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# Proliferation-Resistant Nuclear Power Systems:
## A Workshop on New Ideas
## June 2–4, 1999

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CGSR
Center for Global Security Research

Lawrence Livermore National Laboratory
University of California, Livermore, California 94551

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# Contents

# Foreword

The origins of this workshop lie in the convergence of a number of realities that create a need to clarify the potential threat of nuclear weapons proliferation from the production of civilian nuclear power. Much has been written and said on this subject, but time and technology have continued their march and new considerations and approaches are being offered.

The first reality is that nuclear power will be with us for most, if not all, of the next century. It generates about 17% of the world's electricity today and its share is still growing despite concerns about safety, cost, and the disposal of radioactive waste. Most global projections produced by world organizations suggest that the number of nuclear reactors will increase in the first half of the next century. The appropriate question is not, "Will there be nuclear power?" but "How much nuclear power will there be and will it be concentrated in certain countries or regions?" The multinational International Institute of Applied Statistical Analysis in Vienna projects an increase of between 30 and 130% over six scenarios, with four of them clustering around 80%, and all of them leading to growing stores of fissionable materials, most notably plutonium (Pu). Most significant is that at least two-thirds of that increase will take place in the developing world.

Second, it has been almost 20 years since the publication of the International Atomic Energy Agency's International Fuel Cycle Evaluation (INFCE) and the U.S. Department of Energy's Report on the Nonproliferation Alternative Systems Assessment Program (NASAP). Much has happened since then. The accidents at Three Mile Island and Chernobyl. Global economic development has far outpaced most expectations. Few would have predicted the substantial drop in the prices of uranium fuel, oil (recently increased), and natural gas. The Soviet Union's collapse created a number of states whose economic and / or political conditions cast reasonable doubt on their ability to secure and to safeguard nuclear materials. The development of highly efficient aero-derivative turbines has helped to make natural gas the fuel of choice for most new electrical generation in Organization for Economic Cooperation and Development (OECD) countries. Reactor technology, construction methods, and operational reliability have advanced substantially while efforts toward waste disposal have lagged well behind earlier expectations. Technology has made sensors—including those applicable to nuclear safeguards and security—much more sensitive, cheaper, less obtrusive, disruptive, and considerably more tamper-proof. All these factors influence thinking about the future of the civilian nuclear fuel cycle and its linkages to nuclear weapons proliferation.

Third, the technical community disagrees considerably about the relative resistance of the current nuclear power system to proliferation. Some believe it is a very serious threat while others feel it is no threat at all. In the latter camp are those who are convinced there are far easier and more likely ways for a proliferator to obtain materials for nuclear weapons. In addition, the influence of the U.S. on global civilian nuclear issues is declining, and it has found no acceptable goals or solutions to change this.

The June workshop was organized by the Center for Global Security Research (CGSR) to explore and assess new technology ideas and options that may reduce the proliferation risk from civilian nuclear power systems or may assist institutional and policy approaches in reducing that risk. Bridging the technical–policy interface is the Center's principal objective, and it does so by bringing together diverse expert communities to address common challenges with significant policy implications. A nuclear weapons research laboratory is ideally suited to discuss various technical aspects from the proliferator's as well as the safeguarder's point of view. Invitees to the workshop were those knowledgeable about both the technical and policy aspects of the nuclear fuel cycle, nuclear power and/or nuclear proliferation technology and policies, and nuclear weapons. They represented U.S. and international government and non-government agencies, national laboratories, universities, research centers, and industry.

Given the broad differences of opinion characteristic of this subject, the degree of agreement by the participants as to the issues, their importance, and the needs that they elevate was perhaps surprising. Five different breakout groups derived surprisingly similar answers to the questions asked. However, responsibility for the writing of this report rests with the CGSR and the organizers of the workshop.

We wish to thank the Department of Energy and its Offices of Nuclear Energy, Science, and Technology, Nonproliferation and National Security, and Defense Programs; the U.S. Department of State; and the International Atomic Energy Agency for their generous sharing of ideas and personnel to make this workshop possible. Los Alamos National Laboratory organized a mini-workshop several weeks prior to this workshop to discuss metrics for the proliferation resistance of global nuclear energy and presented the results as part of the agenda.

## Organizing Committee

Edward D. Arthur, Los Alamos National Laboratory
Neil W. Brown, Lawrence Livermore National Laboratory
Thomas J. Gilmartin, Lawrence Livermore National Laboratory
James A. Hassberger, Co-chair, Lawrence Livermore National Laboratory
Thomas Isaacs, Lawrence Livermore National Laboratory
Edwin D. Jones, Lawrence Livermore National Laboratory
Seung-Cheol Lim, Korean Ministry of Science and Technology
Robert N. Schock, Co-chair, Lawrence Livermore National Laboratory
William G. Sutcliffe, Lawrence Livermore National Laboratory
Nancy L. Suski, Lawrence Livermore National Laboratory
Eileen S. Vergino, Lawrence Livermore National Laboratory
Richard L. Wagner, Jr., Los Alamos National Laboratory

# Workshop Agenda*

**June 2, 1999**

Plenary Session I—Ronald Lehman II, Session Chair
*Proliferation and proliferation resistance—Current status and challenges*

Welcome / Perspective and Goals of the Workshop—Ronald Lehman II

1. DOE–NE Perspective and Role of NERI—William Magwood, Director, Office of Nuclear Energy, Science, and Technology, U.S. Department of Energy (address delivered by John W. Herczeg)
2. DOE–NN Perspective—Edward Fei, Office of Nonproliferation and National Security, U.S. Department of Energy
3. Nonproliferation: The Diplomatic Dimension—John Dooley, Senior Advisor for Nuclear Cooperation Affairs, U.S. Department of State
4. Design Features to Facilitate Implementation of IAEA Safeguards—Juergen Kupitz, Head, Nuclear Power Technology Development, IAEA
5. Safeguard Challenges in the 21st Century—Johan Swahn, Prof. of Physical Resource Theory, Chalmers University, Sweden

Participant Questions and Comments

Plenary Session II—Robert Budnitz, Session Chair
*Proliferation and proliferation resistance—Current status and challenges (cont.)*

6. Demythologizing Plutonium—Myron Kratzer, Consultant, Annapolis, MD
7. A Global Perspective: Technology and a Sustainable Energy Future—Prof. Atsuyuki Suzuki, University of Tokyo
8. Educating Proliferation-Resistant Technologists—Marvin Miller, Security Studies Program at the Center for International Studies, MIT

Participant Questions and Comments

Plenary Session III—Wolfgang Panofsky, Session Chair
*Relationships between the fuel cycle and proliferation—What are the threats?*

9. Looking at the U.S. Nuclear Industry—David Rossin, Rossin and Associates
10. European Industrial Perspective—Jean-Louis Nigon, COGEMA
11. Future Proliferation Threat—Bruce Goodwin (LLNL) and John Kammerdiener (LANL)
12. Nonproliferation Trust, Inc.: Long-Term Fissile Materials Safeguards and Security Project—Tom Cochran, Director of the Nuclear Program, Natural Resources Defense Council
13. Whatever Happened to Diversion?—Roger Avedon, Stanford University

Participant Questions and Comments

Dinner Speaker: Mitchell Reiss, Assistant Executive Director, Korean Peninsula Energy Development Organization—*KEDO: Past Lessons, Future Challenges*

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*Many of the papers are available at http:/cgsr.llnl.gov under the title of this workshop.

**June 3, 1999**

Plenary Session IV— Atsuyuki Suzuki, Session Chair

*Are there new or emerging technologies that will enhance the proliferation resistance of nuclear power systems or subsystems? What metrics are reasonable?*

14. Proliferation Issues That Technology Can Address, the Risks and the Barriers to Implementation—John Taylor, Vice-President (Retired), Nuclear Power Group, EPRI
15. Attributes and Metrics for Proliferation Resistance (Evaluation of alternative paths)—Mike Golay (MIT)
16. LANL Workshop on Metrics—Richard Wagner, Leader, Nuclear Vision Project, LANL

Participant Questions and Comments

Panel: Briefings on Technical Ideas (posted on the web site)

Alvin Radkowsky (Tel-Aviv University), Paul Chodak III (LANL), Philip MacDonald (INEEL), Ken Tomabechi (Japan Academy of Sciences), Kun-Jai Lee (KAIST), Edward Arthur (LANL), Per Peterson (University of California, Berkeley), Craig Smith (LLNL)

17. Technical Vulnerabilities of the Fuel Cycle—James Hassberger (LLNL)

Breakout Sessions

Session Directors: Ed Arthur (LANL), Sam Bhattacharyya (Argonne National Laboratory), Per Peterson (University of California, Berkeley), Mona Dreicer (State Department), Steve Cochran (LLNL)

Breakout Session Questions:

1. What are the major proliferation and / or safeguards risks and where in the system do they occur?
    a) What are the dominant attributes of these risks?
2. Are there technical options (real or potential) for reducing these risks?
    a) For new technology options, what R&D breakthroughs are required?
    b) What are the opportunities for international collaboration and how should they be developed?
3. What are the impediments to implementation of new technical options?
    a) Would implementation of these technical options adversely impact other areas (e.g., safety, environment, and economics)?
    b) What infrastructure or policy changes are required to implement the technology improvements?
4. What are the logical next steps that need to be taken?

Dinner Speaker: Wolfgang Panofsky, Stanford University—*The Spent Fuel Standard*

**June 4, 1999**

Plenary Session V—Robert Schock, Session Chair

Reports from Breakout Sessions

Panel Discussion—Myron Kratzer, Chair

*What are meaningful goals and solutions utilizing advanced technology? What R&D is needed? What are the implementation, policy, and institutional issues?*

Panel Members: Hal Bengelsdorf, Tom Isaacs, Leonard Weiss, Ed Fei, Young-Myung Choi, Bob Budnitz

Participant Questions and Comments

Summary and Closing Remarks

## Summary and Conclusions

The workshop addressed a number of major questions and challenges surrounding the relationship between the future of nuclear power and the broader issue of proliferation of nuclear materials for weapons or other means of nuclear terrorism. This is but one of at least four issues facing the civilian nuclear power industry, the others of note being safety, economics, and environmental impacts including the final disposition of waste. Various authorities attach different levels of significance to these issues, at least some maintaining that proliferation is the greatest, but all agree that they must be examined in parallel.

Workshop participants were asked to consider several questions:

- What do we mean by nuclear proliferation and proliferation resistance? What metrics are useful for assessing proliferation resistance? What are meaningful goals and solutions?
- Can nuclear power systems and / or sub-systems be developed that are more resistant to proliferation than those in existence or being planned today? What are the barriers to the implementation of such systems? Can these solutions be applied to research, test, and isotope-production reactors?

### Role of the problem

Proliferation from the civilian nuclear fuel cycle is only a small part of the much greater problem of arresting the proliferation of nuclear weapons. At the same time, it is an important problem that needs to be adequately addressed and managed or nuclear power will not be a realistic option for the marketplace in the future. Interestingly, not having enough electrical power to allow significant economic development may in fact increase the proliferation risk from countries seeking to increase their lot, by increasing the attractiveness of military or other means to do so.

> *". . . we must consider how the spread of nuclear materials and technology may play a role in the future geopolitical landscape."*
>
> **William Magwood, IV**

### What are the issues?

Commercial nuclear power is perceived as one path by which a potential proliferator may gain technology, materials, and / or expertise that could be used to develop a nuclear weapons program. How important is this path in relation to other paths? Can technology serve to reduce the risks from this path?

To date, civilian nuclear power has not been the path of choice to acquire nuclear weapons or nuclear materials for weapons, and several international studies have concluded that it is an unlikely path. Two major exceptions are research reactors, which may or may not be associated with civilian nuclear power, and expertise gained from civilian activities, which has been used to accelerate clandestine nuclear weapons programs. Nevertheless, growing stocks of Pu and other weapons-usable material in spent commercial fuel (current estimates of about 1,300 tonnes are expected to grow to 2,000 tonnes in the next decade) and the potential growth of nuclear power in the developing world lead to an increase in at least the perceived risk of proliferation from nuclear power.

Examination of various cycles and the opinions of weapons-design experts lead to the conclusion that there is no "proliferation-proof" nuclear power cycle. Explosive Fissionable Material (EFM) includes most of the actinides and their oxides; most EFMs are potentially available as components of spent reactor fuel. Therefore, while much attention has been paid to light-water reactors (LWR) that produce an abundance of $^{239}$Pu, all nuclear fuel cycles and many fissionable isotopes (including all those of Pu) entail some risk—a conclusion reached 20 years ago in the INFCE and NASAP studies. The degree of risk that any EFM may be successfully used in a nuclear weapon depends on the difficulty of the specific technical problem presented by that EFM and the technical prowess available to a nation or sub-national entity to find an engineering solution to that problem. Almost all technical problems have engineering solutions, and the degree of difficulty of the solution is commensurate with the difficulty of the problem.

Even though there are no proliferation-proof systems, it is important to recognize that there are usually simpler, more direct, cheaper, more clandestine, and therefore more likely ways for a proliferator to acquire both the materials and much of the technology necessary for nuclear weapons, rather than using material from a dedicated civilian power reactor system. Dedicated power reactors and their associated support systems, especially with international controls and safeguards, are probably the last resorts for a determined proliferator to acquire the necessary nuclear materials.

In addition to access to EFMs, a workable nuclear weapon requires sophisticated technology in at least three broad areas: nuclear-materials handling, nuclear weapons design, and the delivery and use of a weapon. Some of the necessary technology for nuclear-materials handling does come with a nuclear power cycle or system using in-country domestic resources, mainly in the enrichment and reprocessing steps. However, the other necessary technologies are not associated with civilian nuclear power. Nevertheless, the use of nuclear materials for purposes of straightforward terrorism requires no such sophistication.

*"It is, of course, possible for a civilian nuclear program to serve as a screen for a parallel military program, and as a source for training in basic nuclear concepts and techniques."*
*". . . civilian nuclear programs should embody technologies that offer the maximum feasible proliferation resistance."*

**John Dooley**

*"The technical objective of safeguards is the timely detection of the diversion of significant quantities of nuclear material from peaceful activities to the manufacture of nuclear weapons. . . and deterrence of such diversion by risk of early detection."*

**Jurgen Kupitz**

Thus, the goal of both technology and policy should be to make the risk of proliferation from the civilian nuclear power cycle as low as possible, and in any case, the lowest of any path. When applied to civilian nuclear power, proliferation resistance combines the active and passive features in a system that keeps technologies, facilities, and weapons-usable materials safe and secure. Such features ensure legitimate use or give the earliest possible warning of the illegitimate use of facilities, equipment, or technologies. Proliferation resistance is comparative—not absolute—and it is effectively accomplished through technical means integrated with institutional policies.

The major proliferation issues that warrant concern from the standpoint of civilian nuclear power are diversion of material for illicit use, theft of material by sub-national groups, facilities that can be used for both civilian and weapons purposes, and the replication of civilian technologies or personnel for weapons applications. All of these may be either overt or covert. The role of technology is to provide safeguards to diversion, theft, and misuse, and to provide nuclear processes and systems that minimize available EFMs and maximize the difficulty of making nuclear weapons.

## What are the needs?

Collectively, the response to these proliferation issues can be grouped by time. Near-term are those activities that can affect proliferation risk in the next few years using today’s technology and requiring little or no R&D. Mid-term are those that, with some R&D, can have an impact on systems already under design. Long-term are those that require extensive R&D, resulting in totally new and improved systems. In a general sense, near-term needs have potential application over the next few years, mid-term over the next 20 years, and long-term beyond that. All these needs can be addressed now, albeit in differing degrees.

### *Near-term Needs*

Much work has been and is being carried out today that relates to the needs of the next few years. New R&D will not have much, if any, impact during this time frame. The principal foci of concern in this time frame are rogue states and terrorists. Technology implementation is often limited by policy (e.g., direct disposal versus no reprocessing). Activities should be and are focused on the goal of reducing diversion and theft threats by moving material to safe areas where modern safeguards ensure their security. Work on permanent repositories, regional compacts for storing high-level waste, consolidated interim storage of spent fuel, and monitoring through safeguards is consistent with this goal. There is concern that the diverse communities from which important advances in technologies that could be used to develop better and more unobtrusive sensors for safeguards are not well tied into the needs of the nuclear power community. In addition, the rapid conversion of the small number of research reactors still operating on highly enriched uranium (HEU) to low enriched uranium (LEU) will be an important step toward reducing the potential for proliferation from these facilities.

*"To prevent proliferation there is no magic formula, but the industrial community must be included in the process."*

**Jean-Louis Nigon**

### *Mid-term Needs*

During this time frame, there should be a move from accumulating separated nuclear materials to reducing their quantities. Nuclear development will still occur mainly in the developed countries, although rapidly developing countries such as China and the Republic of Korea will begin to have an impact. If global climate change is taken seriously by society, the developed countries will most likely lead the way with a push to carbon-free energy technologies, of which nuclear power is a likely one.

R&D done now can have some impact during this time frame, although the implementation of its products depends on infrastructures already in place (e.g., IAEA). Proliferation concerns will still include rogue states and terrorists but could also include regions of instability and the "non-state" groups that go with them. R&D begun now on concepts that reduce weapons-usable materials and work on policies to limit the proliferation of nuclear-materials technology will bear fruit during this time frame. Examples of concepts are high-burnup fuel designs, low- or non-fertile fuel, self-protecting fuel, and self-contained reactor systems that do not require in-country materials technology. (These reactors may have to be small enough to call their economics into question.)

To gain broad acceptance for proliferation-resistance measures, a major need is the development of internationally accepted standards and criteria for nuclear-power systems, including attributes designed for specific regions of instability. Attributes include, among others, the production rate of EFM, the bare critical mass, spontaneous neutron and specific heating rates, and the difficulty of handling and separations. The use of the Spent Fuel Standard in the U.S., while it applies to weapons-usable material, was never intended to imply that spent reactor fuel is sufficiently proliferation-resistant in all circumstances. An international treaty on the protection of EFM could lead to a "Proliferation Protection Standard."

Real-time monitoring and safeguards should take advantage of revolutions in inexpensive sensors, computers, and microprocessors and in communications technology. Many of these technologies need to be radiation-hardened. As with near-term needs, strong efforts have to be made to reach out to the communities that use these technologies to ensure their transfer and utilization.

There are large and growing civilian inventories (>100 tonnes) of separated Pu, and there is a disconnect in that these are receiving far less attention than separated military Pu (>250 tonnes). There is a need for clever and economic approaches to reducing these inventories.

### *Long-term Needs*

In the period beyond 2020, the world may have moved from reducing the quantities of separated nuclear material to actually consuming actinides. R&D on using Pu and other actinides (in either high-flux fast reactors or in accelerators) and on using a systems approach to reduce the amount and toxicity of waste for permanent disposal will likely result in the option of actinide consumption if needed. Managing actinides in such a way necessarily involves reprocessing of spent reactor fuel and R&D on advanced, proliferation-resistant schemes such as pyro-processing is vital.

## Impediments

There are impediments to implementing many of these proliferation-resistant measures. In the near term, there are inconsistent national policies and incomplete international treaties and/or agreements. Consensus is lacking on the need for improving current systems and on standards for proliferation resistance, expressed in a notable lack of planning for the development, testing, and evaluation of new technologies. Some—but by no means all—of this is due to uncertainty in the size of the nuclear energy demand in the future, something that only a perceived crisis is likely to change. In reality, commercial nuclear power is but one of the supply options available; but if projections are close to being accurate, then the option had best be on the table. In any case, the continuous presence of some nuclear power demands that attention be paid to the issues related to it, including proliferation.

There is the continuing loss of nuclear facilities for R&D and testing (particularly in the U.S.) that may ultimately render nations unable to deal with and carry out various options for improving the proliferation resistance of the fuel cycle. There is also a global decline in student enrollment in nuclear sciences and engineering that, given the aging professional cadre, holds the entire future of nuclear power at risk. For the U.S., this brings into question its ability to actively participate in debates about proliferation and the civilian nuclear fuel cycle and to be a significant player in technology development. This decline in student interest questions whether the intellectual capital will be available to devise new civilian reactor schemes and nuclear systems.

## Sessions I and II: Current Status and Challenges

> *". . . a new architecture will have to be built in such a way that both the problems of waste management and the concerns about non-proliferation may be concurrently resolved."*
>
> **Atsuyuki Suzuki**

Two earlier studies are relevant to this issue. NASAP was started in 1976 and INFCE in 1977. The DOE–NASAP study concluded that all cycles entail some risks of proliferation and that there are no technical means to make a "proliferation-proof" nuclear cycle. Nevertheless, it did conclude that fuel cycles differ significantly in their proliferation resistance and that technical and institutional improvements help increase the proliferation resistance of the system. The study found that in-system, gas-centrifuge enrichment plants could be rearranged in weeks to produce HEU. Out-of-system reprocessing plants could change spent fuel to weapons-usable Pu in weeks. These challenges lead to the need for improved safeguards (both institutional and technical). NASAP called for spent-fuel storage under international auspices. It also recognized that research into technical approaches might increase near-term vulnerability due to the need to utilize weapons-usable material in research.

The IAEA–INFCE study agreed no technical fix could defeat a determined proliferator but pointed out that although a closed-cycle system may be the most proliferation-resistant today, time and technology might change this perspective. INFCE also found no support for an international authority or fuel bank. A U.S.–Japan parallel study examined the technical aspects of co-processing and co-location as applied to a Japanese reprocessing plant. In the 1980s, Japan introduced a co-conversion process as a more proliferation-resistant technology. At the time these technologies were introduced, worldwide demand for the recycling of spent fuel was decreasing. The U.S. investigated an Integral Fast Reactor (IFR) based on metallic fuel, liquid-metal cooling, and pyro-processing in an integral fuel cycle. This increased proliferation resistance by burning Pu in a closed system, making $PuO_2$ that is insoluble in aqueous acid solutions and therefore harder to process, and ensuring a high radiation-exposure rate associated with any tampering. Japan is now developing even more proliferation-resistant reprocessing methods.

Los Alamos National Laboratory (LANL) and others propose advanced architectures that involve power reactors with improved safety and economics, internationally monitored retrievable storage sites, an integrated actinide conversion system based on technologies such as IFR or particle accelerators, and repositories for the small amount of waste discharged. Pu would typically be under a continuous high-radiation barrier and the system would be under international management and monitoring.

An effective way to increase the proliferation resistance of the civilian nuclear fuel cycle is through increased transparency coupled with an effective compliance–verification regime. As a side benefit, increased transparency has historically resulted in facilities that cause fewer environmental insults. However, the levels of transparency to be achieved must be carefully defined so that they can be verified and do not induce economic penalties. Recent developments may indicate that society is comfortable with the concurrent paths of nuclear-arms reduction and materials disposition and reduced proliferation from civilian nuclear power programs.

> *"To assess the nonproliferation implications of such fuel cycles, additional information on the criteria of weapons usability is required and it is my impression that such information can be made available within the constraints of classification."*
>
> **Myron Kratzer**

Current IAEA measures to facilitate the implementation of safeguards in advanced LWRs are to—

- Minimize the number of access points in the reactor containment and other shielding structures through which fuel moves.
- Adequately illuminate the containment access points, the reactor vault, and the fueling mechanism areas.
- Organize fuel transport routes so that containment and surveillance systems can be deployed and so that safeguards information can be clearly interpreted, particularly as routine or nonroutine.
- Minimize the effect of safeguards on plant operation by selecting locations for safeguards equipment that are accessible for inspection, monitoring, and maintenance and which do not obstruct operations.
- Ensure that all safeguards activities can be accomplished safely and expeditiously and that safeguards equipment will be reasonably protected.
- Clearly label all installed items relevant to safeguards to avoid inadvertent interruptions in surveillance and monitoring.
- Provide water-purification equipment to ensure water clarity in the visible and UV spectrum (a problem in some spent-fuel pools today).

For advanced designs beyond the LWR systems, the IAEA deems several technological options as important:

- Once-through fuel cycles
- International fuel cycle centers
- Long core life
- Sealed reactor vessels.

The IAEA is planning an international R&D project on innovative reactors and fuel cycles and the technical measures to facilitate the implementation of safeguards. A major thrust of this effort will be to assure the public of the proliferation resistance of current reactors and fuel cycles, and to guide the technology development so as to inhibit the use of EFM for weapons and similar purposes.

Preventing the spread of nuclear weapons to additional countries is a fundamental objective of U.S. national security and foreign policy. The components of this policy have been to promote and strengthen the political will of other nations not to proliferate, to extend the U.S. nuclear umbrella to allies, to reduce regional tensions and encourage regional confidence-building, to engage in peaceful nuclear cooperation, to create and expand multinational nonproliferation commitments by non-nuclear weapon states, and to interdict problematic exports to countries of concern. Civilian nuclear power programs should embody technologies that offer the maximum feasible proliferation resistance. Issues facing the U.S. government include the disposition of third-party spent fuel at home and abroad, and cooperation with developing country weapons states to achieve transparency.

The DOE has begun a new initiative—the Nuclear Energy Research Initiative, or NERI—that has one part devoted to making nuclear power more proliferation-resistant than ever before. The other parts deal with safety, economics, and waste. One path for technology development through this program may be to examine the potential of small, modular reactor systems to reduce manufacturing costs, be passively safe, and have long-lived cores that are replaceable without in-country refueling. Another path is to develop a high-burnup design fueled with fissile Pu and fertile thorium oxide to achieve a high conversion of thorium to $^{233}$U while reducing the Pu inventory. Another path develops a proliferation-resistant fuel that forms a waste form superior to spent LWR fuel without processing. Yet another path is the development of a mixed thorium–uranium dioxide fuel characterized by high burnup, lower fuel costs, better proliferation resistance, and less toxic waste.

The view of the U.S. nuclear industry typically is that the government is in the business of weapons production and they will follow government rules as to both classified information and standards. The European industry is somewhat more proactive about setting up new safeguards and control systems in existing plants and integrating safeguards and control systems in the design phase of new facilities. A balance in both places is sought between imperative nonproliferation requirements and legitimate business aspects.

> *"They (the U.S. civilian nuclear industry) do not ask for classified information, and they accept government standards for safeguards of fissionable material. They do not believe that they are the ones who should be devising rules to prevent proliferation."*
>
> **David Rossin**

*"As nuclear weapons design and engineering expertise combined with sufficient technical capability become more common in the world, it becomes possible to make nuclear weapons out of an increasing number of technically challenging explosive fissionable materials."*

**Bruce Goodwin**

## Session III—What are the Threats?

The requirements for the indigenous development of nuclear weapons include—

1. National or sub-national desire (to use or threaten to use a credible delivery system) and resources (financial, political, and technical)
2. Explosive fissionable material (EFM)
3. Science and engineering expertise to design and build nuclear weapons
4. A technical and manufacturing base to make the components.

Except for the first, all of these can be obtained from foreign sources.

EFM is any fissionable material that can be assembled such that an explosive disassembly is possible. EFM includes elements (metals) and compounds (e.g., oxides) and mixtures of these materials with non-fissionable materials. A nuclear weapon must have EFM and EFM includes materials in addition to those designated as nuclear-weapon-usable by UN Resolution 687. The technical challenges associated with EFM are availability, the rapid assembly of a critical mass, the lifetime of the nuclear components, intrinsic radiation, and thermal heat. Technical challenges can usually be overcome with engineering solutions. Experience has shown this to be true in the case of Pu and U, and it is therefore reasonable to assume that similar challenges can be overcome with other materials. For example, due to LWR operation, the EFM americium (Am, not a designated UN weapon-usable material) is projected to increase in abundance from 100 tonnes today to almost 200 tonnes in the next decade. Could it become a threat? In general, as nuclear weapon design and engineering expertise combined with sufficient technical capability become more common in the world, it becomes possible to make nuclear weapons out of an increasing number of technically challenging EFMs, many of which are components of spent reactor fuel.

Without explicit advocates, diversion is at a disadvantage and suggests that the development of alternative civilian nuclear fuel cycles will have little effect on the already high level of proliferation resistance. Only Iraq has ever tried to covertly divert EFMs from its civilian sector, and then only as one part of parallel efforts by other means. The application of a sophisticated game theoretical model to a proliferator’s decisions about acquiring a nuclear fuel cycle and a route to proliferation adds an important dimension to the problem of proliferation resistance. A comparison of the relevant technical factors and a consideration of the interaction between the three relevant constituencies (political, military, and scientific) and the roles they each play leads to the conclusion that diversion is unlikely to gain a constituency in any of these groups.

## Session IVa—Metrics

Many new technologies create systems and / or sub-systems that promise to increase the proliferation resistance of civilian nuclear power. The method used to compare these proposed schemes becomes very important. Such methods also facilitate and focus discussion among proponents and observers.

A small, one-and-a-half day workshop was held several weeks before this workshop with the objective of developing a rudimentary framework for comparing alternative power systems. This was done under the chairmanship of Toeves and Wagner and held at LANL. While quantitative metrics have great utility for engineers and R&D planners in such a framework, it is difficult to achieve a consensus, especially within the time frame involved. More importantly, the goal should be to compare by degrees and not absolutes. Thus, qualitative comparisons are very useful, initial steps.

Two general conclusions emerged from the meeting:

1. A better institutional and analytic approach is needed for assessing possible proliferation risks and for developing approaches to risk reduction.
2. It is essential to greatly expand collaborative R&D on civilian nuclear energy technologies to reduce proliferation risks, if nuclear power is to be accepted as a substantial part of energy production.

The participants in the LANL workshop observed that current costs for augmenting proliferation resistance of civilian nuclear power are small, at least in comparison with revenues. Furthermore, although safeguards have worked to date, the possibility of proliferation from civilian nuclear power systems in the future involves scenarios that are largely unknowable. One way to deal with this uncertainty is to create options, yet current approaches to nuclear power are too narrow (e.g., the fuel cycle can be viewed as an opportunity to be a sink for fissile materials as well as a source). Any use of metrics will be situation- and time-dependent. A framework for analysis (and therefore invention) is to consider who potentially proliferates, how and when proliferation is instigated, and the measures that can be taken to prevent it. Transparency is an objective and a metric. More attention should also be paid to the access to fissile materials in permanent geologic repositories.

*"With careful consideration of the roles that each group (military, politicians, scientists) plays in the decision (to proliferate), as well as the concerns and interests of each group, it is clear that diversion (from civilian systems) is unlikely to acquire any of the groups as a constituency."*

**Roger Avedon**

At this workshop, it was suggested that a general approach to the devolution of workable metrics is to first keep the number of metrics small to enhance discussion and avoid endless arguments about which are more important, to be as quantitative as possible about steps in their evolutionary path, and to focus on the resource requirements to use a specific system to proliferate. Three general types of threats are recognized: wealthy, technically sophisticated nations, poor nations struggling with technology, and terrorists. The measures or barriers that deter each threat differ. Each threat has at least three measures of merit: the attractiveness of the material, the ability to handle the material, and the reliability or probability of success. Technology can reduce the attractiveness of fissile material (for example, through degraded isotopic compositions or reduced enrichment), reduce the availability of fissile material (for example, through reduced spent-fuel accumulation or reduced process losses), enhance safeguards against misuse, diversion, and / or theft, and enable other processes and / or architectures that make safeguards and other barriers more effective.

## Session IVb—New or Emerging Technologies

A number of schemes for improving current LWR technologies or for developing alternatives were discussed. It was not the intent of the workshop to evaluate or compare these concepts and they are only noted here. Many have extensive publications in the literature and comparison must be left to subsequent exercises, using standardized metrics, perhaps initially as qualitative attributes:

(1) The Radkowsky Thorium Reactor (RTR) concept seeks to solve the problem of the current production of about 70 tonnes / yr of Pu from more than 400 commercial power reactors world-wide. RTR utilizes thorium as a fertile component of nuclear fuel with uranium at less than 20% enrichment. A thorium blanket surrounds a uranium core and breeds $^{233}$U. The $^{233}$U is denatured by having slightly enriched $UO_2$ added to the thorium. The concept can be used in existing LWRs. There is a reduction of Pu generation by 85 to 90% compared to that of an LWR, and the weapons capability of that material is degraded because of high amounts of $^{238}$Pu with a high heat emission.

(2) Chodak introduced a concept utilizing non-fertile fuels in existing LWRs. This prevents the generation of new Pu. By configuring the fuel, more than 60% of total Pu and more than 80% of $^{239}$Pu is burned.

(3) Heering discussed a long-lived fuel with high burnup based on (U, Th)$O_2$. The goal is to achieve 60–70,000 MW days / tonne in comparison with 45,000 MW days / tonne for current PWRs. The Pu produced, which is 12% $^{238}$Pu, has decayed heat that is increased by a factor of five and a spontaneous neutron flux that is higher by a factor of two than the Pu from LWR spent fuel. In terms of spent-fuel management, needed space in a repository will be reduced by 40 to 60% per MW day of generated power.

(4) Lee discussed the South Korean concept of direct use of PWR fuel in a CANDU reactor (DUPIC). Spent PWR fuel is re-fabricated and placed in a CANDU reactor. The proliferation-resistant features are no fissile material separated and high radioactivity inhibiting access.

(5) Arthur presented a new architecture for a fuel cycle that would greatly reduce inventories of discharged fuel while recovering much of their energy, keep Pu protected by a high-radiation barrier at all times, and reduce world-wide inventories and the quantity that would go to a repository. A new type of facility, an Integrated Actinide Conversion System (IACS), is the heart of this new system, processing discharged fuel from power reactors and generating additional electricity.

(6) Smith presented a conceptual design for a Secure Transportable Autonomous Reactor (STAR) for use in developing countries. While not designed solely for its resistance to proliferation, it relies on a closed transportable core brought to remote locations to provide power, and when the core is depleted, it is removed, transported back to the supplying country, and replaced with a fresh core.

(7) Tomabechi introduced an International Fuel Bank which would process or store spent fuel and deposit waste as well as perform enrichment services. Any country could deposit spent fuel and, if it wished, withdraw it in a variety of forms, depending on its needs. There would be need for only a few such banks, possibly two, to meet the world needs. International control would assure the proliferation resistance of the material while it is with the bank.

(8) Cochran presented the concept of Non-Proliferation Trust, Inc., whose purpose is to provide a framework for the development of an international spent-fuel storage and disposal facility in Russia, using the income generated to modernize and improve the security of Russian nuclear facilities.

(9) Peterson discussed the importance of geologic barriers and introduced attributes for geologic repositories. The costs to a proliferator of recovering and processing spent fuel from a geologic repository might be comparable to the costs to clandestinely enrich fuel, build a production reactor, and then process weapons material.

## Next Steps

Based on the discussions during the presentations and the breakout groups, follow-on activities are clearly indicated that would enhance the proliferation resistance of civilian nuclear power systems:

- Devise a workable set of attributes and / or metrics to effectively compare proposed alternative systems and sub-systems to the current LWR systems. Ideally, these attributes should be qualitative at first and then be allowed to develop into quantitative metrics after some consensus and familiarity is developed about their use. Part of this effort should be convening a follow-on to the IAEA’s "New Realities" study and push toward future criteria identification (attributes) and technology approaches. The U.S. should be an active participant.

- Fund innovative R&D that shows promise of effectively increasing the proliferation resistance of civilian nuclear power systems over a variety of time frames:

  —For the near term, the principal concerns are rogue states and terrorists. Activities should be focused on reducing threats from diversion and theft. Work on permanent repositories, regional compacts for the storage of spent fuel and high-level waste, consolidated interim storage of spent fuel, and monitoring through safeguards are examples of activities consistent with this goal.

  —For the mid to long term, proliferation concerns will still include rogue states and terrorists but now also include regions of instability and the non-state groups that go with them. R&D begun now on concepts that reduce weapons-usable materials and work on policies to limit the proliferation of nuclear-materials technology, will bear fruit in this time frame. Examples of concepts are high-burnup fuel designs, low- or non-fertile fuel, self-protecting fuel, and self-contained reactor systems. There is a need for approaches to reducing inventories of separated Pu, which are increasing due to civilian contributions. R&D on utilizing Pu and other actinides in either high-flux fast reactors or in accelerators, and on utilizing a systems approach to reduce the amount and toxicity of waste for permanent disposal will likely result in the option of actinide consumption being available, if needed.

- Identify supporting technologies that can significantly improve the safeguarding of nuclear facilities and processes. In particular, involve those technical communities (sensor materials, cyber-security, information technology, etc.) that are rapidly advancing and can effectively support proliferation resistant nuclear-power objectives.

- Involve policymakers in discussions on the roles new technologies can play in increasing the proliferation resistance of civilian nuclear power systems while increasing the safety and lowering the cost of future nuclear-power systems.

- Continue efforts to find interim storage and repository solutions to complete the nuclear fuel cycle. The repository solutions should involve different environments to increase the options. Moves should be made to consolidate interim fuel storage as a step toward co-located international management and ownership.

- Take steps to convert as many research reactors as possible to low-enriched uranium.

- Begin work on an international convention on the protection of weapons-usable materials (Proliferation Protection Standard).

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