Technological Opportunities To Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS)

January 2001

Report by the TOPS Task Force of the Nuclear Energy Research Advisory Committee (NERAC)

TECHNOLOGICAL OPPORTUNITIES TO INCREASE THE PROLIFERATION RESISTANCE OF GLOBAL CIVILIAN NUCLEAR POWER SYSTEMS (TOPS)

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INTRODUCTORY NOTE

The U.S. Department of Energy (DOE) Office of Nuclear Energy, Science, and Technology and DOE's Nuclear Energy Research Advisory Committee (NERAC), established a special Task Force in 1999 to identify near and long-term technical opportunities to increase the proliferation resistance of global civilian nuclear power systems (TOPS) and to recommend specific areas of research that should be pursued to further these goals. The Task Force was also encouraged to recommend areas where international collaboration can be most productive.

This special report reflects the results of the Task Force studies. It consists of:

- An Executive Summary that contains the major findings and conclusions of the group.

- A more detailed report, plus attachments, that addresses various specific questions and issues in more detail.

The membership of the TOPS Task Force was designed to represent a broad spectrum of backgrounds and viewpoints and includes the following individuals:

John J. Taylor, Chair, EPRI
Robert N. Schock, Vice Chair, Lawrence Livermore National Laboratory
John F. Ahearne, Sigma Xi, Duke University
Edward D. Arthur, Los Alamos National Laboratory
Harold Bengelsdorf, Bengelsdorf, McGoldrick and Associates, LLC
Matthew Bunn, Harvard University
Thomas Cochran, Natural Resources Defense Council
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Mark Strauch, Lawrence Livermore National Laboratory
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Since the subject of enhancing proliferation resistance through advances in technology has broad international implications and can only succeed with international support, the Task Force included knowledgeable international representatives. Beyond this, major efforts were undertaken to factor the views of various research groups, industry, and technical organizations into the deliberations through the sponsorship of workshops and meetings with interested individuals and organizations.

The Task Force believes that there are a number of promising areas of research and development (R&D) that can be, and should be, pursued by the United States in collaboration with other countries that are likely to enhance the proliferation resistance of existing and potential advanced nuclear power systems. It is recognized that proliferation resistance is only one of the important components of complete nuclear power systems that are in need of further research and development; others are steps that will advance economy, safety and waste disposal. Continued U.S. participation in strengthening the global nonproliferation regime will depend, in part, on the preservation of U.S. technological capabilities in the civil nuclear sector, including a strong U.S. capability to carry out realistic and well-focused nuclear energy supply research and development. In turn, achieving and preserving this capability will require both greatly increased government investment in forward looking R&D and the application of effective selectivity in deciding which of the several competing approaches should receive priority. This is a matter of compelling significance from the perspective of achieving vital U.S. foreign policy, arms control and energy security.

DOE recently has been attempting to revive R&D capabilities in this very important area. The amounts now being spent on civilian nuclear energy R&D, including proliferation resistance, are far smaller than those being directed toward other areas of energy R&D, and are substantially smaller than would be needed to make substantial progress in nuclear energy technology. As the 1997 report of the President's Committee of Advisors on Science and Technology concluded, it is important to establish nuclear energy as a broadly acceptable and viable energy option to help respond to future greenhouse challenges, if possible, and to do so additional R&D investment is needed to address concerns over waste management, safety, weapons proliferation, and cost.

Accordingly, in the view of the Task Force, a larger, more proactive and more directed research and development program in these areas would significantly strengthen U.S. influence in shaping proliferation-resistant approaches to nuclear energy around the world.

While the Task Force's principal charter was to review R&D opportunities to develop new technologies to enhance proliferation resistance, we felt compelled also to point out that a wide range of policy opportunities exists to improve proliferation resistance using technologies that already exist. In particular, it is urgent to:

- Reduce the risk of theft of potential weapons material (particularly in the former Soviet Union, where the risk of such theft has been described by the National Academy of Sciences as a clear and present danger, by applying available technologies to ensure that all such material is secured and accounted for to the most stringent practicable standards;
- Strengthen the international safeguards systems, including increasing the resources available to the International Atomic Energy Agency (IAEA), to allow it to effectively implement both traditional and newly developed safeguards measures; and
- Strengthen efforts to control the export of technologies that could significantly contribute to nuclear weapons programs.

John Taylor, Chairman
TOPS Task Force

Robert Schock, Vice Chairman

EXECUTIVE SUMMARY

Purpose

In 1999 the U.S. Department of Energy (DOE) formed a special task force, called the TOPS Task Force, from the Nuclear Energy Research Advisory Committee (NERAC) to identify near- and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems. Recommendations on specific areas of research were called for, as well as on areas where international collaboration could be most productive. This report is the response to this ambitious charge and is essentially a work in progress, suggesting directions of effort for the cognizant organizations.

The membership of the TOPS Task Force was chosen to represent a broad spectrum of backgrounds and viewpoints. Since the subject has broad international implications, knowledgeable representatives from overseas were included. Beyond this, major efforts were undertaken to factor in the views of various research groups, industry, and technical organizations through the sponsorship of workshops and meetings with interested individuals and organizations. The task force operated on a consensus basis: While there were differences of opinion on the merits and relative promise of some of the opportunities for development of advanced reactor and fuel cycle systems, all members fully support the basic recommendations.

The report covers four major topics: (a) the overall context in which nuclear power is being pursued at the present time, (b) the need and challenge to develop more systematic comparative nonproliferation assessments of different nuclear systems and their potential applications, (c) the technological opportunities meriting exploration that have the potential to increase the proliferation resistance of future civilian nuclear power systems, and (d) the principal research and development (R&D) objectives that the U.S., working in a spirit of collaboration with other countries, should pursue to enhance the global nonproliferation regime.

The Context of the Study

Two working premises guided this study:

- Nuclear power has the potential to continue making important contributions in helping meet future global energy needs under terms that are compatible with safety, economic, nonproliferation, and environmental objectives, including the desire to abate air pollution and greenhouse gas emissions.
- Unless the U.S. pursues a much more proactive R&D program in the civil nuclear field, its technical influence in advancing those aspects of the non-proliferation regime that relate to civil nuclear energy could seriously erode as could its ability to help shape and influence proliferation resistance choices in other countries.

After an in-depth review based on these premises, we have concluded that there are promising technical approaches that might well increase the proliferation resistance of civilian nuclear systems. Furthermore, a significant investment in R&D is warranted to evaluate these approaches and pursue those identified as most promising.

The international community has developed a wide range of measures collectively known as the "international nonproliferation regime" under which the majority of nations have agreed to forego the manufacture or acquisition of nuclear weapons. The centerpiece for this regime has been the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which was extended indefinitely in 1995 and now has 187 signatory nations. After the Gulf War of 1990-91 and the discovery of clandestine nuclear weapons activities in Iraq, new safeguards measures were developed to give the International Atomic Energy Agency (IAEA) additional capability to investigate undeclared activities. In addition to new measures using existing legal authorities, a new Model Protocol for the IAEA was agreed to which provides authority for additional measures expanding their safeguards capabilities. These new provisions comprise the most significant improvement in international safeguards in recent times. More broadly, the institutional features of the global nonproliferation regime, including safeguards, constitute an essential, if not dominant, element of the efforts to abate the spread of nuclear weapons. It is in this context that the recommendations of this report have been formulated.

The Task Force recognizes that technology can play a very important role in strengthening the overall nonproliferation regime along the following lines:

- Improving the effectiveness of surveillance, monitoring, inspection, accountancy, and physical security measures that are embedded in institutional controls;

- Devising new inherent technical features which promise to make nuclear power systems more resistant to proliferation;

- Reducing opportunities for the misuse of, or the diversion and theft from, civilian nuclear activities;

- Increasing the complexity, transparency, and cost of diverting nuclear materials for use in nuclear weapons, as well as the time it would take for a state to divert nuclear materials so as to give the international community sufficient time to detect such activity and take appropriate action;

- Reducing the accessibility of weapons-usable nuclear materials; and

- Reducing the degree to which civilian nuclear energy programs may provide opportunities for States or groups to build up expertise for potential proliferation and to acquire (overtly or covertly) technologies that could be employed for nuclear weapons programs.

- Specific technologies employed in the civilian nuclear sector are likely to have only a modest impact on the overall rate of nuclear proliferation. Historically, the preferred approach for nations seeking nuclear weapons generally has been to establish a dedicated military program to produce the nuclear material rather than attempting to divert material from internationally safeguarded nuclear facilities. Nevertheless, civilian nuclear activities can make direct or indirect contributions to the spread of nuclear weapons.

Consequently, the continued exploration of new technical ways in which nuclear power systems can be made more resistant to proliferation should constitute an important ongoing feature in the improvement of the global nonproliferation regime. This will occur more effectively when institutional schemes are devised so as to reward technical increases in proliferation resistance. Further, within this context and as an organizing theme, the Task Force believes that U.S. R&D planners should pursue the following important objectives:

- Systematically evaluate the nonproliferation implications of existing and new technologies

- Support the exploration, and as appropriate the further development, of systems that:
  - increase the effectiveness and efficiency of institutional non-proliferation measures (e.g., safeguards measures);
  - make weapons-usable materials highly inaccessible, including the evaluation of advanced open and closed fuel cycle systems that avoid direct access to these materials;
  - reduce the attractiveness of nuclear materials for potential weapons purposes;
  - reduce the quantities of weapons-usable material utilized and produced per unit of energy output; and
  - limit the spread of highly specialized knowledge and skills that can be directly used to design and fabricate nuclear weapons.

- Evaluate, in cooperation with other interested countries, a range of reactor and fuel cycle options that could potentially meet the above objectives. (This effort should be appropriately integrated with other efforts designed to assure that future systems will be economical, safe, and environmentally friendly.)

Comprehensive assessments have been performed within the United States and with other countries, on the comparative inherent nonproliferation characteristics of different nuclear power systems. Two key assessment efforts in the 1970s were the Nonproliferation Alternative Systems Assessment Program (NASAP) review carried out by the U.S. followed shortly thereafter by the major International Nuclear Fuel Cycle Evaluation (INFCE) convened under the auspices of the IAEA that involved the participation of more than 60 nations and international organizations. The Task Force has drawn and benefited from these reviews as well as more recent assessments and has employed them as a beginning basis for assessing the proliferation resistance of different nuclear power systems.

<u>Current and Near Term Status of Nuclear Power</u>

At the present time, 434 nuclear power stations are located and in operation in 34 countries around the world and the clear preponderant reactor of choice is the light water reactor, with 344 plants. In the nearer term, there are limited prospects for constructing new nuclear power plants in Europe or in the Americas although new plants are being built or are planned in some Asian countries.

While several developing countries have long expressed an interest in nuclear power, it has not yet figured significantly in the energy plans of many less-advanced nations, due to several considerations. Most notably, many developing countries lack the sophisticated technical infrastructures and grid sizes to absorb and deploy currently available large-sized nuclear reactors in their electricity systems. Yet, at the same time the needs and demands for electricity in some developing countries are expected to grow substantially and the question arises as to whether nuclear power can help meet these needs.

In this regard, some attention is being devoted to evaluating the merits of smaller, modular, simpler, and more passively safe reactor systems that might be better suited for introduction in less advanced countries. In addition, in the interest of enhancing proliferation resistance, attention also is being given to the merits of fueling some of these concepts with materials that would markedly reduce the frequency of refueling or the production of materials attractive for nuclear weapons.

Enrichment facilities, primarily using diffusion and centrifuge processes, have been constructed in ten countries. Worldwide installed enrichment capacity is currently on the order of 50 million separative work units (SWU) annually, against a demand on the order of 36 million SWU. The situation is more complex than these bare figures suggest as, on the one hand, a significant part of the demand is being filled with enriched material blended from dismantled weapons and civilian recycled plutonium, while on the other hand enrichment plants are most profitable when operated at maximum capacity. However, the basic point remains that world enrichment capacity is more than sufficient to meet near-term demands. Given this over-capacity and the high cost of building and operating enrichment plants, if new facilities are built in the near term it will be most likely for reasons of energy autonomy or national pride, not because of the financial attraction of such facilities. Yet, in the longer term, if nuclear power expands greatly, more enrichment facilities would needed and could become more widespread.

The basic technology of reprocessing has been declassified and widely available for many years, but only a few industrialized countries are now engaged in reprocessing programs on a commercial scale. Nevertheless, the inventories of separated plutonium substantially exceed current demand and as a result more than 200 tons of separated plutonium is now in civilian stockpiles around the world, a figure that is continuing to grow. Beyond this, much larger amounts of plutonium in spent fuel are dispersed in numerous locations around the world. Since spent fuel has an ongoing sensitivity from a proliferation perspective, there has been a growing interest in exploring ways that the inventories of these materials can be aggregated under IAEA safeguards in a limited number of stable countries with strong nonproliferation credentials, independent of the question as to whether the plutonium in the spent fuel should be directly utilized in reactors. Studies are also underway to evaluate the merits of transmuting spent nuclear fuel to forms of less proliferation concern.

In carrying out this study, no attempt has been made by the Task Force to perform an exhaustive assessment of the <u>likelihood</u> of different scenarios for the potential growth and use of nuclear power. Projections prepared by various groups range from a modest decline in global capacity to a substantial growth in nuclear energy by the year 2050. A middle ground has been chosen by the Task Force that postulates a civilian nuclear world in the next few decades with the following major features:

- The light water reactor is likely to be the reactor of choice in the nearer term, although some nations will continue to have an interest in heavy water reactors. Most nations now employing light water reactors of Western design will be successful in their efforts to obtain regulatory approvals and/or implement effective aging management programs to extend the operating lives of their reactors. Some older, more poorly performing plants, or plants of more controversial design may be shut down.

- It seems likely that most nations will opt to store their spent fuel on an interim basis, pending decisions on later disposition, processing, or transmutation of these materials. However, a limited number of nations will continue to reprocess some of their spent fuel and recycle some of their separated plutonium as mixed oxide (MOX) fuel in thermal reactors, pending possible later use in more advanced reactors.

- While Germany and Sweden have adopted laws requiring eventual shut-down of all their nuclear power plants, it is unlikely that most nuclear power programs will be phased out entirely. Even if this were to occur, the nations involved as well as the international nuclear community will face an ongoing responsibility for managing the inventories of separated plutonium and other weapons-usable materials in their possession as well as the vastly greater inventories of plutonium that exist in spent fuel.

- There are different views within the international community as to how the "back-end" of the nuclear fuel cycle can best be managed or whether this question simply should be deferred. The United States, for its part, does not now "encourage the civil use of plutonium and accordingly, does not itself engage in plutonium processing." However, while the U.S. actively seeks to limit reprocessing in regions of proliferation concern, it has emphasized that it will "honor its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan."[1]

- Although most fast reactor demonstration programs have been curtailed and the economic commercialization of fast reactors has not been achieved, a limited number of nations remain interested in the development of this technology. This relates to the fact that fast spectrum reactors use dramatically more of the energy content of uranium and may reduce long-lived waste production over currently deployed reactor systems. Several of these countries are assessing new technical approaches that could be more proliferation-resistant through processes that would avoid the presence of separated plutonium.

- In the current climate, only a limited number of nations have deployed uranium enrichment technologies, and key enrichment technologies remain tightly controlled. Nevertheless, some States have succeeded in overtly or covertly acquiring enrichment technologies that have been used in their nuclear weapons programs. Taking these factors into account, one must assess the proliferation implications of different approaches to the future of nuclear energy. In the process, all potential technical routes to the acquisition of nuclear weapons must be considered, including those involving access to highly enriched uranium (HEU) (U-235 and U-233), Pu-239, and other fissionable isotopes.

In the foregoing overall context, the Task Force believes that different fuel cycles and reactor choices may continue to be followed by different nations. However, in all practicable cases, it will be desirable for the United States to be involved in cooperative R&D efforts with other nations and to have the technical ability to influence these programs so that they advance in ways that enhance proliferation resistance while also advancing economic and safety objectives. To this end, a new U.S. effort to pursue R&D at least initially at the conceptual level (and involving the conduct of analytical and experimental studies) that would evaluate and explore advances in proliferation resistance in different nuclear systems could strengthen the U.S. ability to exert a constructive technical influence on future developments. More broadly and for the longer term, for nuclear power to provide a significant fraction of the carbon-free energy the world is likely to need in the 21st Century, the utilization of nuclear power would have to expand many fold. The realization of this goal may be dependent, in part, on broad confidence in governments and publics that such an expansion will not significantly aggravate the proliferation problem. Thus, continued improvements in proliferation resistance, like continued improvements in nuclear safety, waste management, and economics are important to the future growth of nuclear power.

<u>Proliferation Resistance Assessment Initiatives and Their Potential Application</u>

A wide range of significant factors will determine whether additional nations will acquire nuclear weapons. Specific technologies employed in the civilian nuclear sector are likely to have only a modest impact on the overall rate of nuclear proliferation. Historically, the preferred approach for nations seeking nuclear weapons generally has been to establish a dedicated military program to produce the nuclear material rather than attempting to divert material from internationally safeguarded nuclear facilities. Nevertheless, civilian nuclear activities can make direct or indirect contributions to the spread of nuclear weapons. Some nations have employed nominally civilian nuclear programs as a pretext to acquire technologies for military programs or they have acquired materials, equipment, technologies, or technical personnel from the civil sector for their nuclear weapons programs. Consequently, the United States and many other countries have had a strong incentive for many years to develop a series of measures to assure that the utilization of nuclear power and civil nuclear cooperation will take place only under terms designed to seriously inhibit the misuse of the technology to acquire nuclear weapons.

These possibilities of misuse, however, cannot be eliminated entirely. Accordingly, the "proliferation resistance" of a given system is a matter of degree, not an absolute attribute. Developing an acceptable methodology is difficult, since both quantitative and qualitative factors contribute, and weights assigned to different factors are inherently a matter of judgment. Factors inherent to the particular reactor and fuel cycle system design under consideration, as well as

[1] White House National Policy Statement of September 1993.

institutional factors, must be considered and balanced. Moreover, the proliferation risk posed by a particular system depends on the character of the threat, whether it be a sophisticated or unsophisticated state seeking nuclear weapons, or even a terrorist group.

In view of the need to advance the evaluation process and in spite of the difficulties, efforts should be undertaken to improve and, where practicable, standardize the proliferation assessment of different reactors and fuel cycle approaches for use in planning future R&D programs. These methodologies should not be considered to yield definitive, quantitative assessments, but should be viewed as a useful means to help the peer review process evaluate the merit of specific proposals and proposed courses of action. It is of key importance that such methodologies provide an integrated assessment that includes the effectiveness of both the technical features ("intrinsic barriers") and the necessary institutional measures ("extrinsic barriers").

A number of such methodologies have been considered and are under development. Two such efforts, described in Appendix 2 of this report, have been examined by the Task Force to help illuminate the discussion. The first is an integrated safeguards evaluation methodology (ISEM) being developed under the U.S. support program for the IAEA safeguards system. The second, called an "attributes methodology" identifies the intrinsic, or material/technical barriers against proliferation in a given nuclear system, attempts to evaluate their effectiveness against the challenges imposed by different types of potential proliferators, and seeks to identify the needed extrinsic barriers to complement the intrinsic barriers. Other assessment methods are also under consideration.

An initial effort to apply the attributes methodology to defining the comparative features of several specific nuclear power systems was made by the TOPS Task Force. This was only done in a preliminary fashion, and the cases covered were not complete in themselves nor do they cover the full scope of systems today or under development. The primary purpose of the exercise was to help identify the major characteristics of various nuclear systems and potential R&D needs. The systems covered in this preliminary analysis included:

- A light water reactor (LWR) operating on a "once through" fuel cycle where the resultant spent fuel is stored for a protracted period or disposed of geologically in a nominal permanent geologic repository. This included concepts such as using non-fertile fuel and thorium-uranium fuels.
- An LWR system operating on a so-called closed fuel cycle where the fuel is reprocessed through a classic aqueous (or PUREX) system with the plutonium either recycled as MOX fuel in LWRs or kept in protracted storage pending decisions on later disposition—which might include use in fast spectrum reactors.
- A fast spectrum reactor operating in a burner or breeding mode employing an advanced recycling technology that does not involve at any stage the separation of pure plutonium.
- A postulated small modular reactor system employing a long-lived core for possible use in both advanced and developing countries.
- Two types of modular high temperature gas-cooled reactors (HTGR): a pebble bed fueled system and a fixed prismatic configuration fuel system.

In general, some of these systems would incorporate substantial intrinsic barriers to theft or diversion of nuclear material for use in nuclear weapons, while others rely more on extrinsic, institutional barriers. In the course of the discussions, some weaknesses in these barriers were identified and some R&D programs were recommended to evaluate or address them.

It would appear that the intrinsic barriers in some systems could be strengthened by successful completion of R&D, but the ongoing need to preserve the strength of extrinsic barriers has been strongly reinforced in the analysis of the Task Force to date. In addition, as an important matter, the application of extrinsic barriers to specific reactor and fuel cycle systems can be made more effective if proliferation resistance assessments, including trade-off studies between intrinsic and extrinsic measures, become an integral part of the overall design and engineering process.

Recommended Areas for Research and Development – Proposed Strategy

As a result of its deliberations, the Task Force recommends that, in collaboration with other countries, the United States should initiate a new R&D program in three major areas. The primary goal of this R&D effort would be to assure that the utilization of civil nuclear power remains a comparatively unattractive route for those nations or groups interested in acquiring nuclear weapons and to limit the degree to which the civilian nuclear energy system contributes to dedicated military programs. Achieving this goal will require a more explicit definition of the goal itself and a systems perspective. This will require an emphasis on the comparative evaluation of various potential pathways to acquiring nuclear weapons including pathways other than civilian nuclear power.

The recommended R&D programs that should be explored and pursued by the U.S., working as appropriate in close collaboration with other countries, are grouped under three major headings:

- Development of improved methodologies for assessing the proliferation resistance of different systems, including those that further the understanding of the trade-offs between intrinsic and extrinsic measures;

- Development and adaptation of technologies to further strengthen the application of extrinsic or institutional barriers to proliferation with major emphasis on safeguards and material protection, control, and accountability (MPC&A); and

- Exploration and further pursuit as appropriate of the development of new technologies to enhance the intrinsic barriers of various systems against proliferation thereby upgrading the global nonproliferation regime and reducing the burdens placed on the extrinsic or institutional systems.

Since research and development will be critical in helping to make subsequent decisions on the appropriate paths to actually follow, the effective implementation of this proposed new R&D initiative will require a strategic planning approach that provides a basis for prioritization and subsequent selection of the desired longer-term R&D portfolio. It is recognized that at each significant step of R&D the evaluation of the benefits/risks of new technical approaches and advanced systems has to take into account other significant objectives including safety, environmental impact, economics, and waste management as well as proliferation resistance.

Framing and implementing the desired new R&D agenda also will require a systems perspective and an emphasis on comparative evaluation. The pursuit of most of the individual projects designed to improve barriers to proliferation should be carried out in the context of the overall development of the reactor or fuel cycle concept to which they are intended to apply and should address all the facilities of an integrated system so as to significantly reduce proliferation and national security concerns. Since several of the advanced concepts that one might choose from will take many years to commercialize, proliferation-resistant improvements should be given significant attention in the early stages of development.

Establishing appropriate and realistic time frames for R&D is important. In concept, R&D programs should be established with three distinct time frames in terms of completion of the development and implementation of the technologies. The initiation of related R&D to be pursued in all three time frames would ideally start now, but selections will need to be made on the desired starting times based on the amount of available funding and, following further screening, the priorities given to various programs. The time phases should include:

- Shorter-term projects likely to produce tangible results in about five years' time.

- Intermediate projects likely to produce tangible results up to about 15 years from now.

- Longer-term projects. A commitment is critical to the longer-term exploration and, as appropriate and feasible, further development of advanced reactors and fuel cycles. However, nearer-term concrete needs should not be ignored in this process.

There is likely to be a high level of synergy among activities in each of these three time frames.

To provide tangible results that can affect proliferation resistance in the nearer-term period of up to five years' time, emphasis should be devoted to such areas as:

- Developing improved and standardized methodologies, including quantitative ones, for performing comparative assessments of the proliferation attributes and merits of different reactor and fuel cycle systems;

- Pursuing various nearer-term and concrete ways to strengthen the application of the extrinsic (or institutional) nonproliferation regime with emphasis on supporting international safeguards and national MPC&A programs; and

- Performing analytic studies and experiments designed to evaluate potential improvements in the intrinsic proliferation barriers for existing nuclear systems as well as potential advances in proliferation resistance in several advanced nuclear reactors and fuel cycle systems.

With regard to extrinsic factors, it was recognized by the Task Force that new technical efforts to strengthen international safeguards have to build on and be well-coordinated with the national support programs for the IAEA safeguards systems that already are underway, as well as U.S. R&D programs that directly and indirectly address these problems. In addition, and as a very important objective, there has to be a closer exchange and integration of ideas and plans between designers of possible new nuclear systems or applications and safeguards specialists.

While the Task Force has not reviewed the extensive ongoing safeguards R&D supported by the United States and other governments, at the TOPS International Workshop held in Washington, DC in March 2000, a working group that included safeguards experts developed a list of potential areas where additional R&D in support of international safeguards and national MPC&A systems would be useful. These included ways to improve: (a) information technologies for safeguards; (b) safeguards system integration and studies (including integrating and balancing traditional and new safeguards measures); (c) material accounting and facility monitoring; (d) wide-area environmental monitoring; (e) material and item tagging; (f) safeguards cost-effectiveness; and (g) the integration of technological developments from a wide range of areas, including areas outside traditional nuclear science, to advance safeguards. Approaches in each of these areas and others should be evaluated and the most promising should be pursued, in close coordination with other safeguards R&D.

Also, in the nearer-term, it will be important to pursue the evaluation of the adverse as well as positive implications that certain technological advances or deployments (such as those permitting production of weapons-usable material in smaller and more readily concealed facilities) might have for the global "extrinsic" nonproliferation regime. In addition, international efforts should be supported that will serve to improve the tracking and resultant transparency of movements of nuclear materials in international commerce as well as in national programs. New R&D approaches also should be pursued that will facilitate the aggregation of spent fuel and provide for improved safeguards at geologic repositories.

The initial emphasis in developing improvements in intrinsic barriers in the nearer-term should be on examining ways to improve proliferation resistance in existing systems and assessing through analytic studies and experiments the potential inherent barriers that might be associated and pursued with the development of more advanced systems. For the first five years of research, the primary focus on intrinsic barrier improvement would be on LWR "once through" systems — e.g., incrementally higher fuel burnup. While not urgent, transient testing and the enhancement of fabrication capabilities for higher burnup fuel could be feasible in the nearer-term. In addition, it is assumed that in the nearer-term DOE will continue to support the development of research reactor fuels that would permit the remaining research reactors using HEU to convert to lower enrichments.

To provide tangible results that could affect proliferation resistance in the intermediate period (from about 6 to 15 years in the future), R&D themes should be explored or pursued that ultimately could lead to advances in the introduction of greater intrinsic proliferation resistance in existing or future nuclear systems. The R&D that has shown particular promise in meeting the nearer term goals should continue to be pursued to seek further improvements.

Among the specific technical options for reactor and fuel cycle systems that have been proposed to improve proliferation resistance are:

- LWR fuel systems designed to produce smaller amounts of less attractive nuclear material in their spent fuel (such as higher burnup, thorium-uranium [Th/U] fuels, and non-fertile fuels);
- LWR systems designed to allow recycle without separating weapons-usable material or providing facilities and processes that could not be readily modified for such separation (such as dry chemical reprocessing or recycle without reprocessing);
- High-temperature gas-cooled systems designed so that the material in their spent fuel would be highly unattractive for weapons use;
- Liquid metal reactor and fuel cycle systems designed to avoid the production and separation of weapons-usable material, or the provision of facilities and processes that could be readily modified for such separation;
- Options for faster and more proliferation-resistant reductions in the world stockpiles of separated plutonium;
- Small modular reactor systems, designed to offer a nuclear energy option with little potential for the host state to have access to weapons-usable materials and only very limited requirements for

transfer of knowledge and technologies that could contribute to nuclear weapons programs;

- Transmutation technologies for spent fuel and nuclear wastes, which could reduce long term safeguards requirements; and
- Dual-use advanced monitoring and analytical systems that can handle both safeguards needs and efficient plant operations, seeking improvements on systems already in place in countries like the United Kingdom and France.

The potential proliferation resistance of these various technological options should be evaluated and R&D should continue to be pursued on those determined to be most promising and that would also meet other basic nuclear criteria (such as improved economics and enhanced safety) central to the DOE nuclear R&D program. The R&D on intrinsic barriers for particular systems that may be selected for support should be conducted from the outset as part of the overall development of such systems.

To provide tangible results that can improve proliferation resistance later than 16 years out, projects/programs should focus on the further evaluation, and, as appropriate, more active development, possibly through pilot plant or demonstration projects, of selected advanced systems and concepts. These efforts should consider and assess advanced light water reactors, liquid metal reactors, liquid-fuel reactors, and gas cooled reactors. Various size reactor concepts should be investigated that do not require refueling for 10 to 15 years, with a realistic emphasis upon reducing dependence on high quality human support. Advanced closed fuel cycle options also should be investigated when they offer potential opportunities for improving proliferation resistance and international security. This should include the examination of systems that would avoid the presence of separated plutonium and HEU and of facilities and processes that could readily be adapted to produce such materials. Systems also should be explored that avoid the transfer of technologies or expertise that could readily be employed in either the covert or overt design and manufacture of nuclear weapons. The incorporation of advanced control systems for performance, reliability, and economics offers the opportunity to bring greater transparency to reactor operations through remote monitoring and other means.

Concluding Recommendations

Taking into account these findings, the Task Force strongly recommends that the subject of proliferation resistance R&D should be allocated at least an additional $25 million in the DOE budget for fiscal year 2002, potentially increasing subsequently if particularly promising opportunities requiring increased R&D funds are identified. A significant portion of these funds, in the range of $5-$8 million annually, should be devoted to adding to ongoing efforts in international safeguards and MPC&A technologies that could improve the extrinsic barriers to proliferation in existing reactor and fuel cycle systems. These new funds should be targeted toward improving the understanding of the interfaces and trade-offs between intrinsic and extrinsic barriers, supporting the development of technologies required to safeguard new fuel cycles (e.g., Th/U in which there is little safeguards experience or technology for measurements, etc.), and improving the transfer of technologies from other fields to international safeguards enhancement programs. A small portion, perhaps $2 million in the first year, should be devoted to improving methodologies for assessing and comparing the proliferation resistance of different proposed systems. The remaining $15-18 million would be devoted to the evaluation, analysis, and experimental work on approaches that could improve the intrinsic proliferation resistance of current and future reactor and fuel cycle systems.

A program such as outlined above would allow the United States to maintain an influential position in the international non-proliferation arena as it relates to civil nuclear technology. It would also provide a base upon which to build a strong proliferation resistance component into the future generation of reactor and fuel cycle designs. DOE will not be able to pursue these goals in anything like a credible fashion unless it is given far greater resources to pursue these R&D goals and unless the nuclear R&D program is reoriented to become more "results-oriented."

International collaboration in proliferation resistance R&D is of prime importance to generate an international consensus on proliferation-resistant technologies as ways to strengthen the global nonproliferation regime. It will also be vital to the preservation of U.S. influence and credibility in these areas.

Collaborative R&D among international partners should focus on the major theme categories identified in this report. Prospects for increased collaboration could include cooperative efforts to improve the methods for assessing proliferation resistance, measures to strengthen international safeguards, R&D related to high burnup fuels, and collaboration in Th/U fuels, non-fertile fuels, and advanced fuel cycle concepts. Given prospective limitations on resources, a careful screening of the merits of different options will have to take place before any major commitments are made to scale up the programs in support of any particular choices.

I. INTRODUCTION

A. Scope and Purpose

At the direction of the U.S. Department of Energy (DOE) and its Nuclear Energy Research Advisory Council (NERAC), a special task force was established in 1999. This group, called the TOPS Task Force, was directed to identify near and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems and to recommend specific areas of research that should be pursued. The Task Force was also encouraged to recommend areas where international collaboration can be most productive.

The charge to, and the membership of, the TOPS Task Force is given in Appendix 1. The membership of the TOPS Task Force was designed to represent a broad spectrum of backgrounds and viewpoints. Since the subject of enhancing proliferation resistance through advances in technology has broad international implications and can only succeed with international support, the Task Force includes knowledgeable representatives from overseas. Beyond this, major efforts were undertaken to factor in the views of various research groups, industry, and interested technical organizations into the deliberations through the sponsorship of workshops and meetings. Most notably an international workshop on this subject was held in Washington, DC on March 29 and 30, 2000. Another meeting was held in Chicago on June 15-16 to gain insights from various reactor system developers about the proliferation-resistant features of some of their advanced designs as well as their views about related research and development requirements. In addition, the members of the Task Force actively participated in several major international meetings that have been held under the sponsorship of DOE to help develop guidelines for possible use by DOE and other organizations on the desired characteristics of future advanced nuclear power systems (otherwise known as "Generation IV Reactor Systems"), including features for enhancing proliferation resistance that might merit support.

This special report reflects the results of these Task Force studies. The Sections that follow cover the following major topics:

- The context of the study: the potential role of civilian nuclear power, the non-proliferation regime and past non-proliferation assessment efforts;
- Some new nonproliferation assessment initiatives that have been pursued as well as their potential applications;
- A definition of the principal barriers and their effectiveness against proliferation threats that must be considered in evaluating new approaches to proliferation resistance;
- The feasibility and practicability of developing new technical approaches and assessment methodologies to enhance proliferation resistance in the civil nuclear sector, as well as a preliminary comparative description and assessment of the distinguishing nonproliferation attributes of some illustrative nuclear power systems;
- Technological opportunities to increase the proliferation resistance of future civilian nuclear power systems, including potential new areas for international cooperative R&D; and
- The principal R&D objectives and directions that the United States government should pursue in endeavoring to enhance the proliferation resistance of existing and advanced nuclear power systems.

This report is essentially a work in progress. The charge given to the Task Force was extremely ambitious and all that could be done in the time allotted was to suggest directions of effort and hope that the responsible organizations will take on the challenging tasks that the report identifies. The Task Force operated on a consensus basis: While there were some differences of opinion on the merits and relative promise of some of the opportunities for development of advanced reactor and fuel cycle systems, all members fully support the basic recommendations in this report.

Two working premises guided this study:

- Nuclear power has the potential to continue to make important contributions in helping to meet future global energy needs under terms that are compatible with economic, nonproliferation, and environmental objectives, including the desire to abate air pollution and greenhouse gas emissions.
- Unless the U.S. pursues a much more proactive R&D program in the civil nuclear field, its technical influence in advancing those aspects of the non-proliferation regime that relate to civil

nuclear energy could seriously erode as could its ability to help shape and influence proliferation resistance choices in other countries.

After an in-depth review based on these premises, we have concluded that there are promising technical approaches that might well increase the proliferation resistance of civilian nuclear systems and that a significant investment in R&D is warranted to evaluate these approaches and then subsequently pursue those identified as most promising.

B. The Potential Role of Nuclear Power

Given the very sizeable increases in population expected to occur over the next few decades, almost all scenarios foresee a large increase in demand for electrical energy. Various projections show global electricity consumption growing from about 1500 gigawatts electric (GWe) at present to between 4000 and 6500 GWe by 2050 (Ref. 1,2). By any standard, this amount of electricity will be difficult to bring to the market in this short time, which may be made even more difficult because the growth rates are not likely to be linear.

There have been differing estimates as to how much of this electricity can and will be provided by nuclear power. As an example, six International Institute for Applied Systems Analysis/ World Energy Council (IIASA/WEC) scenarios project increases in nuclear electricity generation from 10 and 485% by the year 2050, with the lower number associated with a scenario that phases out nuclear power by 2100. The other five scenarios project increases that range from 135% to 485% by 2050, depending on differing assumptions about economic growth and other electricity sources. Most significant is that two-thirds of any forecasted increase is projected to be in the developing world. The Nuclear Energy Agency takes one of these scenarios and devolves three variants; continued nuclear growth with a 205% increase in capacity by 2050, phase out by 2050 (100% decrease) and stagnation followed by revival between 2030 and 2050, resulting in a 215% increase by 2050 (Ref. 3).

The Task Force does not know how much electricity will be generated in the future from nuclear sources or where it will be generated. We do know that nuclear power, which currently supplies about 17% of the world's electricity, will be with us in some form for a long time to come and that the nuclear materials from civilian nuclear power will be with us for an even longer time. Some of us believe that it is essential to establish fission power as an acceptable and viable option to both industrialize developing countries and to stabilize greenhouse gas emissions, a conclusion also reached by the President's Committee of Advisors on Science and Technology (PCAST) (Ref. 4).

There are growing pressures in the developed nations to devise approaches that could alleviate the “greenhouse” problem (that is, to come up with the installation of new energy sources that greatly reduce net carbon dioxide emissions). On the other hand, the pressures on the developing and under-developed nations are primarily economic and are a cause of political instability and in some cases international conflict. If nuclear power hopes to help in meeting these needs of the environment and world stability, its utilization will have to grow many times over current levels. From a resource perspective this should be achievable since the resource base of nuclear fuels, if effectively utilized, is several times greater than the resource base of fossil fuels. One percent or less of natural uranium provides fission energy in the case of the once-through fuel cycle; 60 to 80% of natural uranium contributes energy in a closed fuel cycle.

The Task Force recognizes that the optimal contribution of nuclear power in meeting these global needs will be contingent upon the realization of a number of important goals, including the ability of the technology to be competitive with all major energy alternatives, successful adherence to rigorous safety standards, achievement of timely and acceptable solutions to the disposition of nuclear wastes, and continued ability to assure that the utilization of civil nuclear power remains a comparatively unattractive route for those nations or groups interested in acquiring nuclear weapons. In addition to preserving economic competitiveness, nuclear energy will have to achieve greater public acceptance. This can be influenced positively by success in addressing these problems, including alleviating public concerns about the association between nuclear power and nuclear weapons.

C. The Relation of Civil Nuclear Technology to the Acquisition of Nuclear Weapons

A wide range of significant factors will determine whether additional nations will acquire nuclear weapons. Specific technologies employed in the civilian nuclear sector are likely to have only a modest impact on the overall rate of nuclear proliferation. Historically, the preferred approach for nations seeking nuclear weapons generally has been to establish a dedicated military program to produce the nuclear material rather than attempting to divert material from internationally safeguarded nuclear facilities.

Nevertheless, civilian nuclear activities can make direct or indirect contributions to the spread of nuclear weapons. Some nations have employed nominally civilian nuclear programs as a pretext to acquire technologies for military programs or they have acquired materials, equipment, technologies, or technical personnel from the civil sector for their nuclear weapons programs. Consequently, the United States and many other countries have had a strong incentive for many years to develop a series of measures to assure that the utilization of nuclear power and civil nuclear cooperation will take place only under terms designed to seriously inhibit the misuse of the technology to acquire nuclear weapons.

To this end, the international community has developed a wide range of measures, many of an institutional character, that have collectively become known as the "international nonproliferation regime." These have included the successful promotion of a broad political/societal norm or "ethic" under which the great majority of nations have openly agreed to forego the manufacture or acquisition of nuclear weapons, and the codification and integration of these political positions in a variety of legal instruments. The centerpiece for this regime has been the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which was extended indefinitely in 1995 and now has 187 signatory nations. The NPT regime seals a complex bargain. It defined five nations as Nuclear Weapons States because they possessed nuclear weapons before signature of the treaty, while assigning the status of Non-Nuclear Weapons States to all other signatories of the treaty. While the treaty explicitly enjoins Nuclear Weapons States from transferring nuclear weapons and nuclear weapons know-how from Nuclear Weapons States to Non- Nuclear Weapons States, it provides a number of important measures to ameliorate what may be perceived as discriminatory features. In particular, recognizing the "dual-use" nature of nuclear energy technology, it provides that Nuclear Weapons States should assist Non- Nuclear Weapons States in the peaceful exploitation of nuclear power, provided that the resultant civilian nuclear energy developments in Non-Nuclear Weapons States signatory to the NPT are carried out under a full scope and comprehensive international safeguards and inspection system administered by the International Atomic Energy Agency (IAEA). Furthermore, the NPT provides that the Nuclear Weapons States should in good faith de-emphasize the role of nuclear weapons in their international policies and strive for the eventual elimination of nuclear weapons.

The regime also has involved continued efforts to assure that the principal nuclear supplier states support prudent and commonly agreed conditions governing nuclear exports, including appropriate restraints on the transfer of "sensitive" nuclear technologies like reprocessing and enrichment. Finally, in adverse circumstances, national laws, bilateral agreements, and international treaties call for the application of sanctions in the event nations misuse nuclear materials or violate their nonproliferation obligations.

Initially the IAEA devoted most of its energies to safeguarding and inspecting civil nuclear facilities that were openly declared by the signatory Non-Nuclear Weapons States under the NPT. But, after the Gulf War and the discovery of clandestine activities by Iraq, new measures were developed to give the IAEA additional capability (beyond the powers it already possessed to perform special inspections) to detect and investigate undeclared activities. In addition, new measures have been agreed to, in an Additional Model Protocol (Ref. 5), that provide authority to IAEA for expansion of its capability in this area. These new provisions comprise the most significant improvement in international safeguards in recent times. They extend IAEA's scope of safeguards actions to the entire nuclear fuel cycle. The Additional Protocol is a culmination of decades of evolution of the safeguards system. The detection by the IAEA of any undeclared illicit operations is the limit of the IAEA's authority, but such detection is designed to trigger responsive actions by the United Nations Security Council, as well as by all nations that are committed to advancing nonproliferation objectives. The institutional features of global nonproliferation, including safeguards, constitute an essential, if not dominant, element of the efforts to abate the spread of nuclear weapons. It is in that context that the recommendations of this report have been formulated.

Taking these factors into account, the Task Force recognizes that:

- A combination of political, institutional and inherent technical factors is required to avert the spread of nuclear weapons. The dominant factor remains the creation of political and economic conditions to reduce the desire to acquire such weapons by those nations not now possessing them. However, the nonproliferation regime can be strengthened by a combination of advances in technology as well as in institutional mechanisms. It is the sum of the institutional and inherent technological factors that will determine the technical proliferation resistance of nuclear power facilities.
- The potential proliferation risk posed by different nuclear fuel cycles and technologies varies

depending on the specific circumstances in the State in which the fuel cycle is being pursued.

- Some nuclear technologies may be inappropriate for certain State environments (States of concern, States with little technological expertise or infrastructure, or States in areas of regional instability), but their energy needs could be served by commercial supply and regional facilities.

The Task Force also recognizes that technology can play a very important role in strengthening the nonproliferation regime along the following lines:

- Improving the effectiveness of the various surveillance, monitoring, inspection, accountancy, and physical security measures that are embedded in institutional controls;
- Devising new inherent technical features that make nuclear power systems more resistant to proliferation;
- Reducing opportunities for the misuse of, or the diversion and theft from, civilian nuclear activities;
- Increasing the complexity, transparency, and cost of diverting nuclear materials for use in nuclear weapons, and the time it would take for a state to divert nuclear materials for the purpose of acquiring nuclear weapons so as to give the international community sufficient time to detect such a diversion and take appropriate action
- Reducing the accessibility of weapons- usable nuclear materials
- Reducing the degree to which civilian nuclear energy programs may provide opportunities to build up expertise for potential or likely proliferation and to acquire, overtly or covertly, technologies, for nuclear weapons programs.

Consequently, the continued exploration of new technical ways in which nuclear power systems can be made more resistant to proliferation should constitute an important ongoing feature of the global nonproliferation regime. This will occur more effectively when institutional schemes are derived that reward such resistance features. Further, within this context and as an organizing theme, the Task Force believes that U.S. R&D planners should pursue the following important objectives:

- Systematically evaluate the non-proliferation implications of existing and new technologies.
- Support the exploration, and as appropriate the further development, of systems that:
  - increase the effectiveness and efficiency of institutional nonproliferation measures, e.g., safeguards measures);
  - make weapons-usable materials highly inaccessible, including the evaluation of advanced open and closed fuel cycle systems that avoid direct access to these materials;
  - reduce the attractiveness of nuclear materials for potential weapons purposes;
  - reduce the quantities of weapons-usable material utilized and produced per unit of energy output;
  - limit the spread of highly specialized knowledge and skills that can be directly used to design and fabricate nuclear weapons.
- Evaluate, in cooperation with other interested countries, a range of interesting reactor and fuel cycle options that could potentially meet the above objectives, including the evaluation of advanced closed fuel cycle systems that avoid direct access to these materials. This effort should be appropriately integrated with other efforts designed to assure that future systems will be economical, safe, and environmentally friendly.

II. THE ROLE AND RELEVANCE OF PAST ASSESSMENTS

It has been a characteristic of the development of the global nonproliferation regime to analyze periodically the proliferation risks associated with the spread of nuclear technology and utilization of nuclear power and to try to develop constraints, barriers, and disincentives that will serve to discourage the misuse of nuclear reactors and nuclear fuel cycle facilities. Comprehensive assessments have been performed in the past, both within the United States and with other countries on the comparative non-proliferation attributes of different nuclear power systems as well as on the specific non-proliferation characteristics of specific systems or technological approaches. In the late 1970s, during the Administration of President Carter, the United States undertook the domestic Nonproliferation Alternative Systems Assessment Program (NASAP) review (Ref. 6) as to how the U.S. once-through LWR fuel cycle compared to other options. This was followed shortly thereafter by the major International Nuclear Fuel Cycle Evaluation (INFCE) (Ref. 7) convened under the auspices of the IAEA that involved the participation of more than 60 nations and international organizations. INFCE was intended to be a comprehensive comparative assessment of the nonproliferation characteristics of different nuclear fuel cycles and nuclear systems that would lead to recommendations on steps that nations could take to help strengthen the nonproliferation regime.

The NASAP review reached several conclusions, including the judgment that "the LWR fuel cycle with spent fuel discharged to interim storage . . . is a more proliferation-resistant nuclear power fuel cycle than other fuel cycles which involve work with highly enriched uranium (HEU) or pure plutonium." The INFCE study concluded that institutional factors were likely to be more determinative than technological factors in determining whether civil nuclear fuel cycles will be misused by potential proliferators. In contrast to NASAP, the INFCE review did not conclude that one particular nuclear power or fuel cycle approach was inherently more resistant to proliferation than the alternatives.

In the interval since these major reviews were conducted, the U.S., from time to time, has performed more specialized and focused non-proliferation assessments of specific technological options. This included evaluations of the Integral Fast Reactor (IFR) concept, as well as assessments of the implications of different options for disposing of excess weapons plutonium, including an assessment of various approaches for "immobilizing" excess weapons materials, such as the use of the so-called "can-in-canister" approach. The Task Force has drawn from and benefited from all of these past assessments and used them as a starting point for assessing the proliferation resistance of global nuclear power systems and how they may evolve in the next few decades.

While using results and experience from past assessments, the Task Force derived particular benefit from the methodologies used by the National Academy of Sciences to evaluate different options for the disposition of excess weapons materials in the United States and Russia. The Task Force has drawn and benefited from these reviews (Ref. 8) and more recent assessments (Ref. 9) and has employed them as a beginning basis for assessing the proliferation resistance of different nuclear systems. An effort was also made to define a useful analytical framework for identifying and comparing the non-proliferation attributes and implications of different reactor and fuel cycle approaches.

While several of the past assessments, such as the INFCE exercise, were exhaustive and very time-consuming, they were prepared in a different era more than twenty years ago. At that time it was expected that there would be much more rapid growth in the use of nuclear power leading to optimistic expectations, for example, as to the time when fast spectrum reactors—and their supporting fuel cycle systems—might be fully developed and deployed on a commercial scale. In the interim, there has been a notable reduction in the growth rates for nuclear power programs in most countries and in national budgets in support of advanced reactor systems. However, several nations continue to look to nuclear power to play a major role in meeting their future requirements. Concurrently, some sentiments have surfaced recently that if nuclear power is to play a desirable and enhanced role in helping to meet future energy demands and in countering the threat of global warming, the technological options that are available for future nuclear power programs may have to be reconfigured. Such actions are seen as necessary to make sure they are suitable for introduction into a greater number of nations and especially to nations in the developing world.

III. CURRENT AND NEAR TERM STATUS OF NUCLEAR POWER

At the present time, 434 nuclear power stations are located and in operation in 34 countries around the world and the clear preponderant reactor of choice is the light water reactor, with 344 plants (ref. 10). In the nearer term, there are limited prospects for the construction of new nuclear power plants in Europe or in the Americas although new plants are being built or are planned in some Asian countries.

While several developing countries have long expressed an interest in nuclear power, and while there may be a growing interest in the application of this technology in the developing world, nuclear power has not yet figured significantly in the energy plans of many less advanced nations, due to several considerations. Most notably, many developing countries lack the sophisticated technical infrastructures and grid sizes to be able to absorb and deploy currently available large-sized nuclear reactors in their electricity systems. Yet, at the same time, given anticipated burgeoning demands for energy, they conceivably could benefit considerably if nuclear power options could be fashioned that would meet their growing needs in an economically competitive, safe and secure fashion. This has raised substantial questions of late as to whether more emphasis should be devoted to planning the next generation of reactors or to designing new systems that could be more amenable to introduction in developing countries.

In this regard, some attention is being devoted to evaluating the merits of smaller, modular, simpler, and more passively safe reactor systems that might be better suited for introduction in less advanced countries. In the interest of abating the growth in inventories of separated plutonium, as well as enhancing proliferation resistance, attention also is being given to the merits of fueling some advanced concepts with materials that would markedly reduce the frequency of refueling or the production of materials attractive for nuclear weapons. As yet, no modular and fully licensed small reactor has been built in an industrialized state that is now ready for export. However, a few countries like South Africa and Argentina are initiating programs aimed at developing and producing such reactors with an eye to their export potential. A few industrialized nations also continue to have an ongoing interest in developing advanced reactors including water-cooled and gas-cooled thermal reactors, and liquid-metal-cooled fast spectrum reactors for indigenous use.

Enrichment facilities, primarily using diffusion and centrifuge processes, have been constructed in ten countries. Worldwide installed current enrichment capacity is on the order of 50 million SWU annually, against a demand on the order of 36 MSWU (Ref. 11). The situation is more complex than these bare figures suggest as, on the one hand, a significant part of the demand is being filled with enriched material blended from dismantled weapons and civilian recycled plutonium, while on the other hand, enrichment plants are most profitable when operated at maximum capacity. However, the basic point remains that world enrichment capacity is more than sufficient to meet near-term demands. Given this over-capacity and the high cost of building and operating enrichment plants, if new facilities are built in the near term, it will be most likely for reasons of energy autonomy or national pride, not because of the financial attraction of such facilities. Yet, in the longer term, if nuclear power expands greatly, more enrichment facilities would be needed and could become more widespread

Gaseous diffusion technology provides relatively low separation coefficients, and must be cascaded to produce high enrichments. An enrichment cascade designed and constructed for particular levels of output enrichment and tails assay would require major modifications in order to achieve a significant increase in the output enrichment beyond the design limit. Centrifuge technology has much higher separation coefficients and may be re-arranged relatively more easily. Both technologies rely on special materials. These materials are subject to various nuclear export laws and nuclear supplier agreements, the primary vehicle for controlling the spread of enrichment technology. One of the major proliferation threats associated with enrichment facilities has been the diversion of technology and expertise.

The basic technology of reprocessing has been declassified and widely available for many years, but only a few industrialized countries are now engaged in reprocessing programs on a commercial scale. Nevertheless, the inventories of separated plutonium are substantially exceeding current demand. As a result, more than 200 tons of separated plutonium is now in civilian stockpiles around the world, a figure that continues to grow (Ref. 12). Beyond this, much larger amounts of plutonium in spent fuel form are dispersed in numerous locations around the world

While much of the plutonium in spent fuel form currently is subject to high radiation barriers and hence is a relatively unattractive material for diversion by potential proliferators (and, particularly, by potential sub-national adversaries)—the effectiveness of these radiation barriers will diminish over a period of decades. This is one of the basic reasons why the safeguarding and disposition of spent fuel itself poses a significant nonproliferation challenge. There has been a growing interest in exploring ways the inventories of these materials can be aggregated under IAEA safeguards in a limited number of stable countries with strong nonproliferation credentials, independent of the question as to whether the plutonium in the spent fuel should be directly utilized in reactors. Studies are also underway to evaluate the merits of transmutation of the spent fuel to forms of less proliferation concern.

IV. LIKELY NEARER-TERM DEVELOPMENTS

In carrying out this study, the Task Force has not attempted to perform any exhaustive assessment of the likelihood of different scenarios for the potential growth and use of nuclear power, although we believe nuclear power has the potential to make a significant contribution to meeting future energy demands. While it is possible to describe widely different cases ranging from a major renaissance of nuclear power to a drastic phase-out in the utilization of the technology, a middle ground has been chosen by the Task Force that postulates a civilian nuclear world in the next few decades with the following major features:

- The light water reactor is likely to be the reactor of choice in the nearer-term, although some nations will continue to have an interest in heavy water reactors. Most nations now employing light water reactors of Western design will be successful in their efforts to obtain regulatory approvals and/or implement effective aging management programs to extend the operating lives of their reactors. This is the direction being taken in the United States where most of the operating nuclear plants are achieving cost competitiveness and record high availability (Ref. 13.) Some older or more poorly performing plants, or plants of controversial design, may be shut down.

- It seems likely that most nations will opt to store their spent fuel on an interim basis, pending decisions on later disposition, processing, or transmutation of these materials. However, a limited number of nations will continue to reprocess some of their spent fuel and recycle some of their separated plutonium as MOX fuel in thermal reactors, pending possible later use in more advanced reactors.

- While Germany and Sweden have adopted laws requiring eventual shut-down of all their nuclear power plants, many believe that it is unlikely that most nuclear power programs will be phased out entirely. Even if this were to occur, the nations involved, as well as the international nuclear community, will face an ongoing responsibility for managing the inventories of separated plutonium and other weapons-usable materials in their possession as well as the vastly greater inventories of plutonium that exist in spent fuel.

- There are different views within the international community as to how the so- called "back-end" of the nuclear fuel cycle can best be managed and whether plutonium should be recycled either now or in the future or whether this question should simply be deferred. The United States, for its part, does not now "encourage the civil use of plutonium and accordingly, does not itself engage in plutonium processing." However, while the U.S. actively seeks to limit reprocessing in regions of proliferation concern, it has emphasized that it will "honor its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan." (Ref. 14)

- Although most fast reactor demonstration programs have been curtailed and competitive commercialization of fast reactors has not been achieved, a limited number of nations remain interested in the development of this technology. This interest relates to the fact that fast spectrum reactors use dramatically more of the energy content of uranium and reduce long-lived waste production over currently deployed reactor systems. Several of these countries are assessing whether such systems can be developed in ways that could be more proliferation-resistant through processes that would avoid the presence of separated plutonium.

In the current climate, only a limited number of nations have deployed uranium enrichment technologies, and key enrichment technologies remain tightly controlled. Nevertheless, some states have succeeded in overtly or covertly acquiring enrichment technologies that have been used in their nuclear weapons programs. Taking these factors into account, one must assess the proliferation implications of different approaches to the future of nuclear energy. In the process, all potential technical routes to the acquisition of nuclear weapons must be considered including those involving access to highly enriched uranium (U-235 and U-233), Pu-239, and other fissionable isotopes.

In the foregoing overall context, the Task Force is of the view that different fuel cycles and reactor choices may continue to be followed by different nations but that in all cases it will be desirable for the U.S. to have the ability to influence these programs so that they advance in ways that enhance proliferation resistance while also advancing economic and safety objectives. A U.S. effort to pursue R&D involving the conduct of analytical and experimental studies that would evaluate and explore advances in proliferation resistance for a variety of fuel cycle approaches could strengthen the U.S. ability to exert constructive technical influence on these issues. Where appropriate, these studies should be carried out in collaboration with other countries. More broadly and for the longer term, for nuclear power to provide a significant fraction of the carbon-free energy the world is likely to need in the 21st Century, the utilization of nuclear power would have to expand many fold. The realization of this goal may be dependent, in part, on broad confidence in governments and publics that such an expansion will not significantly aggravate the proliferation problem. Thus, continued improvements in proliferation resistance, like continued improvements in nuclear safety, waste management and economics may be very important to the future growth of nuclear power.

In addition, all of these situations strongly suggest that if the U.S. aspires to have a significant role in developing technologies that may help to enhance proliferation resistance on a global scale, it should adopt a flexible orientation in pursuing R&D that will enable the international community to better cope with a variety of situations that may evolve as various nations chart different fuel cycle courses.

In addition, the Task Force has been guided in its analysis by two other key assumptions. First, one of the major U.S. objectives should be to preserve an international regime where misuse of the civilian nuclear fuel cycle will be the least attractive technical route open to potential proliferators. Secondly, it must be recognized that all nuclear systems involve some risk and opportunities for misuse. There is no reactor or fuel cycle system that is foolproof from a proliferation perspective although diversion from some systems may be substantially less attractive than separate dedicated military production. In the interest of promoting nonproliferation objectives, all nuclear power programs will have to remain subject to an array of nonproliferation measures of a basically institutional character.

The severity of proliferation risks depends very much on a wide variety of technical, institutional, and political factors. These range from the political incentives or disincentives that could lead a nation or sub-national group to divert or steal materials capable for use in nuclear weapons, the institutional disincentives that may apply in a given case to discourage misuse, and the nature of the threat itself**.** In addition, other relevant factors will include the degree of technical sophistication of the parties, the nature of the nuclear program in the country involved, and the degree of access and availability of directly usable nuclear materials.

It also is important in mapping out nuclear deployment and export strategies to consider the prospective role that the transfer of a given peaceful nuclear technology can play in proliferation—either by enhancing the ability or incentive of a recipient State or dissident group to acquire nuclear weapons.

Finally, political realities in some circumstances may simply call for withholding the transfer of nuclear reactor technologies to certain nations if there are serious doubts whether they can fulfill their nonproliferation obligations, are seriously lacking in political or institutional stability, or if there are grounds for serious concerns that the introduction of nuclear technologies will have destabilizing effects in certain regions**.** On the other hand, not having enough electrical power to allow sufficient economic development, particularly in less advanced nations, may in fact increase the proliferation risk in countries seeking to increase their influence, by increasing the attractiveness of the military means to do so.

In view of the complexity of all of these factors, it is difficult to generalize or make rank order judgments about the relative nonproliferation risks associated with differing national nuclear programs or nuclear power systems. One needs to assess the total context in which a national nuclear program is evolving to form a meaningful and balanced assessment of likely benefits and risks as well as positive impacts realized through the application of technology advances, recognizing that such advances should be taken into account at an early phase of the design stage.

V. PROLIFERATION RESISTANCE ASSESSMENT INITIATIVES AND THEIR POTENTIAL APPLICATION

A. The Need for Improved Assessment Methods

All civil nuclear power plants and their associated fuel cycles theoretically can contribute to the risk that weapons-usable fissionable materials, facilities, technology or expertise might be diverted or misused. Accordingly, "proliferation resistance" is a matter of degree, not an absolute attribute. Developing a generally acceptable methodology for proliferation risk assessment is difficult since both quantitative and qualitative factors contribute and the weights to be assigned to different factors are inherently a matter of judgment. Moreover, proliferation risk depends on the character of each threat, whether it be a sophisticated or unsophisticated state seeking nuclear weapons or even a terrorist group. In addition, such factors are both inherent to the particular fuel cycle and also are external, that is, institutional, in nature.

In view of this need and in spite of these difficulties, efforts should be undertaken to improve and, where practicable, standardize the proliferation assessment of different reactors and fuel cycle approaches for use in planning future R&D programs. These assessment methodologies should not be considered to yield definitive, quantitative assessments; rather, they should be viewed as useful means for helping the peer review process evaluate the merit of specific proposals and proposed courses of action and provide an important base for discussion of this topic.

Nevertheless, a desirable long-term goal is to develop more quantitative methods by which reactor designers can evaluate the relative proliferation worth of various fuels and materials in order to balance proliferation resistance R&D costs with benefit.

It is of key importance that such methodologies provide an integrated assessment that includes the effectiveness of both the technical features ("intrinsic barriers") and the necessary institutional measures ("extrinsic barriers") that are likely needed to apply to a given case. A number of methodologies have been considered and are under development. Two efforts presently underway to develop methodologies have been examined by the TOPS Task Force to help illuminate the discussion of integrated assessments.

The first is an integrated safeguards evaluation methodology (ISEM), being developed under the U.S. Support Program to the IAEA safeguards program, that has as its focus the extrinsic barriers to proliferation. This approach would lead to an optimum combination of all safeguards measures available to the IAEA so as to achieve maximum effectiveness and efficiency within the available resources. It would be a potential tool for the IAEA to evaluate safeguards proposals for compliance with the goals and objectives of integrated safeguards. Although developed for a different purpose, elements of the ISEM approach might find application in evaluation and comparison of fuel cycle concepts with respect to their ability to be effectively safeguarded and thus could contribute to the broader analysis of proliferation resistance of different reactor and fuel cycle approaches.

The second, called an "attributes methodology" (Ref. 16), places initial focus on the intrinsic barriers to proliferation. The basic process is to identify the intrinsic barriers of a given nuclear system, evaluate their effectiveness against the challenges imposed by different types of potential proliferators, and then identify the features needed in the extrinsic barriers to complement the intrinsic barriers such that the sum of both the extrinsic barriers and intrinsic barriers achieves the specified standard. A matrix displaying the qualitative effectiveness of each barrier can be developed for different fuel cycles and reactor systems. This methodology is potentially a tool for the reactor system designers and those with oversight of the design process. It would be used to help carry out an integrated assessment of the overall proliferation resistance of a proposed reactor system. This approach was used by the Task Force in a very preliminary fashion to address various fuel cycles and elements of fuel cycles. To the extent that the ISEM and attributes approaches may be used to evaluate proliferation risks of different nuclear fuel cycle systems, they could evolve and become complementary to each other because of the difference in their focus. These two methodologies are reviewed in Appendix 2.

The subject of the attributes methodology of assessment was the principal topic of a special working group at the TOPS International Workshop on Technology Opportunities for Increasing the Proliferation Resistance of Global Nuclear Power Systems, held in Washington, DC on March 29-30, 2000. The detailed findings of that group may be found in Reference 17. The Workshop concluded that continued emphasis needs to be devoted to improving and standardizing the methodologies for performing comparative assessments of the proliferation attributes of different systems. On the other hand, the Working Group underscored that it did not wish to imply that informed judgments about future program directions could not be made as needed given that such admittedly new and elaborate methodologies are not yet in place.

B. Initial Application of the Assessment Methodology

An effort to apply the attributes methodology to several specific nuclear power systems also was made at a Technology Assessment Meeting sponsored by the TOPS Task Force in Chicago on June 15-16, 2000 and reported on in Reference 18. The cases covered were formulated by reactor developers who volunteered their effort on short notice at the request of the Task Force. Because of the time limitations, U.S.-based developers were primarily involved. The cases were not complete in themselves nor did they cover the full scope of systems operating today or under development. Their primary purpose was to identify system characteristics and R&D needs. To some extent, these presentations were, in effect, an initial “field test” of the application of the attributes methodology. Experts on specific systems were requested to apply a process generally consisting of the following steps. They were requested to:

1. Outline the phases of the fuel stream for the given system that comprise the focus of diversion threats.

2. Identify the principal potential proliferation pathway(s) in each fuel cycle phase (e.g., covert or overt diversion of material and/or misuse of facilities by an NPT signer state, covert theft or diversion of materials by a sub-national entity).

3. Specify, for each of its fuel cycle phases, those key intrinsic materials and technical attributes of the system which provide the primary barriers against proliferation.

4. Define the generic characteristics and capabilities of the government and non-government organizations that are potential proliferators.

5. Estimate the relative importance of each key intrinsic and extrinsic barrier in thwarting proliferation by the entities in (4) on the path(s) in (2) which pose a credible threat.

6. In light of the findings from (5), identify the MPC&A and international safeguards measures (“extrinsic barriers”) that are needed to supplement the intrinsic barriers in each fuel cycle phase.

7. On the basis of the results from (5) and (6), recommend R&D and technology applications that are needed to verify or strengthen the proliferation resistance of the system.

The systems that were covered in this comparative analysis at the Chicago meeting included:

- An LWR operating on a so-called “once- through” fuel cycle where the resultant spent fuel is stored for a protracted period or disposed of geologically in a nominal permanent geologic repository. This included concepts such as using non-fertile fuel and Th/U fuels.

- An LWR system operating on a so-called closed fuel cycle where the fuel is reprocessed through a classic aqueous (or PUREX) system with the plutonium either recycled as MOX fuel in the light water reactors or kept in protracted storage pending decisions on later disposition—which might include use in fast spectrum reactors.

- A fast spectrum reactor operating in a burner or breeding mode employing an advanced recycling technology that does not involve at any stage the separation of pure plutonium.

- Postulated small modular LWR and LMR reactor systems employing a long-lived core for possible use in both advanced and developing countries.

- Two types of modular high temperature gas-cooled reactors: a pebble bed fueled system and a fixed prismatic configuration fuel system.

In addition, papers were prepared by individual members of the Task Force on the application of the methodology to aspects of the fuel cycle that many systems have in common: enrichment, transportation, and the geologic repository for spent fuel.

The results, reported in Reference 18, are not uniform in completeness nor in the degree of conformity with the guidelines provided. Therefore they are not amenable to comparison as to proliferation resistance. Weaknesses in the intrinsic barriers in some systems were identified and R&D programs were recommended either to address them or to enhance the evaluation of the concepts. It was demonstrated that the application of the extrinsic barriers to specific reactor systems could be more effective if proliferation resistance assessment becomes an integral part of the design process. A simple engineering design example cited was to provide in the initial plant layout for locations of video monitors and their field of vision that would assure full coverage of fuel assembly movements in the plant. It was acknowledged that, except for some recent technical programs such as the Integral Fast Reactor (IFR) concept, proliferation resistance has been considered after the basic designs were completed with a resultant limitation on the effectiveness of the application of the extrinsic barriers.

The value of the “attributes” methodology as a proliferation assessment tool was not clearly demonstrated. In some respects, most of the findings from the analyses were not new and simply reinforced the judgments that had arisen over the years. Yet, there were several indications of the potential constructive value of such a methodology if it is further developed.

The evaluations highlighted three areas for increased R&D attention: (1) the enrichment phase where clandestine facility modification could circumvent strong intrinsic barriers, (2) the spent fuel repository phase where the strong radiological barrier is weakened by radioactive decay over a period of decades, and (3) the scenarios of undeclared alterations in fuel content or the undeclared introduction of target material for the express purpose of producing weapons-usable material.

An area identified as common to all systems is the need to evaluate the impact of complexity and the cost-benefit of new intrinsic proliferation-resistant barriers, a capability that does not exist in the present assessment methodologies. Such evaluations should search out the optimum balance between the intrinsic and extrinsic barriers, safety, economics, and environmental impact. Intrinsic barriers must not add complexity to the extent that safe operation is negatively impacted.

VI. RECOMMENDED R&D AREAS

A. Overall Strategy

Drawing from the results of the TOPS International Workshop held in March (Ref. 17), the applications of the attributes methodology described above, and the individual contributions of the Task force members, recommendations have been formulated by the Task Force for R&D programs to increase proliferation resistance. The primary goal for this R&D is to help assure that the utilization of the civilian nuclear fuel cycle remains a comparatively unattractive route for those nations or groups that may be interested in acquiring nuclear weapons, including limiting the degree to which technologies and expertise from the civilian nuclear energy system can serve to contribute to dedicated military nuclear programs.

The primary technological opportunity areas should be defined and funded under major "theme categories" that advance the following goals:

- Improve the effectiveness of surveillance, monitoring, inspection, and accountancy, and physical security measures that are embedded in institutional controls;
- Devise new inherent technical features which promise to make nuclear power systems more resistant to proliferation;
- Reduce opportunities for the misuse of, or the diversion and theft from, civilian nuclear activities;
- Increase the complexity, transparency, and cost of diverting nuclear materials for use in nuclear weapons, as well as the time it would take for a state to divert nuclear materials so as to give the international community sufficient time to detect such activity and take appropriate action;
- Reduce the accessibility of weapons-usable nuclear materials; and
- Reduce the degree to which civilian nuclear energy programs may provide opportunities for States or groups to build up expertise for potential or likely proliferation and to acquire (overtly or covertly) technologies that could be employed for nuclear weapons programs.

As a basic approach towards advancing these themes, the United States and other interested countries should be prepared to evaluate promising major options in a non-doctrinal fashion. This would include, for example, the application of "just-in-time" inventory control of separated plutonium as well as the exploration of advanced closed fuel cycle systems that serve to reduce direct access to weapons-usable materials. R&D on such advanced options will advance the state of the art in proliferation-resistant technologies and will allow the United States to collaborate more constructively with other countries.

The recommended programs are grouped under three primary purposes or objectives for the R&D:

(1) To develop improved methodologies for assessing proliferation resistance;

(2) To develop technology to strengthen the application of extrinsic (institutional) barriers against proliferation; and

(3) To develop new technologies to enhance the intrinsic barriers against proliferation, thereby reducing the burdens on the extrinsic system.

Since research and development will be critical in helping to make subsequent decisions on the appropriate paths to actually follow, the effective implementation of this proposed new R&D initiative will require a strategic planning approach that provides a basis for prioritization and selection of the desired longer-term R&D portfolio.

A systems perspective will be needed with an emphasis on comparative evaluation. The pursuit of most of the individual projects designed to improve barriers to proliferation should be carried out in the context of the overall development of the reactor or fuel cycle concept to which they are intended to apply. In addition, all the facilities of the integrated system should be addressed in evaluating overall proliferation resistance. Since many of the advanced concepts will take many years to commercialize, proliferation- resistant improvements should be given significant attention in the early stages of development.

To meet these needs, appropriate and realistic time frames for implementation of the research and development should be established. In concept, three distinct time frames should be defined in terms of <u>completion of the development and implementation of the technologies</u>. Initiation of related R&D in all three time frames would ideally start now, but selections will need to be made on the starting times dependent on the amount of funding available and priority designations of the various programs. The time frames should include:

- Shorter-term projects likely to produce tangible results in about five year's time;
- Intermediate projects likely to produce tangible results to about 15 years from now; and
- Longer-term projects. A commitment is critical to the longer-term exploration and, as appropriate and feasible, development of advanced fuel cycles, but nearer term concrete needs should not be ignored in this process.

There is likely to be a high level of synergy among activities in each of these three time frames. For example, fruitful nearer-term results can contribute to longer-term projects including their prioritization and selection; evaluation of the longer-term concepts can identify new needed near-term proliferation resistance studies.

B. R&D Opportunities for the Nearer-Term

To provide tangible results that can affect proliferation resistance <u>in the nearer-term period of up to five years</u>, emphasis should be devoted to development of the assessment methodologies, to technology that improves the effectiveness of the application of institutional barriers, and to R&D that can strengthen the intrinsic barriers of existing systems. It is noted that substantial detail is provided on the first two areas since the work therein will have more immediate impact and the more successful elements of it will continue into the later time frames. The recommended content of the three R&D areas is given below:

1. R&D Recommended to Develop Assessment Methodologies

Important emphasis needs to be devoted to improving and standardizing the methodologies for performing comparative assessments of the proliferation attributes of different reactor and fuel cycle systems and to evaluate the effectiveness of technology recommendations. Although these methodologies should not be considered to yield definitive, quantitative assessments, they can provide a useful means by which reactor designers can evaluate the relative proliferation worth of various fuels and materials in order to balance R&D costs with benefit. Specific to the "attributes" methodology referred to earlier, the U.S. (working with other interested countries) should develop the capability to complete the application of this methodology to a variety of nuclear systems, including filling in with confidence the elements in the matrices. The U.S. should also continue to support the development of ISEM for use in developing effective and efficient international safeguards systems and other assessment methodologies. Ultimately, quantitative assessment methods are desirable, provided that they can be formulated in a practical fashion.

Methodologies should be developed to include intrinsic proliferation resistance barriers in the cost analysis of life cycles. Improved analytical tools for economic evaluation of nuclear systems should be developed for life cycle cost and cost-benefit analyses so as to extend the traditional economic evaluation of nuclear facilities (capital, fuel, and O&M cost) to include an evaluation of the entire system that reflects the economic implications of proliferation features. A cost component is the manpower required to perform inspections to be applied to different types of reactor and fuel cycle systems. Such manpower requirements should be determined by making the composite of intrinsic and extrinsic barriers cost effective and will probably be small compared to the overall costs of energy production.

An evaluation should be performed of the practicality of a fault tree approach (Ref. 15) for quantitatively describing proliferation resistance, a method that conceptually utilizes the methods in common use in probabilistic safety analysis to evaluate the intrinsic proliferation resistance of reactor/fuel cycle systems.

A major consideration in assessing the proliferation resistance of a given fuel cycle involves the determination of the type of nuclear materials present and their quantities. The initial "attributes" basis for a comparative analysis set forth in Reference 16 contains a list of fissile isotopes that are of concern and require attention. Since the proliferation worth or potential of the various isotopes are not equivalent on a per gram basis, 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 costs and benefits. An assessment tool is needed to take into account not only the mass of material necessary to be useful for weapons purposes, but also inherent physical characteristics that may make it less attractive for weapons purposes.

Since the goal of proliferation resistance of civilian nuclear power is to assure that it remains a comparatively unattractive route for those nations or groups interested in acquiring nuclear weapons, appropriate methodologies need to be developed to assess the proliferation resistance of alternate pathways.

2. R&D Recommended to Strengthen Extrinsic (Institutional) Barriers

Given the central importance that extrinsic or institutional factors play in defining the entire nonproliferation regime, the Task Force recognizes that R&D should address three questions that affect the extrinsic regime:

- How may different intrinsic options affect extrinsic factors and what kinds of new R&D proposals and intrinsic developments might strengthen components of the extrinsic regime?
- How might technological advances (including those outside the traditional nuclear science and engineering fields) serve to strengthen the international safeguards regime and national MPC&A systems?
- What possible adverse as well as positive implications might certain technological advances or deployments have for the extrinsic non-proliferation regime?

In assessing the implications of different systems, it is important to identify the comparative burdens and challenges that some advances would put on the global extrinsic or institutional regime in contrast to alternatives. New technologies that would allow production of nuclear weapons materials in more readily concealed facilities pose particular issues.

The major attributes for an effective international safeguards system should shape the specific goals for R&D on extrinsic barriers. Those attributes are:

- Availability and access to all relevant information. This must include effective information analysis, including a proper identification of credible threats as well as an analysis of the particular facility where the safeguards are in place to determine if the safeguards promise to adequately protect against such threats. The identification should be done by both national and international agencies.
- Completeness of coverage. Safeguards must provide a significant probability of detection of all credible/plausible diversion scenarios; however, measuring the degree of "completeness" is a challenge.
- Timeliness of detection.
- Material accountability using high quality measurements.
- The application, where feasible, of reliable containment and surveillance measures.
- Design review and verification. (An important matter to be considered is how well the measures now actually in place really work.)
- Detection and confirmation of undeclared activities. This is an important new area to which the IAEA now is devoting much attention.
- The availability of competent staff (while instrumentation has an important role in safeguards, there is no substitute for a significant involvement of human inspectors).
- The presence of effective training and motivation.
- The availability of reliable/effective non-destructive analysis and other equipment.

A working group at the TOPS International Workshop, that included safeguards experts, developed a list of potential areas where additional R&D in support of international safeguards and national MPC&A systems would be useful (Reference 17). This list included ways to improve (a) information technologies for safeguards; (b) safeguards system integration and studies (including integrating and balancing traditional and new safeguards measures); (c) material accounting and facility monitoring; (d) wide-area environmental monitoring; (e) material and item tagging; (f) safeguards cost-effectiveness; and (g) the integration of technological advances from a wide range of areas, including areas outside traditional nuclear science, to advance safeguards. It was recommended that approaches to each of these areas and others should be evaluated, and the most promising should be pursued, in close coordination with other safeguards R&D.

Taking the results of the March 2000 Workshop into account, the Task Force recommends specific R&D areas that should be pursued in the nearer-term. These are summarized below and covered in more detail in Appendix 3. They include:

- Ways to improve information technologies – better integration of sensors and data monitoring systems, expert intelligent systems for data analysis, the development of systems to provide real-time surveillance, the development of new methods to certify authenticity of source data.

- Ways to better pursue system studies – the analysis of the systems for facility security assessments, integrated data management system development, the relation between economies of scale and proliferation enhancement.

- Ways to improve material accounting and facility monitoring – higher accuracy, lower-cost assay technology, improved fissile material measurement of spent fuel and residues, integrated national and IAEA systems to increase the likelihood of detection of diversion of material, new technologies for long-term, low-cost monitoring of geologic repositories.

- Ways to improve wide-area environmental monitoring – the development of tools and assessments of effectiveness, and robust capabilities.

- The development of enhanced material tagging measures – improved material and plant surveillance technologies, tracer chemicals or isotopes to track material, remote identification technologies, and the use of more transparent technologies.

- The development of lower cost surveillance techniques – direct event formalisms, direct access to data methods.

- Technical advances (including those outside traditional nuclear science) that would serve to improve assay technologies, to develop improved threat definition and analysis, and to improve the human-automation interface.

The Task Force notes several areas requiring increased emphasis in the implementation of this R&D program:

- The safeguards and MPC&A systems are not taking full advantage of cutting edge information technology that is being developed for e-commerce.

- The U.S. national laboratories should provide appropriate state-of-the-art technology for wider application in safeguards and MPC&A.

- New technical efforts to strengthen international safeguards have to build on and be well coordinated with the extensive national support programs for the IAEA safeguards programs that already are underway.

- There has to be a closer exchange and integration of ideas and plans between designers of possible new nuclear systems or applications and safeguards specialists.

- Emphasis should be placed on the engineering trade-offs between intrinsic and extrinsic measures, designing in safeguards from the beginning as an integral part of the overall system.

- Evaluations should address the adverse as well as positive implications that certain technological advances (such as those permitting production of weapons-usable material in smaller and more readily concealed facilities) might have for the global "extrinsic" non-proliferation regime.

- Future fuel cycle facilities should be designed to maximize inherent transparency of processes contained in the facility. It is recognized that, by designing processes and operations such that they are more observable (e.g., through remote sensing, environmental sampling, etc.), the potential for undetected proliferation will be reduced and international political and public confidence in nonproliferation intentions will be enhanced.

- International efforts should be supported that will serve to improve the tracking and resultant transparency of movements of nuclear materials in international commerce as well as in national programs.

- As with nuclear materials, nuclear facilities should 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 safeguardability should be an important attribute in assessing proliferation risks.

The Task Force did not perform a detailed review of the existing and planned safeguards technology R&D portfolio that is already underway in support of the IAEA safeguards system. Therefore, the R&D recommendations listed above and in Appendix 3 should not be considered a criticism of the R&D program that is already underway. Indeed, the R&D we propose in these areas should be pursued in full coordination with the safeguards R&D support programs that are underway elsewhere in the U.S. government and internationally. In the U.S., safeguards R&D (or technology development) is currently supported by the new DOE security organization primarily for domestic purposes and by the National Nuclear Security Administration, Office of Arms Control and Nonproliferation (NN-44) for international safeguards. In addition, the Office of Nonproliferation Research and Engineering (NN-20) provides base technology R&D in nuclear materials detection, tags and seals, etc. that are all related. The Defense Threat Reduction Agency (DTRA) is supporting the development of transparency and monitoring technologies that can be used for safeguards purposes. There are also related technologies in the emergency search and intelligence communities. It is important that these efforts continue with improved coordination and collaboration and be expanded where practicable. The DOE Office of Nuclear Energy (NE) should coordinate and integrate any new recommended R&D activities it may support in these areas with the above activities as well as with the advanced reactor engineering and research programs that NE may support, such as the Nuclear Energy Research Initiative (NERI) and the programs under the NERAC Long Term Nuclear R&D Plan (LTRDP).

The international safeguards system consists of a blend of detection systems capable of identifying nuances in operations as well as an intelligent motivated staff capable of observing, interpreting, and understanding the information provided. Neither is possible without adequate funding. It was the conclusion of the Task Force that the long-standing policy, shared by the U.S. of only permitting "zero real-growth" funding of IAEA safeguards is harmful to the non-proliferation regime and should be abandoned. Furthermore, the development of international safeguards technology has been greatly advanced by an active program of voluntary support by key IAEA member states. This program of technical support must be continued and strengthened. There remain, however, areas of technical promise that are unlikely to be covered by the existing program of formal assistance to the IAEA. The existing support program is largely focused on application of developed technologies and does not fund basic or applied research in areas of technical promise that could have large impacts on IAEA safeguards.

2. R&D Recommended To Strengthen Intrinsic Barriers

The initial emphasis in developing improvements in intrinsic barriers in the nearer-term should be on evolutionary improvements in the proliferation resistance of existing systems and assessments, through analytical studies and experiments, of potential inherent barriers that might be associated and pursued with the development of more advanced systems. The primary focus on evolutionary intrinsic barrier improvement would be on LWR "once through" systems – e.g., incrementally higher fuel burnup. Transient testing and the buildup of fabrication capabilities for higher burnup fuel could be feasible in the nearer term. It is assumed that in the nearer term DOE will continue to support the development of research reactor fuels that would permit the remaining research reactors using HEU to convert to lower enrichments.

C. R&D Opportunities for the Intermediate Term

It is assumed that selected R&D programs on assessment methodology and strengthening extrinsic barriers will continue in the intermediate and long-term periods to seek out further improvements, but the emphasis in the intermediate term will shift strongly to obtaining tangible results from intrinsic barrier R&D. The programs recommended are as follows:

1. Light water reactors (LWR) and their fuel cycles:

- Extended fuel burnup. This could reduce the quantity and quality of plutonium produced, the number of re-fuelings, and the number of spent fuel assemblies, modestly easing the safeguards task.
- Ultra-long lived fuel for high conversion reactors with ten years or more lifetimes that gain the energy value of plutonium without traditional reprocessing.
- Enrichment process developments that make it impractical to modify the process to produce weapons-useable enrichments either through increased probability for detection or via inherent features that would make the process

or facility incapable of reaching higher enrichments.

- Spent fuel repository R&D: to address the security and relative proliferation resistance of repositories many decades ahead. In the shorter term, R&D is needed to establish the standards and scientific basis for regional and international repositories.
- Thorium-uranium oxide fueled LWRs, which could result in reducing the quantity and attractiveness of weapons-usable material in spent fuel. Three variants: homogeneous mix of ThO2-UO2; micro-heterogeneous mix of ThO2-UO2; macro heterogeneous mix with a seed-blanket core. Further evaluation is needed to permit selection of the most promising variant.
- LWRs with non-fertile fueled cores: fuel fabrication development, scaling up from bench-scale to full size fuel elements; irradiation testing and post irradiation characterization of non-fertile fuel. Economic impact assessments of such fuels and core performance are also needed.
- Methods to accelerate the rate at which LWR irradiation could reduce current stockpiles of separated plutonium (e.g., through fuels that would increase the amount of plutonium in the core), and methods to improve the proliferation resistance of this process (through increases in both intrinsic and extrinsic barriers).
- Methods to recycle fuel in LWRs that would have higher proliferation resistance than current approaches, such as recycling without conventional reprocessing (recycling spent fuel pellets without extracting the fission products, maintaining the radiation barrier throughout the process), or reprocessing approaches that never separate weapons-usable material and do not provide facilities or technologies that could be readily adapted to do so.

2. High temperature gas-cooled reactors

General development of both pebble bed and fixed prismatic core variants of these systems should be pursued, including especially development of fueling approaches that do not rely on weapons-usable material in fresh fuel, from which it would be very difficult to divert material, and resulting in production of small quantities of highly unattractive material in the spent fuel. This would include, but not be limited to:

- Design and development of coatings to increase burnup.
- Development of thorium-fueled designs.
- Development of sophisticated on line weighing systems and gamma ray spectrometers to detect abnormal pebbles in the pebble-bed reactor systems.
- Application of approaches such as AIROX and pyrometallurgical reprocessing, designed so as not to fully separate fissile materials from fission products and transuranics.

3. Fast Spectrum Reactors

- Evaluation of concepts that would breed and burn material without reprocessing (such as high neutron economy systems in which plutonium is bred in the blanket and the blanket elements are then moved to the core).
- R&D on processing systems whose extractants cannot be altered to recover weapons-usable material.
- Ultra-long lived fuel – near-unity conversion reactors with ten year or more core lifetimes that gain a greater energy value from recycled Pu without traditional reprocessing.
- Operation without breeding blankets, so that the reactors do not produce significant quantities of high-grade plutonium.
- Performance data for fast reactor nitride fuels, which enable a low decontamination factor, non- aqueous fuel cycle, and potentially higher proliferation resistance.
- Examine the sensitivity of electro-refining to perturbations to determine the ease of extraction of uranium and plutonium; determine the gaseous release properties of electro-metallurgical treatment operations.

4. Small modular reactor systems

- Evaluate possibilities for factory-manufactured, passively safe systems with very long core lives, requiring much less buildup of in-country nuclear expertise – conduct R&D on fuel and core designs for very long core lives.

- Develop and demonstrate characteristics that support the envisioned autonomous controls.
- Conduct R&D on structural materials and coolant chemistry control required for long-life operation.

5. Research Reactors

Further develop very high performance LEU fuels for research reactors (in cooperation with the RERTR program) – fuels designed to make possible the conversion of those research reactors still using HEU, at competitive cost.

6. Transmutation technology

Evaluate proliferation resistance advantages and disadvantages of a variety of proposed systems designed to transmute weapons-usable isotopes in spent fuel to non-fissionable form, including the entire fuel cycle for such systems.

All of these programs cannot be carried to ultimate fruition because of the enormous resources that would be required. But the effective implementation of this proposed R&D initiative requires a strategic planning approach that provides a basis for prioritization and timing of the R&D portfolio effort. 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. The pursuit of the individual proliferation barrier projects should therefore be carried out in the context of the overall development of the reactor concept to which it is intended to apply the barrier. Systems also should be explored that avoid the transfer of technologies or expertise that could readily be employed in either the covert or overt design and manufacture of nuclear weapons.

D. R&D Opportunities for the Longer- Term

To provide tangible results that can improve proliferation resistance in the longer term, that is, from about 16 years out, projects/programs should focus on the evaluation, and, as appropriate, development of selected advanced systems and concepts. These efforts should consider and assess advanced light water reactors, liquid metal reactors, liquid-fuel reactors, and gas cooled reactors. Various reactor concepts should be investigated that do not require refueling for 10 to 15 years. Advanced closed fuel cycle options also should be investigated when they offer potential opportunities for improving proliferation resistance and international security. This should include the examination of systems that would avoid the presence of separated plutonium. R&D that addresses all the facilities of an integrated system might better minimize proliferation risks and national security concerns.

E. International Collaboration

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 the role and credibility of the U.S. in these areas. Only a technology that is broadly accepted worldwide can strengthen the nonproliferation regime. It is from R&D results that standardization is developed. Such standardization, particularly in proliferation resistance, is meaningless unless accepted and practiced internationally. Particularly important for international collaboration is R&D that addresses the extrinsic barriers, because an international consensus on their validity and effectiveness is required if they are to be utilized.

International collaboration also has been an important aspect of successful R&D programs for many years. 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. Collaborative R&D among international partners should be expanded, focusing on the theme categories defined above. Near-term prospects for increased collaboration that should be pursued include R&D related to high burnup fuels, Th/U fuels, non-fertile fuels, and advanced fuel cycle concepts. The President's Committee of Advisors on Science and Technology (Ref. 20) recommended as a high priority item in the nuclear area "addition of an explicit international component to DOE's new Nuclear Energy Research Initiative (NERI) promoting bilateral and multilateral research focused on cost, safety, waste management, and proliferation resistance of nuclear fission energy systems".

VII. CONCLUSIONS

There are a number of promising areas of research and development that the U.S. could undertake, preferably in collaboration with other interested countries, that could make a constructive contribution to enhancing the proliferation resistance of nuclear power systems both in the near and longer-term. These could be pursued under terms that are fully compatible with the need to assure that nuclear power continues to adhere to rigorous safety and environmental standards. Moreover, many of the options would appear to be compatible with the objective of assuring that nuclear power is competitive with alternate energy sources.

If the United States is to be able to explore, let alone develop, some of these options in a serious and sustained manner and as an effective international partner in collaborative R&D, the Federal Government will have to increase significantly its R&D dollars devoted to civil nuclear power and to enhancing proliferation resistance. These resources are now inadequate in view of these needs, and are absurdly low when compared to other energy R&D budgets in DOE.

In our view, the stakes here are high and go beyond the important objectives of maintaining the viability of nuclear power and enhancing the proliferation resistance of the civil nuclear fuel cycle. Unless the U.S. maintains a very active R&D program in the civil nuclear field, its credibility and leadership in the field of nonproliferation as it relates to civilian nuclear energy will seriously erode, as will its ability to help shape and influence the course and direction of foreign nuclear programs. The competitive strength of the United States in participating in the international nuclear market will also suffer.

This study identifies three major R&D areas that should be pursued:

- Develop improved methods to evaluate the comparative proliferation resistance features of different nuclear systems:
  - Improve and standardize the proliferation assessment of different reactors and fuel cycle approaches to plan R&D programs.
  - Provide a useful means to evaluate the worth of proliferation resistance features of reactor designs in order to balance R&D costs with benefit.
- Support R&D designed to enhance the efficacy of the extrinsic nonproliferation systems, through technologies that:
  - Speed the flow of information;
  - Improve the effectiveness of the international safeguards; and
  - Improve the effectiveness of national MPC&A processes.
- Support near and longer-term R&D aimed at improving the intrinsic proliferation resistance of specific nuclear power systems.

As a major point, in order to properly focus available resources, well-defined research and development themes and associated time frames need to be adopted by the United States, hopefully in a spirit of amicable cooperation with other interested nations. Suggested major themes to guide the program should include: the reduction of the quantity of weapons-useable material per unit power output; making weapons-useable material highly inaccessible; reducing the attractiveness of nuclear materials and facilities for potential use in making nuclear weapons; and designing facilities to minimize opportunities for diversion and increase transparency.

In mapping out its future R&D strategy in the proliferation resistance area, DOE should plan its programs in three distinctive time frames: shorter-term projects likely to produce tangible results in about five years, intermediate term projects producing tangible results up to 15 years from now, and longer- term projects with fruition times beyond 15 years. A commitment to the longer-term development of advanced fuel cycles is critical, but near-term needs should not be ignored in this process.

While the central role that political and institutional measures play in maintaining the efficacy of the global nonproliferation regime is recognized, several promising ways have been identified by which nuclear power systems and nuclear fuel cycles conceivably can be made more "intrinsically" resistant to proliferation and misuse. Such measures may hold the promise of providing more durable barriers to proliferation if they reduce the burdens on external and institutional systems and if they hold out the promise of being more stable than institutional measures, which can change in time.

At the same time, institutional measures will remain central to the viability of the global nonproliferation regime and significant opportunities remain to strengthen safeguards and measures of MPC&A through technological advances. Although the civil nuclear fuel cycle has not been the preferred technical avenue for acquiring nuclear weapons, it has been the source of materials and technologies that can be used to help make nuclear weapons. Accordingly, it is vital that all civil nuclear power programs be subject to improved, cost-effective nonproliferation controls.

Taking into account these findings, the Task Force strongly recommends that the subject of proliferation resistance R&D should be allocated at least an additional $25 million in the DOE budget for fiscal year 2002, potentially increasing subsequently if particularly promising opportunities requiring increased R&D funds are identified. A significant portion of these funds, in the range of $5-$8 million annually, should be devoted to adding to ongoing efforts in international safeguards and MPC&A technologies that could improve the extrinsic barriers to proliferation in existing reactor and fuel cycle systems. These new funds should be targeted toward improving the understanding of the interfaces with and trade-offs between intrinsic and extrinsic barriers, supporting the development of technologies required to safeguard new fuel cycles (e.g., Th/U in which there is little safeguards experience or technology for measurements, etc.) and used also to improve the transfer of technologies from other fields to programs to enhance international safeguards. A small portion, perhaps $2 million in the first year, should be devoted to improving methodologies for assessing and comparing the proliferation resistance of different proposed systems. The remaining $15-18 million would be devoted to the evaluation, analysis, and experimental work on approaches that could improve the intrinsic proliferation resistance of current and future reactor and fuel cycle systems.

An initial program such as outlined above, would allow the United States to maintain a position in the proliferation arena with respect to the technology. It would also provide a base upon which to build a strong proliferation resistance component into the future generation of reactor designs.

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. technical leadership, participation and credibility in these areas. Only a technology that is broadly accepted can strengthen the nonproliferation regime. Collaborative R&D among international partners should focus on the major theme categories identified in this report. Prospects for increased collaboration could include cooperative efforts to improve the methods for assessing proliferation resistance, measures to strengthen international safeguards R&D related to high burnup fuels, collaboration in Th/U fuels, non-fertile fuels, and advanced fuel cycle concepts.

The most appropriate R&D programs for international collaboration are those which address the extrinsic barriers, because an international consensus on their validity and effectiveness is required if they are to be utilized.

International collaboration has been an important aspect of successful R&D programs for many years. 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 opportunities.

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APPENDIX 1

TOPS TASK FORCE CHARGE AND MEMBERSHIP

A. Task Force Charge:

The Office of Nuclear Energy, Science and Technology (NE) has established a new task force under NERAC to identify the various technical opportunities for increasing the proliferation resistance of reactor and fuel cycle technologies for civilian nuclear power application and to recommend specific research areas. This task force will include two or three individuals recommended by the NN Advisory Committee.

The focus of the subject task force will be to address both near and longer term technology opportunities that can enhance the proliferation resistance of commercial nuclear power systems. Attributes and associated metrics will be developed and applied to evaluate proposed systems and subsystems. Third generation light water reactors using a once-through fuel system will be the reference standard. The task force will call upon experts and apply, as needed, a series of conferences and small focus workshops to analyze technologies and research issues.

Near-term issues, impediments and implementation, and long-term issues, impediments and implementation, will be examined in the context of future scenarios. For the near term, fuel and fuel cycle issues in light water reactors are expected to present the greatest benefits. In the longer term, new nuclear power systems (e.g. Generation IV reactor technologies), which also address needs such as better management of nuclear waste, enhanced safety, and enhanced economics are key to this effort.

A task force report, planned for the summer 2000, will identify and prioritize near and long-term technologies and clarify what research is needed to make these opportunities available to the international community.

B. **Task Force Members:**

John Taylor, Chair, EPRI

Robert Schock, Vice Chair, Lawrence Livermore National Laboratory

John Ahearne, Sigma Xi, Duke University

Edward Arthur, Los Alamos National Laboratory

Harold Bengelsdorf, Bengelsdorf, McGoldrick and Associates, LLC

Matthew Bunn, Harvard University

Thomas Cochran, Natural Resources Defense Council

Michael Golay, Massachusetts Institute of Technology

David Hill, Argonne National Laboratory

Kazuaki Matsui, Institute of Applied Energy, Japan

Jean Louis Nigon, COGEMA, France

Wolfgang Panofsky, Stanford University

Per Peterson, University of California, Berkeley

Mark Strauch, Lawrence Livermore National Laboratory

Masao Suzuki, JNC, Japan

James Tape, Los Alamos National Laboratory

C. **Final Report Editorial Board**

An Editorial Board was formed to develop the drafts of the final report for the many Task Force reviews. The Board was comprised of four Task Force members: Hal Bengelsdorf, Dave Hill, Bob Schock, and John Taylor, assisted by Jim Hassberger (LLNL), John Herczeg (DOE), Rob Versluis (DOE), and Buzz Savage (JUPITER).

APPENDIX 2

PROLIFERATION RESISTANCE ASSESSMENT METHODOLOGIES

A. The IAEA Integrated Assessment Methodology

The IAEA has identified the need for an assessment method that would lead to the optimum combination of all safeguards measures available to the Agency, including those from the Additional Protocol, in order to achieve maximum effectiveness and efficiency within the available resources. As a State-level approach, it takes into account a particular State's nuclear fuel cycle and nuclear-related activities and will allow the IAEA to provide credible assurance as to the non-diversion of declared nuclear material and of the absence of undeclared nuclear material and activities in the State. In addition to providing assurances about both declared and undeclared materials and activities, it is hoped that these so-called integrated safeguards will result in efficiencies that will allow the relaxation of some traditional nuclear material verification measures and a corresponding reduction in costs for such verification activities (Ref. 21), although this is a matter still under review. It is in the context of considering means to optimize safeguards and reduce the risk of proliferation from the civil fuel cycle that proliferation resistance-technology options can be identified.

The Standing Advisory Group on Safeguards Implementation (SAGSI) of the IAEA and others have advised that a methodology be developed by which all integrated safeguards proposals (ISPs) can be evaluated for compliance with the goals and objectives of integrated safeguards. With this goal in mind, the United States has undertaken the development of an integrated safeguards evaluation methodology (ISEM) as a major activity in its Member-State support program. (The methodology was utilized recently by the IAEA's Safeguards Concepts and Planning Division to evaluate an IAEA ISP in a trial application that also was an evaluation of the methodology itself. The exercise demonstrated that ISEM was practical and effective in evaluating integrated safeguards proposals.)

The ISEM is a structured framework consisting of a set of stages for evaluating an ISP (Figure 1). Its central feature is the determination of the completeness, effectiveness, and efficiency of coverage by proposed safeguards measures of all credible paths to the acquisition of weapons-usable fissionable material that are relevant to the proposal.

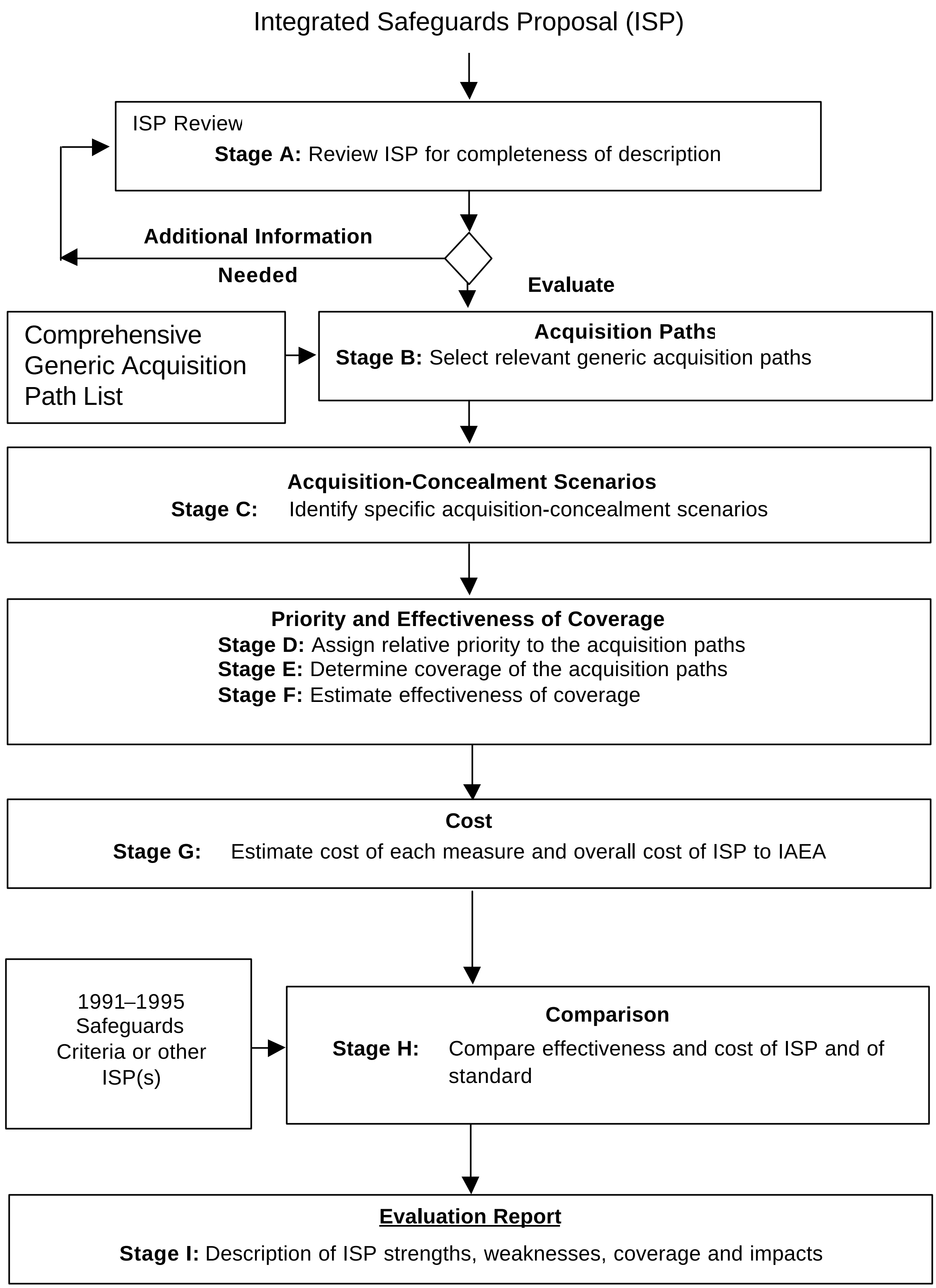

Figure 1. ISEM Logic Diagram

The ISEM begins with an ISP, which is first reviewed to ensure it is sufficient in terms of the information provided in the ISP. Once an ISP is judged sufficiently complete for at least an initial or preliminary evaluation, the ISEM addresses the acquisition paths relevant to its scope. After identification of all **covert** acquisition paths and their associated concealment methods is complete, each of these acquisition/concealment scenarios describes a detailed acquisition path for the purposes of applying the ISEM. Acquisition-path prioritization in ISEM is presently based on time requirements, cost, and difficulty but could involve a variety of other factors as well.

The ISEM is designed to provide a determination, with respect to each detailed acquisition path, as to whether the proposal includes one or more safeguards measures capable of detecting an attempted use of the path or whether, conversely, no measure is included that is capable of such detection. In addition to coverage, a measure of the degree of effectiveness of the proposed safeguards is also needed. The ISEM provides decision-makers with a reasoned estimate of the effectiveness of each safeguards measure, that is, the likelihood, expressed in qualitative terms, that the measure in question will detect the event or condition that it is designed to detect. This estimate, in combination with the previous determination of acquisition-path priority, allows a decision-maker to determine if the strength of coverage is appropriate.

The ISEM provides aggregated results for acquisition paths and acquisition/concealment scenarios relevant to either generic or State-specific ISPs, for single facilities or entire fuel cycles. Application of the ISEM identifies potential weaknesses or disadvantages in effectiveness, efficiency, and costs, which might be overcome by modifications to the measures to be employed. It also allows for sensitivity analyses to be performed and any proposed tradeoffs between cost and effectiveness to be examined. Thus, through a process of iterations involving a number of alternative ISPs, the desired optimization of available measures that is the central feature of integrated safeguards is practically and effectively approached using the ISEM. Thus the ISEM is intended to show clearly and concisely the strengths and weaknesses of an ISP, its costs, and the degree to which it would meet the IAEA's comprehensive safeguards objective. The ISEM is intended to be neutral with respect to ISPs, i.e., the ISEM should not introduce a bias for or against any ISP or type of ISP. As a consequence, the ISEM should involve a minimum of judgments, particularly subjective judgments, by the evaluator.

Elements of the ISEM methodology might find application in evaluation and comparison of fuel cycle concepts with respect to their ability to be effectively safeguarded and thus could contribute to the analysis of proliferation resistance. It is in the context of considering means to optimize safeguards and reduce the risk of proliferation from the civil fuel cycle that proliferation resistance technology options can be identified and evaluated

B. Attributes Methodology

The question of how best to evaluate and assess in some standardized fashion the relative proliferation-resistant attributes of different nuclear fuel cycles occupied a substantial amount of the Task Force effort. A conceptual framework for approaching this subject is outlined in Reference 16, and has been discussed both within the Task Force as well as with outside groups and critics. The basic approach taken is to evaluate the relative proliferation resistance of specific nuclear systems in terms of a generic set of "attributes." The attributes are derived by first defining the barriers to proliferation inherent in the design of the system, its materials and facilities, and its modes of operation. These "intrinsic" barriers are characterized in generic form as follows:

Material barriers—intrinsic, or inherent, qualities of materials that reduce the inherent desirability or attractiveness of the material as an explosive:

- Isotopic
- Chemical
- Radiological
- Mass and Bulk
- Detectability

Technical Barriers—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:

- Facility unattractiveness
- Facility accessibility
- Available mass
- Detectability of diversion
- Skills, expertise, and knowledge that are necessarily involved
- The influence of time factors, including the time that may be required to obtain access to weapons-usable materials.

The relative importance or effectiveness of a barrier applicable to a given system, subsystem or mode of operation depends on the nature of the proliferant actor posing the threat to the system. Such potential proliferators could be highly industrialized states, developing states, or sub-national groups acting with or without external state sponsorship. Moreover, the actors in question could attempt to divert or misuse materials either clandestinely or they could carry out such activities overtly after having announced their intent, e.g., through the abrogation of international treaties and supply agreements.

Within this context, the following table provides a broad indication of the variations in importance of different intrinsic barriers to diversion or theft as they apply to different potential proliferators.

Table 1. Relative importance of Various Barriers to a Selected Type of Threat

	Sophisticated State, Overt	Sophisticated State, Covert	Unsophisticated State, Covert	Sub-national Group
Material Barriers				
Isotopic	Moderate	Low	Moderate to High	High
Chemical	Very low	Very Low	Moderate to High	High
Radiological	Very low	Low	Moderate	High
Mass and Bulk	Very low	Low	Low	Moderate
Detectability	Not applicable	Moderate	Moderate	High
Technical Barriers				
Facility Unattractiveness	Moderate	Moderate	High	Very low
Facility Accessibility	Very low	Low	Low	Moderate
Available Mass	Moderate	Moderate	High	High
Diversion Detectability	Very low	Moderate	Moderate	Moderate
Skills, Expertise, and Knowledge	Low	Low	Moderate	Moderate
Time	Very low	Very low	Moderate	High

Although strong intrinsic barriers are an inherently desirable feature of a proliferation-resistant system, they are insufficient in themselves to cope with all clandestine activities or the prospect that a state might elect to abrogate its nonproliferation obligations. Intrinsic barriers are insufficient alone to prevent clandestine or abrogation decisions to acquire nuclear materials. Thus, they must be supplemented by institutional or political barriers, including, for example, the international safeguards system administered by the IAEA, the Nuclear Non-Proliferation Treaty, and constraints applied by various nuclear suppliers. The burdens and demands placed on these extrinsic barriers are influenced by the characteristics and importance of the intrinsic barriers that apply in a given case. For instance, the more complete the intrinsic barriers are for a given system, the less intensive and costly the extrinsic barriers need be. Note that for the purposes of this analysis, we have defined institutional barriers somewhat narrowly. Consideration of questions of regional, internationally owned fuel cycle facilities and their impact on proliferation resistance are not considered, although they have the potential of mitigating the threat of misuse of the most sensitive technologies: enrichment and reprocessing.

It is the sum of the inherent barriers and the institutional barriers that defines, along with the level of threat, the overall proliferation resistance in a given case. 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 authorities or by the breakdown of institutional or economic systems. Treaties or other international commitments to establish institutional barriers can be abrogated: access to externally imposed inspections can be denied, funding to pay guards can be interrupted, etc. Thus, intrinsic and institutional barriers are of a basically distinct nature and there is virtue in having institutional barriers reinforced, where feasible, by intrinsic ones.

The analytical process to assess intrinsic barriers evaluates the sequence of steps within each particular fuel cycle and reactor systems at which diversion or theft may occur and tabulates in a matrix the material and technical barriers that are inherent in each fuel cycle and reactor system. The evaluation would follow a separate path addressing a particular proliferant threat or actor to be considered. After completion of these steps, the most significant barriers and threats can be selected and a more in-depth evaluation carried out.

The effectiveness of a barrier can depend on time and more strongly on the interaction of many highly judgmental variables, including the sophistication and motivations of a proliferator, the material in question, the context in which the facilities are used, and more. The transparency of the nuclear power activities involved in a State is paramount. Clearly the maximum level of openness is desirable to ensure international political and public confidence that proliferation is neither intended nor being carried out, thus minimizing the burdens of implementing the external barriers.

For purposes of this analysis, we have defined institutional barriers or constraints somewhat narrowly focusing on the key elements of the existing regime—such as implications for international safeguards and ways to improve them. The evaluation of innovative institutional approaches for the future, such as the merits of establishing regional, internationally owned or controlled fuel cycle facilities and their impact on proliferation resistance have not been part of this study, although they have the potential of mitigating the threat of misuse of the most sensitive technologies; enrichment and reprocessing.

Thus, it is not practicable at this time to obtain a meaningful, quantitative metric by considering technologies in a singular fashion. Further, in keeping with past detailed nonproliferation assessments, (including those carried out in the INFCE Review), a meaningful assessment of proliferation risks and resistance in a given context must consider more than the intrinsic technical and material barriers. Rather, only through consideration of the total context in a given case, including political and institutional concerns, can one obtain a balanced evaluation of likely risks and barriers or impediments to proliferation.

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APPENDIX 3

RECOMMENDED R&D TO STRENGTHEN THE EXTRINSIC BARRIERS TO PROLIFERATION

A. Information Technology

- Integration of sensors and data monitoring systems.
- Application of satellite monitoring systems.
- Systems that provide real time surveillance and measurements and store information i.e. remote monitoring.
- Systems that include high fidelity, real-time, high integrity data transmissions.
- Technologies that conduct smarter and faster analysis of information gathered from monitoring systems.
- Creating an information rich management center that integrates information analysis, data mining, and computer networking.
- Methods to improve authenticating source data.
- Need to develop instrumentation that works in more universal applications. Need for simplicity and common safeguards inspection instrumentation to be applied in a variety of installations.
- Application of expert intelligence for rapid automated data analysis.
- Enhanced use of common safeguard systems rather than site specific instrumentation.

B. System Studies

- Development of optimized approaches to combining traditional and new safeguards concepts, and integrating wide range of safeguards, open-source, and other information for safeguards purposes.
- 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.
- Identification of information technologies, information protection, and reliability commonalties so 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 facility security assessments, taking care that key security features are not disseminated in the interest of nonproliferation. (For example, the French classify key characteristics of their physical protection systems.) Results of the analysis and information learned can then be fed back into facility design to improve proliferation and MPC&A weaknesses.

C. Improved material accounting and facility monitoring

- Develop higher accuracy, lower-cost assay technology to reduce uncertainties in material accounting, particularly for large-scale bulk processing facilities.
- Develop improved technologies for measuring fissile material in spent fuel and in heterogeneous materials such as plutonium-bearing scrap and residues.

- Develop approaches to integrating information from national material control and physical protection systems into containment and surveillance systems for international safeguards, increasing likelihood of detection of removal of material from a facility.
- Develop new technologies for long-term, low-cost monitoring of geologic repositories to ensure that any removal of material would be detected, including measures to detect covert tunneling attempts (e.g., passive and active seismic, ground-penetrating radar, etc.).
- Develop improved surveillance technology to detect enrichment plant modifications intended to allow HEU production.
- Develop new material control regimes to increase transparency of reprocessing operations.
- New techniques to allow for fast, accurate, quantitative fissile material measurements.

D. <u>Wide Area Environmental Monitoring</u>

- Wide area monitoring can be among the most powerful safeguards tools for providing assurances of the absence of undeclared activities, but assessment is needed of the effectiveness of this measure in detecting activities employing extensive concealment measures.
- Enhanced capabilities for detection of undeclared power plants, reprocessing facilities, and enrichment plants, ranging from improved analysis capabilities for samples collected from ground sites and air-based platforms to approaches for laser detection of trace effluents.
- More robust monitoring capability to minimize the chances of breakdown of extrinsic organization monitoring capabilities.

E. <u>Enhanced Material Tagging Safeguards Measures</u>

- Tracers in material to know its location without interfering with established plant operations.
- Seals with improved tamper resistance and lower cost.
- Fuel assembly tagging, especially for use with MOX and HEU fuels.
- Technologies that would allow remote identification that a spent fuel assembly is still where it is being stored and intact. The large number of existing assemblies and related operational requirements has long-term proliferation implications.
- Develop new material control regimes to increase transparency of reprocessing operations.
- New techniques to allow for fast, accurate, quantitative fissile material measurements.

F. <u>Application of PRA methodology</u>

- Develop risk assessment capabilities, including needed databases, to identify high risk and high probability proliferation pathways or redundancies in detection.
- Examine decision theory and combined PRA methodology to develop metrics uniquely applicable to assessing proliferation resistance

G. <u>Improved, lower cost surveillance and international/regional Safeguards interaction</u>

- Research to determine the most effective report avenues for violations/questions, such as facility data reporting into a multinational center and a means to provide best access to critical data by inspectors or monitoring efforts.
- Utilization of discrete event formalisms to enhance international safeguards agreements.

H. Measures to Improve National MPC&A Systems

The following list of major attributes for a durable national MPC&A system are listed below in relative order of priority:

- Improve assay technology to reduce uncertainties in materials accounting.
- Evaluate adequacy of administrative steps necessary to obtain access.
- Explore ways to optimize human automation interface.
- Evaluate technologies available in defense programs that may be applicable and available.
- Develop improved threat definition and analysis for optimization of protective measures against both inside illicit activities and outside intrusion.

I. Importance of Aggregating Spent Fuel

Substantially greater attention should be given, over the near and long-terms, to the development of new approaches that will facilitate the aggregation of spent fuel in politically stable countries or regions with strong nonproliferation credentials. Achieving this goal is primarily an institutional and political issue but technical contributions can be made through development of cost effective monitoring capability for geologic repositories, and improved inventory systems for spent fuel.

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APPENDIX 4

GLOSSARY

Additional Model Protocol
Officially the "Model Protocol Additional to the Agreement(s) Between States and the IAEA for the Application of Safeguards". Adapted in 1997 after clandestine activities were discovered in Iraq, it gives the IAEA additional capability to detect and investigate undeclared activities.

Attributes Methodology
A method to evaluate and assess the relative proliferation-resistant qualities or properties of different nuclear fuel cycles. It is an extension of the methodology used by the U.S. National Academy of Sciences in its 1994 report on the disposition of weapons plutonium. The method was developed initially by Lawrence Livermore National Laboratory and then refined with the help of others during the development of the TOPS Report. The attributes are derived by defining the intrinsic barriers inherent in the design of the system, materials, facilities, and modes of operation. The effectiveness of a barrier depends on the threat. The method evaluates the relative effectiveness of the intrinsic barriers and aids in identifying those additional extrinsic barriers which, when supplementing the intrinsic barriers, enhance the proliferation resistance of the system. This method is described in Appendix 2.

Back-end of the fuel cycle
The handling, processing and disposition of used nuclear fuel after its discharge from a reactor, in some cases leading to re-fabrication into new fuel elements, and in all cases including the ultimate disposition of the high level radioactive wastes. Reprocessing, where practiced, is part of the back-end of the fuel cycle.

Burnup
The thermal energy produced in a nuclear reactor by a given mass of uranium, plutonium, uranium-thorium mixture, or other fissile material combination. Generally, burnup is cited in terms of megawatt-days thermal per kilogram of initial heavy metal (e.g., uranium and thorium, without regard to its isotopic mix), MW d/kg ihm. Modern light water reactors commonly irradiate fuel to burnups of 45,000 MW d/kg ihm. In gas-cooled reactors, burnup is sometimes cited as fissions per initial metal atom, FIMA. In the Light Water Breeder Program, burnup is cited in fission units, where one fission unit is 1 x 10^{20} fissions per cm^3 of fuel. With an approximate density of 10 grams/cm^3 and 200 MeV of total energy released per fission, the equivalence among the units is:

1 MW d/kg ihm = 0.001 fissions per initial metal atom = 0.27 fission units

Closed Fuel Cycle
A nuclear fuel cycle in which the used fuel is recycled following its use in a reactor. Recycling may or may not result in separated plutonium during one or more steps in the recycling process. One example is separating the plutonium from used fuel, turning it into plutonium oxide, and blending with uranium oxide into mixed-oxide (MOX) fuel for one or more reactor irradiation cycles.

Defense Threat Reduction Agency (DTRA)
A Department of Defense (DoD) agency that integrates and focuses the capabilities of the DoD to address the threat from weapons of mass destruction. Its mission is to safeguard the United States and its friends from weapons of mass destruction by reducing the present threat and preparing for the future threat.

Export Controls
Restrictions placed on the sale or transfer of nuclear technology to a foreign country. Protocols for export controls are contained in the Nuclear Nonproliferation Treaty, as amended. Lists of technologies and information subject to export controls are in the so-called Trigger List. The list contains items that if misused could contribute to a nuclear weapons program, including plutonium, HEU, reactors, reprocessing and enrichment plants, and equipment and components for such facilities.

Extrinsic Proliferation Barrier
An institutional or other external barrier that lowers the risk of proliferation of nuclear materials, such as physical security measures, monitoring techniques, and IAEA inspections. (See also: Intrinsic Proliferation Barrier)

Fertile nuclide
Nuclear isotopes that can be converted to fissile isotopes through neutron absorption (and subsequent decay). Th-232 and U-238 are naturally occurring fertile nuclides. Fertile isotopes do not fission efficiently at low neutron energies (<1 MeV).

Fissile nuclide
Nuclear isotopes that can be fissioned by low energy neutrons. U-233, U-235, Pu-239, and Pu-241 are examples of fissile nuclides.

Fissionable nuclide
All nuclear isotopes that can be fissioned, although common usage applies the term to isotopes that can only be fissioned by high energy neutrons. Th-232 U-238, Pu-240, and Pu-242 are fissionable nuclides.

Fuel
Fissionable uranium, plutonium, thorium and other actinides (and their chemical compounds) that are placed in nuclear reactors for the purpose of producing energy.

Generation IV reactors
The next generation of advanced fission reactors, expected to be deployed by 2030. They are expected to have revolutionary improvements that allow them to be deployed worldwide and to yield energy products such as electricity, hydrogen, process heat, and desalinated water for the civilian market through 2100. The goals of Generation IV designs include lower cost, increased levels of safety, reduced waste, sustainable energy generation, and improved proliferation resistance.

Highly enriched uranium (HEU)
Uranium mixture containing 20 percent or more of the isotope U-235 or 12 percent or more of U-233.

Integral Fast Reactor (IFR)
A liquid metal fast spectrum reactor designed by Argonne National Laboratory and General Electric. It is designed to optimize energy extraction and minimize waste from nuclear fuel through a closed recycle system using pyroprocessing technology. The design and testing effort was stopped when the DOE program was cancelled in 1995.

Integrated Safeguards Evaluation Methodology (ISEM)
An assessment method developed from IAEA initiatives that would lead to the optimum combination of safeguards measures in order to achieve maximum effectiveness and efficiency with available resources. The ISEM process is described in Appendix 2.

International Atomic Energy Agency (IAEA)
Serves as the world's central inter-governmental forum for scientific and technical cooperation in the nuclear field. Carries the responsibility to deter proliferation through surveillance, monitoring, inspection, and accountancy of nuclear materials. A specialized agency within the United Nations system, the IAEA maintains its headquarters in Vienna, Austria.

International Institute for Applied Systems Analysis (IIASA)
Non-governmental research organization located in Austria. The institute conducts inter-disciplinary scientific studies on environmental, economic, technological, and social issues in the context of human dimensions of global change. Sponsored by national member organizations in North America, Europe, and Asia.

International Nuclear Fuel Cycle Evaluation (INFCE)
A major evaluation convened by IAEA in 1978 that attempted to compare the nonproliferation characteristics of different nuclear fuel cycles and nuclear systems that would lead to recommendations on steps that nations could take to help strengthen the nonproliferation regime.

Intrinsic Proliferation Barrier
An inherent quality of reactor materials or the fuel cycle that is built into the reactor design and operation such as high level of radioactivity, chemical processing required to extract, isotopic composition, mass and bulk, sealed systems, high burnup fuels, etc., that reduces its desirability or attractiveness as an explosive, makes it difficult to gain access to the materials, or makes it difficult to misuse facilities and/or technologies for weapons applications.

Material Protection, Control and Accountability (MPC&A)
The set of physical protection, instrumentation, monitoring equipment, and administrative procedures that are placed in effect to improve nuclear material security and accountability in order to preclude or limit the possibility of theft or diversion of nuclear materials for illicit purposes.

Mixed Oxide (MOX) Fuel
Nuclear reactor fuel which is comprised of a mixture of plutonium oxide and uranium oxide. It is manufactured using plutonium extracted from used nuclear fuel or from excess weapons stockpile materials.

Nonproliferation Alternative Systems Assessment Program (NASAP)
A study conducted in 1980 that evaluated how the U.S. light water reactor once-through fuel cycle compared to other options. It concluded that the LWR once-through cycle is more proliferation-resistant than other fuel cycles which involve HEU or plutonium.

Nuclear Energy Research Advisory Committee (NERAC)
A group of independent advisors to the Secretary of Energy and the Director, Office of Nuclear Energy, Science and Technology (DOE-NE), who provide advice on complex science and technical issues that arise in the planning, managing, and implementation of DOE's nuclear energy programs. It was formed in October 1998 in response to a recommendation in the November 1997 PCAST Report on federal energy R&D for the challenges of the 21st century. It has chartered a number of subcommittees and task forces on various nuclear energy issues, including long term planning for nuclear R&D, the future of currently operating nuclear plants, isotopes for medicine and other applications, nuclear infrastructure, and proliferation resistance.

Nuclear Nonproliferation Treaty (NPT)
Treaty developed by the Eighteen-Nation Disarmament Committee starting in 1964 and signed by President Johnson and 61 other national leaders in 1968; ratified by the U.S. Senate in 1970. The treaty limits nuclear weapons to the five states that proclaimed possessing them at the time – the United States, Great Britain, France, Russia, and China. All other signers had to promise not to acquire them. The NPT was extended indefinitely in 1995 and now has 187 signatory nations. With respect to nuclear energy technology, the treaty provides for: a) assurance, through international safeguards, that the peaceful nuclear activities of non-nuclear weapons states will not be diverted to making nuclear weapons; and b) promoting the peaceful uses of atomic energy, to include making available the potential benefits of any peaceful application of nuclear explosion technology to non-nuclear parties (if conducted under international observation).

Nuclear Proliferation
The manufacture or acquisition of nuclear weapons by previously non-weapons states or sub-national groups.

Nuclear Weapons State
A country that has declared itself as possessing and having the capability to deliver nuclear weapons. Declared nuclear weapons states are the United States, Russia, Great Britain, France and China. India and Pakistan are states known to possess nuclear weapons but have not declared themselves nuclear weapons states. Israel is generally considered to possess nuclear weapons capability but has not so declared. Other countries (e.g.; Japan, Germany, Brazil) certainly have the technical capability to possess nuclear weapons but have publicly forsaken their development.

Once-through (or open) fuel cycle
A nuclear fuel cycle in which the fuel is not recycled following its use in a reactor. The used fuel may be reconfigured or repackaged before placement in the ultimate repository. Usually the cladding is not breached, but this may not always be the case.

Plutonium-Uranium Extraction (PUREX)
An aqueous reprocessing system that separates plutonium and uranium from used nuclear fuel. Fission products and other wastes are retained in a liquid waste form and stored in large tanks or converted to solid form for final disposition. PUREX facilities have been operated by DOE at Hanford and the Savannah River Site. Similar operations are carried out in other countries, most notably France and Great Britain, which convert wastes from the PUREX process to a solid form through vitrification.

Proliferation resistance
The degree of difficulty in using, or of diverting material from, a commercial reactor and fuel cycle system for the clandestine production of materials usable in nuclear weapons.

Reprocessing (or Recycling)
The practice of extracting enriched uranium and plutonium from used nuclear fuel and reusing it in new fuel for additional irradiation in a reactor. It is the major element of the closed fuel cycle.

Safeguards
The set of institutional measures taken to preclude or limit the possibility of theft or diversion of nuclear materials for illicit purposes. It includes treaties, IAEA inspections, and monitoring. It consists of a blend of detection systems capable of identifying nuances in operations and people who can understand and interpret the information provided by the detection systems.

Separative Work Unit (SWU)
The standard measure of enrichment services, measuring the effort expended in increasing the U-235 content of uranium above the natural 0.7 percent. It typically measures the amount of enrichment capacity required to produce a given amount of enriched uranium from a particular feed material, while enrichment plant capacities are quoted in SWUs per annum.

Transparency
A measure of the ability to provide confidence between governments that each is abiding by its nonproliferation agreements. Methods include technical and administrative measures such as direct observation and assay.

Weapons-usable nuclear material
Nuclear material (uranium, plutonium, or other actinide) that is sufficiently pure and free of contaminants to allow its use in a functional nuclear weapon or explosive.

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