of potential proliferation actors.

Just because there cannot be total elimination of the proliferation risk inherent in the nuclear fuel cycle by technical means, we face the problem about the standards to which amelioration of proliferation risk should aspire. Customarily the once-through light water reactor serves a useful reference but not a standard with which proliferation resistance can be compared. The reason for this usefulness is not that this conventional fuel cycle is particular singular in terms of proliferation resistance but because it is by far the most copious worldwide. Therefore little use is served by the development and deployment of improved fuel cycles unless it is done on such a scale as to largely displace the once-through LWR. One characteristic of the proliferation resistance of most nuclear fuel cycles, and the once-through LWR cycle in particular, is that they are time dependent. Initially the spent fuel from LWR results in a high radiation barrier which, however, will decay over time. Thus the safeguarding requirements inherent in that reference for proliferation resistance will change in time.

A matter which remains controversial, although in my view there should be agreement on that topic by now, is whether the isotopic composition of spent fuel is a major factor in respect to proliferation resistance. It is now well established that a nuclear explosive can be fashioned from all isotopic mixtures of plutonium, although “weapons grade plutonium” which contains well above ninety percent of ^{239}Pu has been the “material of choice” of weapons designers. However recent extensive analyses at the weapons laboratories has made it clear that the negative contributions to weapons usefulness of isotopic mixtures containing larger fractions of ^{238}Pu, ^{240}Pu, and gamma ray enhancing isotopes can be overcome by appropriate design.

Everyone here recognizes that, wherever nuclear weapons potential has been attained in the past, this has with very few exceptions been achieved without resorting to diversion of materials from the commercial nuclear fuel cycle. In almost all instances, once a political will to acquire nuclear weapons became dominant, a deliberate dedicated military fuel cycle was instituted. Thus there is little historical basis for evaluating the degree of proliferation resistance of commercial fuel cycles but this fortunate fact should not alleviate our concern with the topic.

Let me now briefly turn to an outline of the most prevalent technical factors which appear to affect the elements of the nuclear power fuel cycle: Choice of Reactor Fuel. Key to the proliferation resistance of the total fuel cycle is whether the reactors are fueled by highly enriched uranium, low enriched uranium, plutonium, or as recently come into the forefront again, thorium. Then there is the possibility whether a non-fertile fuel such as a combination of highly enriched uranium and candidate ceramic substances can be used. Finally there is the use of mixed oxide (MOX) fuel consisting of plutonium combined with natural or depleted uranium. Each one of these fuels imply different proliferation risks. Highly enriched uranium is directly weapons usable and therefore must be safeguarded to high standards until withdrawn as spent fuel. Low and high enriched uranium both require enrichment plants which in themselves must be safeguarded to monitor the degree of enrichment and to prevent diversion. Plutonium fuels such as the ones proposed for the high temperature gas cooled reactor are also in themselves weapons usable and must be protected until consumed. Thorium fuels have recently been advocated as being more proliferation resistant and specific fuel cycles have been considered; among those are thorium fuel reactors combined with an initiating blanket of more reactive material or thorium subcritical systems made critical by spallation neutrons from a high energy proton accelerator. Both systems incur proliferation issues on their own: the initiating blanket of a thorium reactor contains “seed” material which is weapons usable and the result of the neutrons generated in thorium fission produces ^{233}U which is in itself weapons usable. While ^{233}U can be rendered weapons unsuitable by blending with ^{238}U, this process itself must be safeguarded. If ^{238}U is directly introduced into the fuel this leads to the generation of plutonium. Thus while the use of thorium fuels has some attraction, partially because its ores appear to be more copiously available both globally and in specific locations than uranium ores, a substantial number of technical issues must be addressed.

The use of mixed oxide fuels have been extensively practiced in Europe and MOX fueling for reactors is one of the options contained in the dual track proposal announced by the Department of Energy as one of the means of disposing of excess weapons plutonium withdrawn from nuclear weapons. Needless to say, this route implies that fuel fabrication and the fuel itself be safeguarded to high standards. Moreover, the plutonium content of spent fuel from MOX burned in light water reactors is higher than those of the same reactors fueled with LEU.

Other Reactor Related Issues: Separate from the question of the choice of primary fuel is whether the spent fuel is or is not to be reprocessed to recover the large energy content of the unconsumed actinides contained in that spent fuel. Current U.S. policy is not to engage in reprocessing spent fuel and to discourage such reprocessing in foreign reactors. The reason is, of course, that the fuel cycle inherent in reprocessing involves isolation of plutonium with consequent increased proliferation risk. This risk can be diminished by shifting from the currently practiced aqueous reprocessing cycles to various forms of pyroprocessing in which the reprocessed materials never get fully separated from highly radioactive fission products.

Separate from these primary issues of material fueling the reactor and of “closing” the fuel cycle by reprocessing are the issues inherent in the operational nature of the fuel cycle. Continuous fueling like practiced in the CANDU reactors requires continuity of the safeguarding process of operating reactors; additionally the small size and weight of fuel bundles make diversion less difficult. Proliferation resistance is also effected by variability in the degree of burn-up under which reactors are operated. Low burn-up results in increased weapons suitability of the plutonium generated and decreases the radiation barrier.

Please forgive this extremely sketchy summary of the technical variables which affect proliferation resistance. More details will be discussed during the workshop. Superposed on the technical proliferation resistance of these technical alternates is the fact that the development status of these various options is extremely variable. In some, even if not all, of these options much additional research and development is needed to determine safety characteristics of the fuel cycle, the precise safeguarding requirements which would be required under applicable standards, and above all economic competitiveness. Where does all this lead us? My primary recommendation is that the U.S. government should greatly intensify its sponsorship of research and development dedicated to examine the characteristics of these alternate fuel cycles and in particular determine the safeguarding requirements associated with each.

Because of the large profusion of the options I have recited, broadening of the research and development support should at the same time be accompanied by an effort to “down select” among the options to be supported. Only by such a systematic approach can an objective assessment be made avoiding the pressures produced by promotion of specific approaches which have been prevalent in the past.

Appendix E: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems

(Draft 1.06 - 3/22/00)
NERAC Task Force
on
Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems

Introduction

Nuclear power will continue to be a major factor in producing abundant and affordable energy in many parts of the world. The choice of nuclear power systems leading to acceptable growth in nuclear power among many countries will have to take into account a number of factors which include economic competitiveness, acceptable safety standards, acceptable waste disposal options, and acceptable risks of proliferation of nuclear weapons from such nuclear power systems. The intent of this document is to propose a process to provide a set of attributes [*Attribute: a quality, character, characteristic or property*] with which to compare the relative proliferation resistance of civilian nuclear power systems, as well as alternative pathways to proliferation. It is intended that these attributes will help to identify R&D areas and programs that would open potential ways to enhance the proliferation resistance of the fuel cycle as nuclear power generation continues, and even expands, world-wide. The goal is to optimize the proliferation resistance of the civilian-cycle to the point where it is not the preferred route to nuclear weapons development.

It is hoped that proliferation resistance attributes will facilitate discussion, particularly beyond TOPS, of proposed reactor systems and sub-systems based on new technology. In short, we would like a system that compares different schemes and methods, as easily as possible, and identifies their relative merits and their weaknesses. We select the current light-water reactor (LWR) system using "once through" fuel as the basis for comparison. LWRs are the system in widest use today and there is considerable documentation on their economics, safety, and the proposed disposition of their waste, and their proliferation resistance.

We are guided by the extensive work on criteria by the National Academy of Sciences Committee on International Security and Arms Control (1994) and the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium (1995). Although the materials and facilities involved here are far more extensive, and the options for proliferation far more varied, we believe their work (and that of the more recent Interim Report by the Panel to Review the Spent-Fuel Standard for Disposition of Excess Weapons Plutonium, July 1999) has applicability to deriving attributes for the proliferation resistance of the entire civilian fuel cycle.

We propose to use attributes qualitatively, but with the realization that they would have additional utility for engineers and R&D planners if they could be transformed into quantifiable metrics that could readily and objectively be compared between different systems or sub-systems. In many cases this may be difficult or impractical to achieve and it will not be attempted in this study.

To develop a comprehensive set of attributes, we must identify the proliferation threats associated with the civilian nuclear power system, examine these threats and identify the barriers to them, and analyze the associated relationships. Barriers may be thought of as the counter of vulnerabilities (i.e, where vulnerabilities exist in the fuel cycle, we must ensure that sufficient barriers exist to prevent their exploitation by a threat). We propose a systematic approach to examine civilian nuclear power systems (from mining to disposal) for of a series of distinct threats with an evaluation of the importance of the barriers against each threat. These barriers can be examined at each point in the fuel cycle, and for each threat, to identify and understand the attributes of the system that can be used to describe its proliferation resistance and compare it to other systems. Thus, the framework for developing attributes is:

- Identify the proliferation threats and the linkages between fuel cycle activities and proliferation
- Identify various barriers to the threats
- For each system or sub-system, outline the important attributes which characterize the effectiveness of the barriers

Since the number of intersections between threats, steps in the fuel cycles and barriers is substantial, it is expedient to first examine the most likely threats and the most important vulnerabilities.

1.0 Threats

General proliferation threats to civilian nuclear power systems are diversion and/or theft of material; misuse of material; misuse of facilities, equipment and technology; and transfer of nuclear specific expertise (skills and knowledge), all for the benefit of a potential proliferator for the purpose of making nuclear weapons. These threats may be either overt or covert. Potential proliferators may be non-nuclear weapons states and sub-national groups. The non-nuclear weapons states can be divided among those that currently have very high technical levels of nuclear sophistication and those that do not (there are obviously all gradations of political will and technical capability, but this distinction will change and probably blur with time and become less important). Sub-national groups can likewise be divided between those that will use material and information for themselves and those that will transfer it to someone else, but again the distinction may become less important as one looks further and further into the future. Other threats include loss by a host state of institutional controls (leading to failure of safeguards and security, among others), and the skills and knowledge that may be gained by the host country that would be beneficial to the development of nuclear weapons, and possibly others.

As discussed above, identification of proliferation threats and the evaluation of resistance to these threats must recognize the temporal nature of the problems and issues. Radiation barriers provide inherent protection of some materials but decay over time, R&D advances change the nature and degree of a threat and the fuel cycle itself, and are likely to enhance the potential of safeguards, and the technical capabilities and sophistication of potential proliferators will also increase with time. The temporal nature of threats also requires judgements about the appropriate social discounting of uncertain future threats versus certain current threats.

The threats as described so far, are general as to type. As a National Academy of Sciences panel pointed out (1995), each threat must also be characterized as to associated organizations, the capabilities of forces in the case of forcible theft, and the likely knowledge, skills, financial resources and technology available to the threat. There are many and diverse threat scenarios involving a plethora of actors, pathways and actions. Given limited time and resources there is a need to examine each scenario to determine which are more serious and involve the most likely threats and are therefore most important, and then propose systems and sub-systems in terms of these threats.

1.1 Materials

The most obvious linkage between civilian nuclear power and nuclear weapons is nuclear material. Each step in the civilian fission fuel cycle involves materials that either are, or could potentially be processed into, weapons useable materials. The potential movement of these materials or the generation of weapons usable material dominates the relationship between the facilities of the civilian nuclear power system and nuclear weapons.

Weapons-usable materials are capable of undergoing explosive fissionable reactions[6]. For our purposes, we can consider all isotopes capable of being assembled into a fast critical mass as weapons-usable. It is important to note that the ease with which any one isotope may be utilized varies with the general engineering and scientific skills and knowledge of a potential proliferator because the isotope properties (half-life, neutron generation, heat generation, and critical mass) vary:

All isotopes of Pu
$U^{233,235}$
Np^{237}
Pa^{231}
$Am^{241,243}$
$Cm^{244,245,246}$
Bk^{247}
Cf^{251}

These materials may be in either metallic form, as a compound (e.g., an oxide), or as mixtures.

In addition, there is another class of materials that can be used to generate weapons-usable materials. The most important of these "fertile" materials are:

U^{238}
Th^{232}

1.2 Barriers

Material qualities, technical impediments and institutional arrangements (including the complex of measures known as material protection, control and accountability or MPC&A) can present barriers that make it more difficult for a proliferator to exploit the civilian nuclear power system. It is important to note that the specific form of the attributes of these barriers will vary depending on the specific system under consideration. The first two types of barriers are intrinsic and the last, extrinsic. Intrinsic barriers are those that are inherent to technical and related elements of the fuel, cycle, and their facilities and equipment. Extrinsic barriers are those that are dependent on implementation details and compensate for weakness in the intrinsic barriers.

National Academy of Sciences panels (1994, 1995, 1999) have devised a useful classification of barriers and their associated attributes. There are obvious advantages to building upon this classification rather than inventing, or reinventing, new ones.

In general the material qualities which act as barriers are the isotopic, chemical, radiologic, and bulk handling characteristics that make it more difficult to produce a nuclear explosive from a particular source material. Material barriers include the isotopic composition of the material (percentage and type), the chemical processing or isotopic separation required to retrieve or produce a weapons-usable substance, the radiation hazard and signature associated with the material at each step in the civilian system and in any process to generate a weapons-usable material, and the detectability and difficulty of movement of the mass and/or bulk of the material.

Isotopic composition controls the relative difficulty of making a nuclear explosive with fissionable material of a specific isotopic composition, or altering its isotopic composition through isotopic enrichment or reactor irradiation to produce explosive fissionable material. Chemical processing refers to the extent and difficulty

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[6] We will not deal with the dispersal of environmentally hazardous nuclear material, leaving that to the proliferation of chemical weapons, but note that some of these as well as other nuclear materials are chemical and/or radiological environmental hazards.

of chemical processing required to retrieve the explosive fissionable material(s) from accompanying diluents and contaminants. The radiation hazard is the radiation field associated with the material and the internal dose potential to humans. The mass and bulk relate to the difficulty of moving the material in the course of theft or diversion, including the difficulty of concealing the activity.

Technical impediments are another set of intrinsic barriers not specifically delineated by the National Academy of Sciences, but which have applicability to civilian nuclear power systems. These are the intrinsic technical and related elements of the fuel cycle and its facilities and equipment that serve to make it difficult to gain access to materials, or to use or misuse facilities to obtain weapons usable materials. These are technical impediments intrinsic to the system, as opposed to the extrinsic institutional barriers to be discussed shortly, and they can affect the proliferation potential of a system in a number of important ways. For example, access to irradiated fuel in an LWR is protected by the technological complications inherent in physically opening the reactor and gaining access to the fuel inside. This is a barrier that is inherent in the technology underlying the LWR fuel cycle and not related to either the physical attributes of the fuel itself or to external institutional issues demanding restricted access to fuel materials. The effectiveness of this technological barrier is one reason that LWR systems are often considered more "proliferation resistant" than CANDU reactors, where the reactor is continually refueled and access to "in-reactor" fuel is easier.

Technical barriers are particularly important when considering the threat of facility and technology misuse. The difficulty and/or time delay associated with modifying or reconfiguring a facility or process to produce weapons usable material is another example of an intrinsic technical barrier. Process material throughput is another technical barrier, at least to the extent that processes with low throughputs may be seen as less attractive to a proliferator or may offer increased probability of detection of diversion (its more likely that diversion of 1 kg of material will be noticed from a process treating 100 kg/day than from one treating 1000 kg/day). Of course, overcoming technical barriers requires specialized skills, tools, materials and supplies.

There may be "other" intrinsic barriers to proliferation. For example, economic barriers are often considered institutional barriers, and are thus extrinsic. An example is the national economic resource available to mount a campaign to divert and then utilize an explosive fissionable material. However, economic penalties associated with (for example) use of an LWR reactor to produce weapons-grade plutonium (costs associated with intensified reactor operations, loss of electric revenues) are a direct result of the reactor being designed to produce electricity continuously and for long periods of time, and are thus intrinsic and technical. Similarly, there will be safety, waste and other barriers that a potential proliferator would have to overcome to abuse commercial nuclear fuel cycle systems for proliferator purposes. Some of these are intrinsic to the systems themselves, and should be considered as technical barriers.

Both material and technical barriers relate to the inherent nature of the fuel cycle. Institutional barriers are those practices, controls, and arrangements designed to protect against various threats, thereby compensating in whole or in part for weaknesses of intrinsic material or technical barriers, or for the potential of other aspects of the nuclear energy system to contribute to proliferation. These include international safeguards, the entire complex of measures known collectively as MPC&A, and other measures such as controls over sensitive information, export controls, and the like. We may again turn to the work done by the National Academy of Sciences to define the attributes for the institutional barriers.

These barriers and their attributes depend on the details of the operation and include locational attributes such as isolation, burial, and the number of sites for the system or sub-system, containment attributes such as buildings, fences, detectors, alarms, and amount of required access, and other institutional attributes such as MPC&A, safeguards and security.

1.3 Attributes

Our goal is to define a set of attributes that can be used to describe the relationship between the elements of the fuel cycle, the threats to those elements and the effectiveness of the barriers to inhibit these threats. This process will help identify where technologies can advance the goal of enhancing the proliferation resistance of civilian nuclear power systems.

Our approach is to review each element of the system (fuel cycle) against a specific threat to determine the important attributes contributing to the effectiveness of the various barriers discussed above. This approach is shown in Table I, where it is proposed to use of a separate table for each class of threat to the system (e.g., covert diversion by technically advanced non-nuclear weapons state in the mid-21st. century). The three types of barriers (two intrinsic, one extrinsic) are listed across the top of the matrix and each is divided into its most important sub-barriers. Each of the steps, barriers and threats may require additional elaboration to ensure that we have adequately defined the overall evaluation framework. The goal is to define a framework that can be applied to any system and provides an assessment of relative risk among various systems and options.

It is useful to indicate the qualitative effectiveness of the various barriers. A National Academy panel (1995) used a qualitative scale where 0 indicates an ineffective barrier, 1 a weak barrier, 2 a medium barrier, 3 a large barrier and 4 a very large barrier. This enumeration is not intended to represent a linear scale, but rather only indicates that some (perhaps substantial) qualitative differences may exist between different rankings. This enumeration is not comparable among the various barriers. That is to say, the effectiveness of a 4 for a radiological barrier is not necessarily equivalent to an chemical barrier with an effectiveness of 4. Similarly, a radiological barrier of 2 could be considered more effective (but not necessarily so) than a chemical barrier of 4. Some barriers may not need the detail represented by a range of 0 to 4, but this scale will still be useful to distinguish between ineffective (0) barriers, medium (2) and very large (4) barriers.

Table I Format (Barriers for Steps in Fuel Cycle) for Comparing Proliferation Risks from Nuclear Power for a Specific Threat and Time Frame

		MATERIAL BARRIERS				|	TECHNICAL BARRIERS					|	INSTITUTIONAL BARRIERS		
	ATTRIBUTE->	Isotopic	Radiologic	Chemical	Mass/Bulk	|	Unattractiveness	Facility Access	Detectability	Skills	Temporal	|	Safeguards	Access Security	Location
						|						|			
STEP	Sub-step					|						|			
						|						|			
Front-end						|						|			
	Mining					|						|			
	Milling					|						|			
	Conversion					|						|			
	Enrichment					|						|			
	Fuel Fabrication					|						|			
	Fuel Shipping					|						|			
Reactor O						|						|			
	Fuel Handling					|						|			
	Reactor					|						|			
	Spent-Fuel					|						|			
Back-end						|						|			
	Transportatio					|						|			
	Processing					|						|			
	Storage					|						|			
	Disposition					|						|			

1.3.1 Attributes of Material Barriers

Material barrier attributes are those qualities of materials that relate to the inherent desirability of the material. Material barriers include the isotopic composition of the material (percentage and type), the chemical processing required to separate a weapons-usable substance, the radiation hazard and signature associated with the material at each step in the civilian system and in any process to generate a weapons-usable material, biological hazards, and the difficulty of moving the mass and/or bulk of the material.

Isotopic Barrier

Attributes of the isotopic barrier indicate how difficult it may be to construct a weapon from a particular fissile material once the material is available in an "acceptable" chemical form. Materials with the lowest isotopic barrier effectiveness (especially HEU and Weapons-grade plutonium) are isotopically attractive for weapons applications. Materials with higher isotopic barrier would require very creative designs and/or isotopic enrichment before being useable in a weapon. Attributes that are important for determining the effectiveness of the isotopic barrier include:

a) Critical mass, i.e. the minimum amount of material needed to achieve criticality to fast neutrons. A small critical mass represents a lower barrier than a large critical mass.

b) Spontaneous neutron generation. Spontaneous neutrons complicate the design, yield and reliability of a device. A lower spontaneous neutron generation rate represents a lower barrier than a high rate. For plutonium, this is strongly dependent on the concentration of ^{240}Pu and ^{242}Pu.

c) Heat generation rate. Heating produced by nuclear decay of the material complicates device design. A lower heat generation rate represents a lower barrier than a high heat rate. For plutonium, this is strongly dependent on the concentration of ^{238}Pu.

d) Radiation. The radiation (especially gamma) released by the material itself interferes with the handling, processing and design of a nuclear device. A lower radiation level represents a lower barrier than a higher radiation level. For plutonium, this is dependent on the concentration of ^{240}Pu and ^{242}Pu; for ^{233}U this is dependent on ^{232}U.

e) Degree of isotopic enrichment. Natural and low-enriched uranium cannot be used directly in a weapon, but they can be converted to weapons-useable material by enrichment or re-enrichment. Thus, the isotopic barrier is high for uranium enriched to low levels of ^{235}U or ^{233}U, and low for uranium enriched to very high levels.

The fissionable materials commonly considered attractive to potential proliferators are classified as follows:

0. *Highly Enriched Uranium (either ^{235}U or ^{233}U)*
1. *Weapon Grade Plutonium (90% ^{239}Pu)*
2. *Typical Reactor Grade Plutonium (Approximately 60% ^{239}Pu)*
3. *Very-high-burnup Reactor Grade Plutonium (40% or less ^{239}Pu)*
4. *Low Enriched Uranium (^{235}U+^{233}U <20%)*

Although not specifically included in this categorization, other potentially weapons-usable materials (such as Cf, Cm, Am) can be folded into these categories by comparing their attributes against those of the uranium and plutonium materials cited here.

Chemical Barrier

The chemical barrier refers to the extent and difficulty of chemical processing required to separate the explosive fissionable material(s) from accompanying diluents and contaminants. Attributes of the chemical barrier generally relate to the degree of technical difficulty needed to refine materials into the appropriate form, be they metals or compounds. Other possible attributes include the existence of admixtures (such as those incorporated to frustrate chemical separations, or denaturing), and the number of separate processing steps needed to obtain materials of sufficient purity for weapons applications.

The chemical barrier effectiveness of some of the more common materials involved in the nuclear fuel cycle can be classified as :

2. *Pure metals*
3. *Compounds (including oxides, nitrides, etc.)*
4. *Mixed compounds (in particular MOX fuel, and including diluents and burnable poisons, but not including fission products or other radiation barriers)*
5. *Spent-fuel and vitrified wastes*

Radiological Barrier

There are many attributes one might select to describe the effectiveness of the radiological barriers, among them: the specific dose rates (for example at the surface of the material or container) or the time required to accumulate a significant dose (say the mean lethal dose). Radiological barriers can, in some cases, complicate chemical processing. Other possible attributes could categorize the materials by the degree of remote handling required; for example (in order of increasing severity) unlimited hands-on handling acceptable, limited or occasionally hands-on access acceptable, long-handled tools and/or isolation and/or remote manipulation (such as in gloveboxes) required, fully remote and/or shielded facilities requires.

The National Academy of Sciences (1995) chose to describe the material radiological barrier effectiveness as follows:

Natural, low-enriched or depleted uranium

Highly enriched uranium

Weapons grade plutonium

Reactor grade plutonium

Spent fuel and plutonium mixed with high-level waste

Mass and Bulk Barrier

To construct a nuclear weapon, a proliferator must obtain at least one critical mass of appropriate explosive fissionable material. If the material is dilute, then the total amount of material one must obtain, transport and process is large, and the mass barrier would be significant. Conversely, if the material is concentrated, then less bulk must be obtained and the barrier is considerably lower. Other attributes besides the concentration of material itself are important. Although fissile material is often in relatively concentrated forms, it is often incorporated into bulky items or configurations that are themselves not easy to obtain or transport; for example, MOX fuel in a complete fuel assembly. The shear bulk and unwieldy character of the MOX fuel assembly acts as a barrier to theft or diversion. Another attribute of the mass and bulk barrier is the ease of concealing the material being diverted or stolen. Materials that are easily transportable and concealable represent a significant risk.

The following characterization is suggested:

0. *Small amounts of weapons-usable materials can be easily concealed and transported, with sufficient concentration that a significant quantity can be accumulated in a few trips*
1. *Similar to 0, but significantly more difficult to conceal*
2. *Large quantities of materials must be transported requiring a significant number of multiple trips and/or several individuals*

3. *Large quantities of materials must be transported requiring commonly available vehicles and equipment*
4. *Large quantities of materials must be transported requiring specialized equipment and/or vehicles and/or Large quantities materials of low concentration requiring many trips using readily available vehicle and equipment*

1.3.2 Attributes of Technical Barriers

As discussed previously, technical barriers are the intrinsic technical elements of the fuel cycle, its facilities, processes and equipment that serve to make it difficult to gain access to materials, and/or to use or misuse facilities to obtain weapons usable materials. Misuse of facilities includes the replication of facilities, processes and technologies to support weapons development programs. Some of the intrinsic technical barriers include: unattractiveness (i.e. lack of utility for weapons use) of facilities, equipment and processes for producing weapons useable material; the extent to which facilities and equipment inherently restrict access to fissile materials; process throughput and materials accountability; applicability of skills, expertise and knowledge; timing and location.

Facility Unattractiveness

The extent to which facilities, equipment and processes are resistant to the production of weapons useable materials is an important intrinsic barrier. Those that cannot be modified to produce weapons useable material have a high barrier, and those that can directly produce weapons useable materials have a negligible barrier to proliferation threats. A number of attributes can be used to describe the difficulty associated with obtaining weapons materials from facilities.

a) The complexity of modifications needed to obtain weapons useable materials, including the need for specialized equipment, materials and knowledge, and the general availability of such specialized skills, material and knowledge.
b) The cost of modifying a facility or process to obtain weapons useable materials
c) The safety implications of such modifications.
d) The time required to perform such modifications.
e) Facility throughput
f) Existence and effectiveness of "observables" (e.g., environmental signatures that can be remotely sensed or observed) associated with facility modification and misuse.

The facility unattractiveness barrier can roughly be characterized as follows:

0. *Those facilities, equipment and processes that routinely use, handle or produce significant quantities of directly weapons-useable materials, and those that can do so with no modifications. Probably no significant observables*
1. *Those facilities whose designs lend themselves to quick, safe and easy modifications (on the order of a week) to produce directly useable materials with reasonable throughputs (a significant quantity / week). Observables difficult to detect prior to accumulation of significant quantities of materials*
2. *Facilities that require considerable engineering expertise, expense and time (~ a month) to modify to produce significant throughputs (~ 1 SQ / month). Probably observable within time required to complete modifications and accumulation of significant quantities of materials*

3. *Facilities capable of modification given substantial time (months to years), money and expertise, compounded by difficult safety and throughput issues, and likely highly observable*
4. *Facilities with little potential or appeal for modification, through a combination of technical complexity, cost, detectability and insignificant throughput*

Facility Access

The extent to which facilities and equipment inherently restrict access to fissile materials represents an important barrier independent from institutional barrier including security and access controls which limit access. For example, reactors with on-line refueling may be considered to have a lower proliferation barrier than those designed for unrefuelled operation throughout their lifetime. Similarly, facilities with a high degree of remote, autonomous processes and operations may be considered to present a higher barrier to proliferation than those with more hands-on operations.

Attributes that help describe the effectiveness of inherent access barriers might include:

a) The difficulty and time necessary to perform operations leading to access to materials, equipment and processes of concern (for example, the time required to remove a reactor head for refueling). Difficult and time-consuming operations represent a higher barrier than quick and simple operations.
b) The need for and availability of specialized equipment, skills and knowledge to gain access. Operations having specialized requirements represent a higher barrier than those requiring no special needs.
c) The extent of manual vs. automatic, remote or autonomous operation, with remote, autonomous operations representing a higher barrier than manual operations.
d) The frequency of operations potentially supporting a proliferator end (such as refueling which may provide access to fuel) with infrequent operations representing a higher barrier and frequent operations a lower barrier.

These attributes can be used to characterize the intrinsic access barrier as follows:

0. *Those facilities with for which access to sensitive materials, equipment and technology is quick and easy, and for which frequent-hands on access is considered normal.*
1. *Facilities where access is normally accomplished via automated, remote processes, and where manual operations are limited to infrequent but routine procedures (such as maintenance) requiring substantial time and effort to obtain access (such as long cool-down times).*
2. *Facilities where access is extremely difficulty, requiring highly specialized skills and equipment not normally found in proximity to the access point, and where access is only required in highly unusual circumstances.*

Facility Materials Detectability

Most processes and operations incur uncertainties in materials accountability and process control, and these uncertainties can serve to mask diversion and/or theft of material. The amount of material considered “unaccounted for” because of these uncertainties increases with throughput and precision of process materials accountability systems. Thus, processes that have high throughputs and high uncertainties represent in themselves a lower barrier to proliferation than those with low throughput and low uncertainties. However, the highest and most precise material accountability is only possible with relatively pure material where spurious radiation signatures are small. These highly purified materials are then a lower barrier to proliferation themselves. For this reason we have chosen as an attribute the ease of detecting diversion and/or theft.

Attributes that can serve to characterize the materials detectability barrier include:

a) The type of material and processes involved and the difficulty of removing highly radioactive material past portal detectors.

b) The type of process is important, and whether high radiation barriers and whether high radiation levels are maintained at all processing stages.

c) Uncertainties in detection equipment, including screening for dummy items.

d) The form of the material is amenable to item counting.

The effectiveness of the materials detectability barrier may be characterized as:

0. Facilities with no or minimal detection equipment and procedures that allow material to easily move without detection.

4. Facilities possessing detection equipment and procedures that make it very difficult and unlikely for material to move without detection.

Skills, Expertise and Knowledge

Most nuclear fuel cycle facilities, operations and processes involve skills, expertise and knowledge that may be applied to support a weapons development program, although not equally in different parts of the fuel cycle. Some attributes that might apply to determining the extent to which such information can support a weapons development program might be:

a) The level of specialized skills and knowledge necessary to support specific element of the fuels cycle (the "availability" of "dual-use" skills – skills that can serve both peaceful and weapons programs). In general, the absence of specialized skills represents a higher barrier than the existence of such skills.

b) The extent to which such information is directly applicable to weapons development, and ("applicability" of "dual-use" skills). A lack of applicable skills represents a higher barrier than the existence of such skills.

c) The extent to which such information is generally available ("alternate sources" of skills). The time required to achieve some level of expertise from available sources may be part of this attribute. General availability and alternate sources of applicable skills represents a lower barrier to proliferation than lack of such sources.

A rough characterization of the effectiveness of the skills, expertise and knowledge barrier is:

0. The process, technology or facility provides significant and unique technical expertise having direct application to a weapons development program

1. Existence of skills, knowledge and expertise that can provide support or insights valuable to a weapons program, or shorten the time required to obtain expertise through training, etc.

2. Only general industrial skills are needed to support the technology or facility and they are well known and are readily available from a number of common sources.

Temporal Aspects

The time that materials (and to some extent facilities and technologies) are available to a potential proliferator is an important element in determining the overall effectiveness of the barriers to proliferation. To a first approximation, storage of materials and equipment represents the greatest time-related proliferation threat. In general, long storage times for materials and equipment provide a potential proliferator with plenty of opportunity for access (and thus a very small proliferation barrier), while materials with very short or no storage delay represent less proliferation risk and therefore a higher barrier to proliferation.

Following is a characterization of the effectiveness of the temporal barrier:

1. *Long storage time (decades) with opportunity for access to materials and/or equipment*
2. *Long storage time but with low opportunity for access*
3. *Intermediate storage time (years) and low opportunity for access*
4. *Short or no storage time (days to months) and low opportunity for access*

1.3.3 Attributes of Institutional Barriers

Institutional barriers are those practices, controls, and arrangements designed to protect against various threats, thereby compensating in whole or in part for weaknesses of intrinsic material or technical barriers, or for the potential of other aspects of the nuclear energy system to contribute to proliferation. These include international safeguards, -MPC&A, highly effective and well-integrated safeguards measures based substantially on real-time monitoring, and other measures such as controls over sensitive information, export controls, etc. There are additional extrinsic barriers that may be considered institutional in nature, such as the economic and political stability of the region or nation where the nuclear system (or its elements) are located and the commitment of the country to nonproliferation goals.

Examples of institutional barriers that technology can directly impact include: safeguards (including MPC&A); access control and security (including both physical security at the installation site and the ability to respond quickly and effectively to threats). National and international laws provide frameworks for controlling use, import and export of nuclear materials, knowledge and supporting technologies; institutional stability; international involvement; and commitment to nonproliferation goals.

Safeguards

Safeguards are effective to the extent that they can:

- Provide reasonable and acceptable assurance that operations are “normal”, i.e. provide effective transparency, and
- Reliably detect illicit activities as early as possible.

Attributes that can help describe the effectiveness of safeguards include consideration of:

a) availability of and access to relevant information
b) minimum detectability limits for materials
c) existence of conspicuous signatures and the ability to detect illicit activities (intrusion, unexpected movements of equipment or materials, illicit processing, etc)
d) response time of detectors and monitors
e) existence, precision and frequency of material and process inventory and control procedures
f) incorporation of safeguards measures into facility and process design and operation

There are many attributes to consider. For our purposes, the safeguards barrier ranges from:

0 *Safeguards monitoring parameters are limited and complex to interpret, evidence for diversion may be ambiguous, uncertainty in materials status increases rapidly if monitoring is restricted or delayed, and margins for error in meeting timeliness of detection goals are small.*

to

4 *Multiple monitored parameters provide easily interpreted, independent data, uncertainty in materials status increases slowly if safeguards monitoring is temporarily degraded or interrupted, and margins for error in meeting timeliness of detection goals are large and robust.*

Access Control &Security

Access control and physical security measures are particularly effective as deterrents to third-party actions leading to theft and diversion of materials, but also serve as a deterrent to misuse of facilities. These are different than facility access in being institutional additions, not inherent to the system. Some of the attributes that may help characterize this barrier include:

a) Administrative steps necessary to obtain access

b) Physical protection and security arrangements

c) Existence of effective backup support

d) How effectively can access control and security be implemented and supported if needed, e.g., whether the technology supports co-location of sensitive activities

The effectiveness of this barrier may be characterized as:

0. *Few administrative or physical access controls*
1. *Administrative and physical access controls with limited local security*
2. *Effective administrative and physical access controls supported by effective security and backup forces and international agreements*

Location

Location represents an important barrier in several ways. Operations at widely dispersed locations require transport of materials between them, and transport itself involves risk. On the other hand, co-located facilities may only require on-site transfers that represents reduced risk (and thus a greater barrier). Site remoteness and difficulty of access to the site also play important roles, but one must be careful to weigh both positive and negative implications of remoteness and/or co-location (e.g., difficulty of obtaining a competent workforce in remote areas. Co-location would appear to lessen the threat of sub-national attack on transport but it might make state diversion easier).

Attributes contributing to the effectiveness of the location barrier include:

a) Distance between associated facilities (co-located facilities require material transport over lesser distances and thus offer a greater barrier to proliferation than widely disperse facilities)

b) Site remoteness (remote sites can be more difficult to access, unauthorized access may be easier to detect)

c) The location barrier effectiveness will need to be characterized only after careful evaluation of the <u>net</u> value of location.

1.3.4 Policy & Legal Frameworks

Although they are outside the realm of technical means, organizational infrastructures to carry out that legal framework are important barriers to proliferation. The development of improved technical means should be compatible with and supportive of this framework. International involvement, including bilateral and multilateral arrangements, in the operation of fuel cycle facilities have served as effective barriers to proliferation by decreasing the probability that the facility or material can be diverted or misused, since multi-party collusion would be needed to implement effectively. A nation's demonstrated commitment to nonproliferation goals is also a significant barrier to proliferation. This commitment is demonstrated not only by developing the national and international legal frameworks discussed above, but also by the implementation of policies supporting nonproliferation goals.

A wide battery of measures have been established with the IAEA as the key international organization. These include the application of international safeguards and inspection measures, a range of important protocols and treaties including broad adherence to the Non-Proliferation Treaty, security guarantees, physical security and related central measures, nuclear export controls and regulations, and supplier state agreements, and the application of national intelligence measures. A broadly held political ethic has been developed in the international community by several nations that is strongly adverse to the acquisition of nuclear weapons.

Much of the effectiveness of this "commitment to non-proliferation" barrier depends on the existence of a stable political, economic and military environment. Stable regions may tend to maintain their commitments (either for or against the acquisition of nuclear weapons). Thus, stable regions committed to nonproliferation goals are likely to remain so, and those desiring nuclear weapons will likely remain committed to that desire. Moreover, regions lacking stability may even choose to subvert or abrogate such controls to acquire nuclear capabilities.

1.4 Nuclear Fuel Cycle

In order to utilize Table I to compare systems and/or sub-systems for their proliferation resistance, the fuel-cycle steps must be considered. While they will vary from system to system, certain basic steps must be acknowledged even if they are replaced or removed. The basic steps are:

Front-End

- Mining, milling and conversion
    - Enrichment
    - Fuel fabrication, including:
  - Fuel material manufacture
  - Fuel material blending (if using recovered/recycled material)
  - Fuel fabrication and assembly
- Fuel shipping

Reactor Operations

- Fresh fuel receiving, storage, handling, and fuel loading
- Reactor operations
- Spent fuel unloading
- Spent fuel storage

Back-End

- Spent fuel transportation
- Interim storage
- Spent fuel reprocessing and/or treatment, including:

  - Chopping/shearing or otherwise disassembling fuel
  - Dissolution and chemical processing
  - Separation from fission products
  - Isolation of concentrated fissile materials
  - Waste processing
- Materials storage
- Materials transport
- Long-term disposition

1.5 Retrospective

This is one approach to determining attributes to apply to the problem of assessing the proliferation-resistance of civilian nuclear power systems. Others have defined proliferation issues, threats, barriers and attributes. Elucidation of attributes by the method described here should help to address the relevant issues. However, other approaches provide a useful check on the work we do. For example, any attempt to ascribe attributes should answer fundamental questions about commonly used criteria such as:

- Material attractiveness (the amount of material, its ease of conversion into a weapon, etc.)
- Material availability (operational factors that produce the material at any step)
- Material accessibility (operational factors that make the material more or less available)
- Facility attractiveness, availability, and accessibility (use of a civilian facility to roduce nuclear weapons and the ease of doing so)
- Materials and facilities detectability and accountability.
- Personnel and expertise applicable to nuclear weapons development.

Similarly, several related key issues should also be resolved:

1. The extent to which the system (or subsystem in the context of the entire system) results in directly weapons-usable nuclear material that might be diverted or stolen.
2. If the system does not involve directly useable weapons material at any point, the relative difficulty and/or time to convert the material to weapons useable material (overtly or covertly).
3. The extent to which the system can be, or is, effectively safeguarded (with active and passive measures) so that diversion of even small quantities would be reliably and quickly detected, and any attempted theft would be quickly and reliably prevented.
4. The extent to which the facilities involved in the cycle could be used directly or readily modified to produce weapons useable material.
5. The extent to which the establishment of this system in a specific state would contribute to building up a base of expertise and trained personnel that would make it easier for that state to produce weapons-usable material, and therefore nuclear weapons.
6. The extent to which the establishment of this system in a particular country provides “cover” for purchases of equipment and technologies that could substantively contribute to a nuclear weapons program, either in that state or elsewhere.

Table 1

		Material Barriers				**Technical Barriers**				
Step	Substep	Isotopic	Radiological	Chemical	Mass/Bulk	Unattractiveness	Facility Access	Detectability	Skills	Time
Front End	Mining									
	Transportation									
	Milling									
	Transportation									
	Conversion									
	Transportation									
	Storage									
	Enrichment									
	Transportation									
	Storage									
	Fuel Fabrication									
	Storage									
	Transportation									
Reactor Operations										
	Storage									
	Fuel handling									
	Reactor irradiation									
	SF handling									
	fuel pool storage									
	handling									
	dry storage									
Back End										
	Transportation									
	Storage									
	Processing for direct disposal									
	Transportation									
	Repository emplacement									
	Reprocessing									
	Storage									
	Fuel Fabrication									
	Transportation									
	Storage									
	(return to reactor operations)									