Preprint
UCRL-JC-142356

A STRATEGIC FRAMEWORK FOR PROLIFERATION RESISTANCE: A SYSTEMATIC APPROACH FOR THE IDENTIFICATION AND EVALUATION OF TECHNOLOGY OPPORTUNITIES TO ENHANCE THE PROLIFERATION RESISTANCE OF CIVILIAN NUCLEAR ENERGY SYSTEMS

James A. Hassberger,
Thomas H. Isaacs,
Robert N. Schock

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This article was submitted to
Global 2001, Paris, France, September 10 - 15, 2001

May 2001

UCRL-JC-142356

"A STRATEGIC FRAMEWORK FOR PROLIFERATION RESISTANCE: A SYSTEMATIC APPROACH FOR THE IDENTIFICATION AND EVALUATION OF TECHNOLOGY OPPORTUNITIES TO ENHANCE THE PROLIFERATION RESISTANCE OF CIVILIAN NUCLEAR ENERGY SYSTEMS"

James A. Hassberger, Tom Isaacs, Robert N. Schock
Lawrence Livermore National Laboratory*
P.O. Box 808
Livermore, CA 94550
USA

ABSTRACT

The United States' Department of Energy Nuclear Energy Research Advisory Committee recently completed a study[1] "Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems (TOPS)." That effort included the development of a set of both intrinsic and extrinsic barriers to proliferation that technologies can directly impact. In this paper we will review these barriers as and framework for assisting in the evaluation of the relative proliferation resistance of various nuclear fuel cycles, technologies and alternatives.

Keywords: Nonproliferation; Proliferation Resistance; Barriers

1 - INTRODUCTION

The commercial nuclear power fuel cycle has not been the path of choice for weapons development in the past. However, continued accumulations of plutonium in spent fuel and of separated plutonium resulting from reprocessing are seen as increasing the proliferation risk associated with the global expansion of nuclear energy. If nuclear power is to remain an option for achieving sustainable global economic growth, the technical and institutional means of ensuring that the civilian fuel cycle remains the least likely proliferation path are vitally important, and must be developed and implemented along with the improvements in safety, economics and waste performance. This is an ambitious undertaking.

Limiting global proliferation risks in the face of future nuclear expansion and growth will require that the proliferation resistance of both current and future nuclear activities be improved beyond that enjoyed by today's systems. Alternatives to address the issues surrounding proliferation risk and resistance invariably involve making trade-offs among different proliferation risks and advantages. For example, thorium cycles reduce the quantity and quality of plutonium in spent fuel, but do so at the expense of increased fresh fuel enrichment and/or production of separable U^{233}. Evaluation of these tradeoffs is difficult, as there are serious and significant differences of opinion regarding the relative merits and significance of the various risks of and barriers to proliferation from commercial nuclear power fuel cycles. In addition, the benefits potentially gained from implementing proliferation resistant technologies must also be considered in the context of the other important issues facing nuclear power, namely economics, safety, waste management and environmental impact.

The United States' Department of Energy Nuclear Energy Research Advisory Committee recently completed a study[1] "Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems (TOPS)." That effort included the development of a set of barriers to proliferation summarized in the report annex[2] "Attributes of Proliferation Resistance for Civilian Nuclear Power Systems." This annex identified both intrinsic and extrinsic barriers to proliferation that technologies can directly impact. The intrinsic barriers are those features fundamental to the nuclear fuel cycle than deter or inhibit the use of materials, technologies or facilities for potential weapons purposes. LEU fuel is an example of a material with a high intrinsic barrier to

---

* This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

proliferation. LEU fuel cannot be made into a weapon without substantial effort (i.e. additional enrichment), and thus inherently presents a higher barrier to proliferation than, say, does HEU fuel. Extrinsic barriers depend on implementation details and compensate for weaknesses in the intrinsic barriers. Safeguards, material control and accountability are examples of these extrinsic barriers, often referred to as the institutional barriers. Since it is fundamentally impossible to construct a nuclear power system that is completely proliferation resistant, an effective combination of both intrinsic and extrinsic barriers is necessary to ensure an adequate level of proliferation resistance from any current or future nuclear energy system.

In this paper we will review the various barriers to proliferation as described by the TOPS work. These barriers form a framework for assisting in the evaluation of the relative proliferation resistance of various nuclear fuel cycles, technologies and alternatives.

We recognize that evaluation of proliferation resistance, and certainly the decisions regarding which technologies and / or fuel cycles should be developed cannot be made in isolation. Issues such as nuclear safety, economics, environment, waste disposal and energy security must also be taken into account. These issues impact a society's or a nation's perspectives on the relative importance of these issues and thus on the weights and significance of the various barriers and attributes described here. While developing a quantitative methodology may be a desirable goal, this "Barriers Framework" serves not so much as a quantitative methodology, but rather as a qualitative vehicle for aiding the dialogue about the effectiveness of various technology option for enhancing proliferation resistance.

2 - A FRAMEWORK FOR ASSESSMENT

Assessment of proliferation resistance must go beyond "simple" comparisons among some group of alternative features and / or technologies associated with various fuel cycles and their options. While such comparisons form an essential element of such assessments (for example, they certainly assist in evaluating progress in improving proliferation resistance), they do not, by themselves, establish a complete framework for the evaluation and implementation of proliferation resistant technologies.

Such a framework requires consideration of a number of other core issues, including issues that we will define here as "context", "thresholds" and "alternative paths" Incorporation of these considerations into an overall evaluation framework is not easy. They do not lend themselves to straightforward quantification, and they are highly subjective. Consideration of these issues must, however, be reflected in the development of "standards" for proliferation resistance.

There are a number of other considerations related to the evaluation of proliferation risk and resistance. Many of these issues (such as the effectiveness of safeguards or the importance of knowledge) have been explicitly incorporated into the TOPS barriers and will be discussed later.

Nuclear activities will never be completely free of proliferation risk. All aspects of nuclear power involve fissile materials and / or technologies dealing with such materials, and therefore can potentially be used as a source of fissile materials for weapons purposes. As we (the entire nuclear community) continue to improve the proliferation resistance of our current and future nuclear activities, we must recognize this link and continue to ensure that these activities remain the least attractive path for a potential proliferator to pursue.

2.1 - Context

Proliferation risk (or proliferation resistance) associated with nuclear activities must be considered in context of several important issues. Perhaps the most important of these is the overall threat environment within which nuclear activities might exist. Political and economic stability reduces the perceived need to develop nuclear weapons and increases the costs associated with their acquisition. Strict and demonstrated adherence to the accepted norms and standards of the nonproliferation regime is a critical indicator of this threat environment. Conversely questionable nonproliferation commitments indicates an unstable and unacceptable threat environment.

Existing nuclear activities also provides context that impacts the development of additional nuclear capabilities. For example, the impact of a country's adding to an existing enrichment capability has a far smaller impact on proliferation risk than a country developing a new capability where one did not exist previously. Similarly, the introduction of MOX recycle in a country already having reprocessing facilities is far less risky than MOX introduction in a country without reprocessing.

Consideration of the importance of existing nuclear capabilities touches on the next issue, that of thresholds.

2.2 - Thresholds

The concept of thresholds recognizes that the nonproliferation impact associated with most nuclear activities are not necessarily linear. Clearly, the significance of the first weapon (or of the nascent capability to produce the first weapon) is much more disturbing than that of the tenth or hundredth. Similarly, the development of initial acquisition of a weapons-significant capability (whether it be enrichment, reactor or reprocessing capabilities) is more important than expansion of or improvements to existing capabilities. While it appears intuitively obvious that such thresholds exist, it is less obvious (and therefore often contentious) where and how important these thresholds are.

2.3 - Alternative Pathways

While relative assessment of proliferation resistance among a variety of options is valuable and useful, such evaluations cannot directly define the acceptable (or required) level of proliferation resistance. Such a definition requires a broad understanding of the importance of alternative pathways to proliferation, i.e., the risks associated with independent (from commercial nuclear activities and infrastructures), presumably covert, weapons development programs and activities. The importance of these alternative pathways will likely become even more significant with time, as their costs (economic, political and technical) are reduced and the general understanding of their technologies expands.

3 - THE LINKS BETWEEN NUCLEAR POWER AND PROLIFERATION

Civilian nuclear power systems can contribute to proliferation through the: (1) misuse of material through its divers or theft; (2) misuse of facilities, equipment, and technology; and (3) transfer of nuclear skills and knowledge—all fo potential proliferator to make nuclear weapons. Threats may be either overt or covert. Potential proliferators may b non-nuclear weapons states and subnational groups.

In the context discussed here, threats posed by nuclear weapons states are considered an arms control issue rather t a proliferation issue. The nuclear weapons states already have the facilities, technologies, and capabilities required t produce weapons and have little need to rely on civilian nuclear technologies for military purposes.

The primary link between civilian nuclear power and nuclear weapons is nuclear material, either by itself (that is, through the misuse of materials normally in the system, such as the diversion of spent fuel), or through the misuse facilities to generate or process weapons-useable material. Other links, while certainly important (such as the use o cells for weapons fabrication or civilian knowledge for weapons design), tend to be less direct. Thus, the discussion barriers presented here focuses on the materials link.

The civilian fission fuel cycle involves materials that either are, or could potentially be processed into, weapons-usa material. Our interest here is in material capable of undergoing an explosive fissionable reaction.[1] We consider all isotopes capable of being assembled into a fast critical mass as potentially weapons-usable and therefore of prolifera concern. It is important to note that the effort required to use any isotope depends on the isotopic properties and th

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

engineering and scientific skills of the potential proliferator because the isotope's properties vary (half-life, neutron generation, heat generation, and critical mass). **Table 1** summarizes some of the nuclear properties of fissile materi For comparison, the table also includes the two major fertile materials, Th^{232} and U^{238}, which in the presence of neut can produce the fissionable isotopes U^{233} and Pu^{239}, respectively.

As indicated in Table 1, a number of materials can physically be assembled into a fast critical mass, and are thus weapons-usable. Although Table 1 shows that Pu^{238} is capable of sustaining a fast critical mass, the International At Energy Agency (IAEA) considers plutonium containing more than 80% Pu^{238} not weapons-usable because of its hig heat generation.

Table 1. Nuclear Properties of Fissile and Fertile Nuclear Materials

Isotope	Half-life (y)	Neutrons / sec-kg	Watts / kg	Critical Mass[a] (kg)
Pa^{231}	32.8×10^3	nil	1.3	162
Th^{232}	14.1×10^9	nil	nil	infinite[b]
U^{233}	159×10^3	1.23	0.281	16.4
U^{235}	700×10^6	0.364	6×10^{-5}	47.9
U^{238}	4.5×10^9	0.11	8×10^{-6}	infinite[b]
Np^{237}	2.1×10^6	0.139	0.021	59
Pu^{238}	88	2.67×10^6	560	10
Pu^{239}	24×10^3	21.8	2.0	10.2
Pu^{240}	6.54×10^3	1.03×10^6	7.0	36.8
Pu^{241}	14.7	49.3	6.4	12.9
Pu^{242}	376×10^3	1.73×10^6	0.12	89
Am^{241}	433	1540	115	57
Am^{243}	7.38×10^3	900	6.4	155
Cm^{244}	18.1	11×10^9	2.8×10^3	28
Cm^{245}	8.5×10^3	147×10^3	5.7	13
Cm^{246}	4.7×10^3	9×10^9	10	84
Bk^{247}	1.4×10^3	nil	36	10
Cf^{251}	898	nil	56	9

[a] Bare sphere.
[b] Not potentially weapons-usable material.

4 - BARRIERS

Material qualities, technical impediments, and institutional arrangements (including the complex of measures know material protection, control, and accountability, or MPC&A) present barriers that make it more difficult for prolifer to exploit civilian nuclear power systems. The specific form and significance of the attributes of such barriers vary depending on the specific system under consideration. The first two types of barriers are intrinsic and the last barri extrinsic. Intrinsic barriers are those inherent to technical and related elements of a fuel cycle, its facilities and equipment. Extrinsic barriers depend on implementation details and compensate for weaknesses in the intrinsic barriers.

Barriers are not absolute, but are in part engineering challenges that may be overcome by a combination of technology and weapon design. Higher, more effective barriers require greater resources and effort to overcome than lower, less effective barriers. Barriers also do not act independently, and the effect of multiple barriers can be greater than the sum of their individual effects.

The set of barriers and attributes described here is not the only mechanism to evaluate proliferation resistance. They are an attempt to formulate an umbrella that incorporates the relevant aspects of other mechanisms specifically to help identify where technology development can play a role in improving the proliferation resistance of commercial nuclear fuel cycles. Such a role requires a clear distinction between intrinsic and extrinsic barriers, as well between those barriers intrinsic to the materials and those barriers associated with the technologies, processes, and facilities.

Other considerations, such as material attractiveness, associated economic penalties, unsafe practices, or generated wastes, are encompassed by these formulations.

4.1 - Material Barriers

Material barriers are related to the inherent properties materials that serve to impede or deter their use in a weapon potential proliferator. Material barriers can act in weapons in several ways. They can: make design and constructio a weapon more difficult, make extraction of weapons-useable material more difficult, make acquisition of material r difficult. Material barriers include the isotopic composition of the material (percentage and type), the chemical processing required to separate a weapons-usable substance, the radiation hazard and signature associated with the material at each step in the civilian system and in any process to generate a weapons-usable material, the difficulty moving the mass and/or bulk of the material, and the inherent detectability of the material itself.

Each of these materials barriers, by necessity, encompasses a wide range of specific attributes and potential measur For example, the "isotopic barrier" incorporates issues and attributes including critical mass, spontaneous neutron generation and heat generation rates, radiation, and so on. The details of how each of these (or of alternate attribute and measures) contribute to proliferation resistance can be quite complex, and often touch on classified issued. We however, often construct scales that account in general ways for many of these complex issues.

In the TOPS work, treatment of the isotopic barrier relied on DOE classification of materials categories, as well as a general indication of the technical sophistication needed to develop a weapon from a particular material. The scale used observed that gun-assembled devices are generally considered less challenging than implosion devices. There materials capable of being made into a gun-assembled device (HEU) are considered to represent a lower material barrier to proliferation than materials requiring an implosion design (plutonium). TOPS also recognized that such categories must also reflect several significant additional points. One is that these categories must overlap (i.e. it ma theoretically possible to construct a gun-assembled device from 30% enriched uranium, but the huge masses involv likely require a more challenging design than a primitive implosion system.) Second, even within broad categories some fine-structure must be accommodated (i.e. the effectiveness of the isotopic barrier must increase somewhat as "assay" of the material – enrichment for uranium, Pu-239 content for plutonium – increases.

This classification of the isotopic barrier effectiveness is summarized on the following table.

Table 2. Summary of the TOPS Isotopic Barrier Characterization

Barrier Effectiveness		**Uranium**	**Plutonium**
Insignificant	(-)	HEU >= 80% Enriched*	
	(+)	HEU between 50 - 80% Enriched*	
Low:	(-)	HEU Below 50% Enriched*	Weapons-grade Pu (>90% Pu^{239})
			Reactor grade Pu (~60% Pu^{239})
	(+)	HEU Above 35% Enriched*	High burnup Pu (~40% Pu^{239})
Medium		HEU between 20 – 35% Enriched*	
High		LEU <20% Enriched*	
Very High		Natural, depleted Uranium	

* Note: Uranium enrichment considering U233 in relation: Enrichment = $(1.67\ U^{233} + U^{235}) / U^{tot}$

Each of the other material barriers (chemical, radiation, mass/bulk, detectability) has been similarly classified, albeit in a preliminary way, and reported in the TOPS report annex [see reference 2.].

4.2 - Technical Barriers

Technical barriers are the intrinsic technical elements of the fuel cycle, its facilities, processes, and equipment that se to make it difficult to gain access to materials and/or to use or misuse facilities to obtain weapons-usable materials. Misuse of facilities includes the replication of facilities, processes, and technologies to support weapons developme Some of the intrinsic technical barriers include the unattractiveness (lack of utility for weapons use) of facilities, equipment, and processes for producing potentially weapons-usable material; the extent to which facilities and equipment inherently restrict access to fissile materials; the amount of attractive material; facility detectability and materials accountability; applicability of skills, expertise, and knowledge; and timing.

One of the major technical barriers to proliferation is the extent to which facilities, equipment, and processes are resistant to the production of weapons-usable materials, i.e., the “unattractiveness” barrier. Those that cannot be modified to produce weapons material have a high barrier, and those that can directly produce weapons-usable materials have a negligible barrier to proliferation threats. A number of attributes can be used to describe the difficulty associated with obtaining weapons materials from facilities:

- the complexity of modifications needed to obtain potentially weapons-usable materials, including the need for specialized equipment, materials, and knowledge, and the general availability of such specialized skills, materia and knowledge;
- the cost of modifying a facility or process to obtain potentially weapons-usable materials;
- the safety implications of such modifications;
- the time required to perform such modifications;
- facility throughput;
- existence and effectiveness of “observables” (e.g., environmental signatures that can be remotely sensed or observed) associated with facility modification and misuse;

Table 3 summarizes the TOPS preliminary characterization of the facility unattractiveness barrier.

Table 3. Summary of the TOPS Facility Unattractiveness Barrier Characterization

Barrier Effectiveness	**Description**
Insignificant	Those facilities, equipment, and processes that routinely use, handle, or produce significant quantities of directly weapons-usable materials, and those that can do so with no modifications. Probably no significant observables.
Low	Those facilities whose designs lend themselves to quick, safe, and easy modifications (on the order of a week) to produce directly usable materials with reasonable throughputs (a significant quantity / week). Observables difficult to detect prior to accumulation of significant quantities of materials.
Moderate	Facilities that require considerable engineering expertise, expense, and time (~a month) to modify to produce significant throughputs (~1 SQ / month). Probably observable within the time required to complete modifications and accumulate significant quantities of materials.
High	Facilities capable of modification given substantial time (months to years), money, and expertise, compounded by difficult safety and throughput issues, and likely highly observable.
Very High	Facilities with little potential or appeal for modification, through a combination of technical complexity, cost, detectability, and insignificant throughput.

4.3 - Extrinsic (Institutional) Barriers

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

Technology development cannot directly impact all of the institutional barriers that contribute to proliferation resistance. The two institutional barriers that technology can directly affect include safeguards (MPC&A), access control, and security (both physical security at the installation site and the ability to respond quickly and effectively threats).

Factors such as treaties, bilaterals, and multinational agreements (including export control and supplier constraints) have proven effective barriers to proliferation. National policies and legislation, especially when combined with stro nonproliferation ethics and supported by societal openness and transparency, are perhaps the major barriers to proliferation, especially among the more technically developed countries, where the material and technical barriers easily overcome with existing facilities and infrastructures. For others, the effectiveness of intelligence and national technical means for detection, supported by effective sanctions and penalties, may prove to be the major barriers to proliferation.

Such factors can have a strong influence on the selection of which technological options might be implemented in th future. Moreover, the development of technical options for improved proliferation resistance must be compatible w and supportive of these factors.

The effectiveness of the institutional barriers can be impacted by the technologies inherent in the nuclear fuel cycle. For example, spiking fresh MOX fuel with fission products has been suggested as a way to increase the proliferation resistance of fresh MOX. While such an approach reduces the attractiveness of fresh MOX and increases its detectability, it could interfere with safeguards inspections and/or increase the cost of safeguards. Thus, any evaluation of technical options for improving the intrinsic barriers to proliferation must consider potential impacts on the extrinsic barriers as well.

A similar relationship exists in the reverse direction. That is, technical improvements to the extrinsic barriers should also consider potential impacts on the effectiveness of the intrinsic barriers, although that link intuitively appears less important.

5 - CONCLUSION

The TOPS work defines a set of barriers to proliferation that can serve as a useful basis for the evaluation of various alternative technologies and options for improving the proliferation resistance of both today's and future nuclear power systems. Such evaluations, however, must be considered within an overall framework that considers other core issues, including the context for nuclear power development, the impact of nonlinearities and thresholds, and the existence of alternative pathways to nuclear weapons acquisition. In addition, it must be recognized that efforts to improve proliferation resistance must be considered along with the needs of the other major issues affecting nuclear power development, namely economics, safety, waste management and environmental impact.

REFERENCES

[1] "Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems (TOPS), Report by the TOPS task force of the Nuclear Energy Research Advisory Committee (NERAC)", January 2001, USDOE. (see: http://www.nuclear.gov/nerac/FinalTOPSRpt.pdf)

[2] "Attributes of Proliferation Resistance for Civilian Nuclear Power Systems, TOPS Task Force Report Annex", October 2000, USDOE (see: http://www.nuclear.gov/nerac/FinalTOPSRptAnnex.pdf)