Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems

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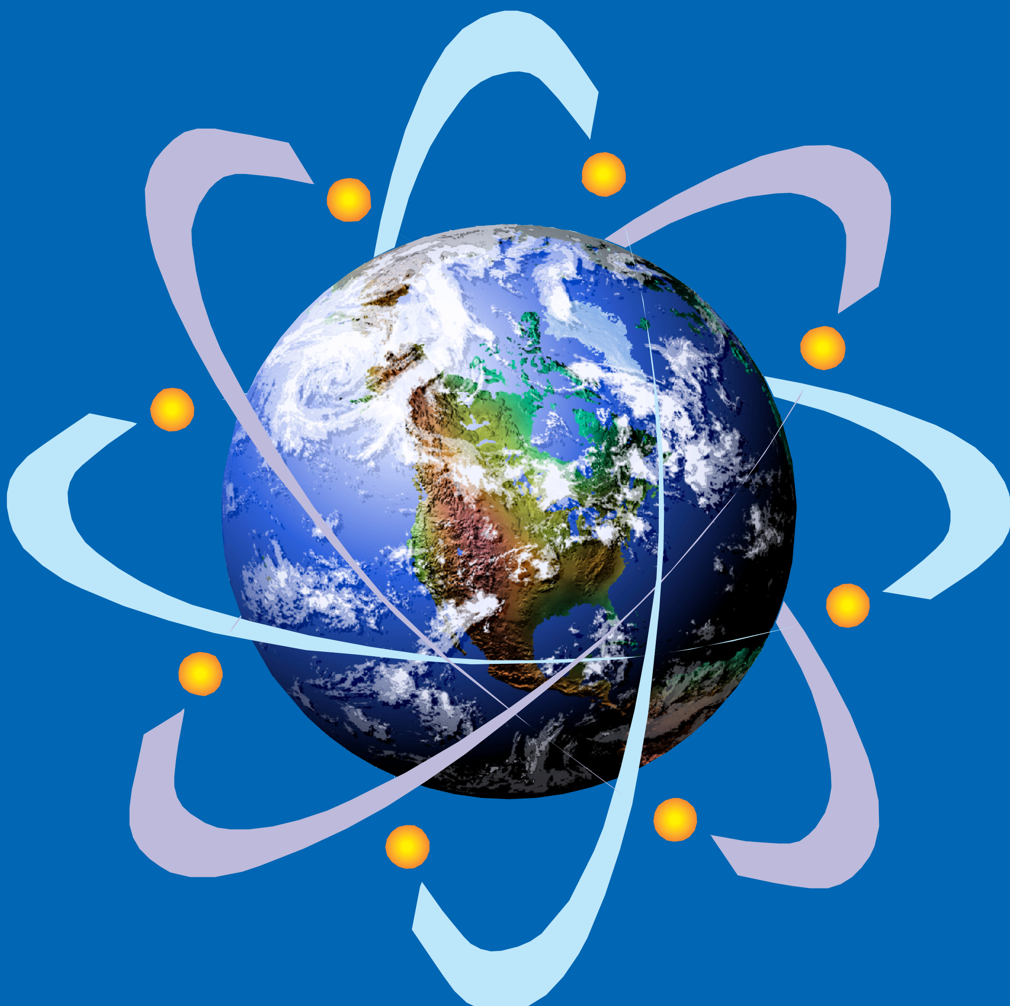

Nuclear Energy Research Advisory Committee (NERAC)

Attributes of Proliferation Resistance for Civilian Nuclear Power Systems

Preface

The NERAC[1] Task Force on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) determined at its first meeting in November 1999 that a set of metrics was needed to judge proliferation resistance and to identify areas in which technical contributions could be useful. However, because of the time constraints imposed on the Task Force and the difficulty of developing quantifiable metrics, it was decided that a set of *qualitative* attributes could be developed and would be useful in providing a framework for both future discussions and for the development of a set of quantifiable metrics.

This annex represents input to the TOPS as a framework to eventually compare and rate different technologies. This "attributes" framework is still in development. Additional work will help refine many of the discussions and ratings of the specific barriers to proliferation, enhancing the utility of the framework. In some cases, further work will allow a broader range of distinctions to be made in the degree of proliferation barriers posed by the features of a nuclear system. At the present stage of development, this framework cannot be used to quantitatively score or rank technologies. Also, in lacking a system to estimate the weights of various attributes, this framework is limited to comparisons of the effectiveness of each attribute among civilian nuclear power systems and proliferation threat scenarios.

Introduction

The choice between nuclear power systems leading to an acceptable growth in nuclear power among many countries must take into account a number of factors, including economic competitiveness, acceptable safety standards, acceptable waste disposal options, and acceptable risks of nuclear-weapon proliferation from such nuclear power systems. A process and a set of attributes (*attribute: a quality, character, characteristic, or property*) are proposed with which to compare the relative proliferation resistance among civilian nuclear power systems. These attributes help identify R&D areas that will open potential ways to enhance the proliferation resistance of the fuel cycle as nuclear power generation continues, and even expands, worldwide. The overall goal is to optimize the proliferation resistance of the civilian cycle such that it remains the less-preferred route to nuclear weapons development. Although civilian facilities can produce materials for nuclear weapons, most if not all those nations that have acquired nuclear weapons have done so using dedicated facilities, not through diversions from safeguarded civilian power facilities. Diversion from civilian research facilities has been tried on occasion and civilian programs can also serve as a cover to acquire the requisite skills, knowledge, and equipment.

[1] Department of Energy, Nuclear Energy Research Advisory Committee

Proliferation-resistance attributes should compare different schemes as easily as possible, identifying their relative merits and weaknesses. The current light-water reactor (LWR) system using once-through fuel serves as the basis for comparison. The LWR is the system in widest use today, and there is considerable documentation on their economics and safety, on the proposed disposition of their waste, and on their proliferation resistance.

We were guided by the extensive work of the U.S. National Academy of Sciences' Committee on International Security and Arms Control[2] and the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium.[3] Although the materials and facilities involved here are far more extensive, and the options for proliferation far more varied, their work (and that of the more recent Interim Report by the Panel to Review the Spent-Fuel Standard for Disposition of Excess Weapons Plutonium[4]) is applicable to deriving attributes for the proliferation resistance of the entire civilian fuel cycle.

In the proposed framework, attributes are used qualitatively, realizing they would have additional utility if they could be transformed into quantifiable metrics which then could readily and objectively be compared with different systems or subsystems. In many cases, this is difficult or impractical, and it is not attempted in this study.

To develop a comprehensive set of attributes, the proliferation threats associated with each civilian nuclear power system must be identified, these threats examined and the barriers to them identified, and the associated relationships must be analyzed. Barriers are the counters to vulnerabilities (i.e., where vulnerabilities exist in the fuel cycle, sufficient barriers should exist to prevent their exploitation). Civilian nuclear power systems are examined systematically, from mining to disposal, to determine distinct threats and to evaluate barriers against each threat. These barriers can be examined at each point in the fuel cycle to identify the attributes of a civilian nuclear energy system for its proliferation resistance. Thus, the framework for developing attributes includes:

- identifying the proliferation threats and the linkage between fuel-cycle activities and proliferation.
- identifying various barriers to the threats.
- for each system or subsystem, outlining the important attributes that characterize the effectiveness of the barriers.

Threats

General proliferation threats to civilian nuclear power systems include: (1) the misuse of material through its diversion or theft; (2) misuse of facilities, equipment, and technology; and (3) transfer of nuclear skills and knowledge—all for a potential proliferator to make nuclear weapons. Threats may be either overt or covert. Potential proliferators may be non-nuclear weapons states and subnational groups. The non-nuclear weapons

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[2] Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, 1994.
[3] Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, National Research Council, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, 1995.
[4] National Academy of Sciences, Panel to Review the Spent-Fuel Standard for Disposition of Excess Weapons Plutonium, *Interim Report*, July1999.

states can be divided among those that have very high technical levels of nuclear sophistication and those that do not (there are obviously all gradations of political will and technical capability). This distinction will change and probably blur with time and may become less important.

Subnational groups can likewise be divided between those that will use material or information for themselves and those that will transfer it to someone else. The nature of these threats is affected by events such as a host state's abrogation of treaties and conventions (facilitating overt transfer of facilities, materials, and expertise to weapons programs) or loss by a host state of institutional controls (leading, for example, to a failure of safeguards and security, among others and thus increasing risk of diversion or theft).

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

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

The threats described so far are general as to type. As the National Academy of Sciences panel[5] pointed out in 1995, any threat must also be characterized as to associated organizations, capabilities of forces in the case of theft, and the likely knowledge, skills, financial resources, and technologies available to make good on the threat. Many and diverse threat scenarios involve a plethora of actors, pathways, and actions. Scenarios must be examined to determine which are the most serious, involve the most likely threats and are therefore the most important—and then propose systems and subsystems to deal with most important threats.

Materials

The primary link between civilian nuclear power and nuclear weapons is nuclear material. Other links, while certainly important (such as the use of hot cells for weapons fabrication or civilian knowledge for weapons design), tend to be less direct. Thus, the discussion of 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-usable material. Our interest here is in material capable of undergoing an explosive fissionable

[5] Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, 1995.

reaction.[6] We consider all isotopes capable of being assembled into a fast critical mass as potentially weapons-usable and therefore of proliferation concern. It is important to note that the effort required to use any isotope depends on the isotopic properties and the engineering and scientific skills of the potential proliferator because the isotope's properties vary (half-life, neutron generation, heat generation, and critical mass). In any case, these skills need to be sophisticated by today's standards. These materials may be either as a metal or as a compound (e.g., an oxide), or as mixtures and will require complex chemical or isotopic separation processes to extract them for explosives use. **Table 1** summarizes some of the nuclear properties of fissile materials. For comparison, the table also includes the two major fertile materials, Th^{232} and U^{238}, which in the presence of neutrons 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 Atomic Energy Agency (IAEA) considers plutonium containing more than 80% Pu^{238} not weapons-usable because of its high 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.

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

Barriers

Material qualities, technical impediments, and institutional arrangements (including the complex of measures known as material protection, control, and accountability, or MPC&A) present barriers that make it more difficult for proliferators 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 barrier is extrinsic. Intrinsic barriers are those inherent to technical and related elements of a fuel cycle, and 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.
Other considerations, such as material attractiveness, associated economic penalties, unsafe practices, or generated wastes, are encompassed by these formulations.

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

The National Academy of Sciences panels (1994, 1995, and 1999) have devised a useful classification of barriers and their associated attributes. There are advantages to building on this classification scheme rather than inventing—or re-inventing—new ones. While there have been proposals to analyze proliferation resistance using risk-based methodologies similar to those used for reactor safety studies, such methods require knowledge or estimates of the probabilities of those risks. Such knowledge is lacking or poor, and the probability estimates required are subject to significant debate. The barriers approach avoids this difficulty by requiring only an assessment of the relative effectiveness of individual barriers, lending itself to qualitative and transparent comparisons among various systems concepts and options.

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

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

The difficulty and/or time delay associated with potentially modifying or reconfiguring a facility or process to produce weapons-usable material is another example of an intrinsic technical barrier. Material throughput is another technical barrier, at least to the extent that processes with low throughputs may be less attractive to proliferators or may offer an increased probability of detection of diversion. (It is more likely that a diversion of 1 kg of material will be noticed from a process treating 100 kg/day than from one treating 1,000 kg/day.) Of course, overcoming technical barriers requires specialized skills, tools, materials, and supplies.

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

The need for institutional barriers specific to a civilian nuclear energy system depends on the effectiveness of the intrinsic barriers of that system. In turn, the intrinsic barriers can have a significant impact on the effectiveness of safeguards and on physical protection, security, and accountability. Thus, those extrinsic institutional barriers that can be affected by material and technology choices are part of the overall framework, recognizing that requirements for specific extrinsic barriers can only be realistically defined following an evaluation of the effectiveness of the intrinsic barriers.

Attributes

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

In this approach, each element of the system (fuel cycle) is reviewed against a specific threat to determine the important attributes contributing to the effectiveness of the various barriers discussed previously. This approach is outlined in **Table 2**, where we propose *a separate table for each type of threat* to the system (e.g., covert diversion by a technically advanced, non-nuclear weapons state in the mid-21st century). The three types of barriers (two intrinsic, one extrinsic) are listed across the top of the matrix. Each barrier is divided into its most important sub-barriers. Each of the steps, barriers, and threats may require additional elaboration to ensure that we have adequately defined the overall evaluation framework. Our goal is to define a framework that can be applied to any system, providing an assessment of relative proliferation resistance among various systems and options. There is no attempt to evaluate the proliferation resistance of any system, subsystem, or option in an absolute or quantitative sense.

It is useful to indicate the qualitative effectiveness of the each barrier. The National Academy of Sciences panel (1995) used a qualitative scale with numbers from 0 to 4, where 4 indicated a very high barrier. We use letters to avoid the implication that at this stage of development this framework can be used quantitatively. I indicates an ineffective barrier, L a low barrier, M a medium barrier, H a high barrier, and VH a very high barrier. This scale is not linear. Some, perhaps substantial, qualitative differences may exist between different rankings. This scale is also not comparable among the various barriers. That is to say, the effectiveness of an H for a radiological barrier is not necessarily equivalent to a chemical barrier with an effectiveness of H.

The framework in Table 2 evaluates the effectiveness of the various barriers to the different elements of the nuclear fuel cycle. To use this table to compare systems or subsystems for their proliferation resistance, all fuel cycle steps must be considered. Some of the fuel cycle steps may have relatively little influence on proliferation resistance; for example, mining, milling, and conversion typically have very high isotopic, chemical, and mass/bulk material barriers. In addition, these barriers tend to have similar proliferation-resistance characteristics for most fuel cycles, and thus do not significantly affect relative comparisons of most fuel cycles. There is also substantial commonality for most fuel cycles in the storage and disposition of spent fuel and processed high-level radiation waste.

Table 2. Barriers Framework Applied to a Generalized Nuclear Fuel Cycle

Stage of the fuel cycle	Material Barriers					Technical Barriers						Institutional Barriers		
	Isotopic	Chemical	Radiological	Mass and Bulk	Detectability	Facility Unattractiveness	Facility Accessibility	Available Mass	Diversion Detectability	Skills, Expertise, and Knowledge	Time	Safeguards	Access Control and Security	Location
Beginning of the cycle														
Mining														
Transport														
Milling														
Transport														
Conversion														
Storage														
Transport														
Uranium enrichment														
Storage														
Transport														
Fuel Fabrication														
Storage														
Transport														
Reactor operations														
Fresh fuel storage														
Fuel handling														
Reactor irradiation														
Spent fuel handling														
Pool storage of spent fuel														
On-site spent-fuel dry storage														
Back-end of the cycle														
Transport (of spent fuel)														
Storage (of spent fuel)														
Once-through														
Processing for direct disposal														
Transport														
Pre-emplacement storage														
Repository emplacement														
Closed cycles														
Reprocessing														
Storage of recovered materials														
Transport of recovered material														
Transport of actinide wastes														
Disposal of actinide wastes														
Storage (recovered materials)														
Fuel fabrication														
Storage														
Transport														
(return to reactor operations)														

Attributes of Material Barriers

Material-barrier attributes are those qualities of materials that relate to the inherent desirability of the material by a potential proliferator. 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 of moving the mass and/or bulk of the material, and the inherent detectability of the material itself.

Isotopic Barrier

Attributes of the isotopic barrier indicate how difficult it may be to construct a weapon from a particular fissile material once the material is available in an "acceptable" chemical form. Materials with the lowest isotopic barrier effectiveness (especially highly enriched uranium (HEU) and weapons-grade (>90% Pu^{239}) plutonium) are most attractive for weapons applications. Materials with a higher isotopic barrier may involve more complex weapon design, material fabrication and handling, and/or isotopic enrichment to be used in a nuclear weapon. Attributes important for determining the effectiveness of the isotopic barrier include:

Critical mass. The minimum amount of material needed to achieve fast-neutron criticality. The barrier scales with the size of the critical mass. A smaller critical mass represents a lower barrier than a large critical mass.

Degree of isotopic enrichment. Natural and low-enriched uranium (LEU) cannot be used directly in a weapon, but they can be converted to weapons-usable material by enrichment or further enrichment. Thus, the isotopic barrier is high for uranium enriched to low levels of U^{235} or U^{233}, and low for uranium enriched to very high levels (see sidebar this page).

Spontaneous neutron generation. Spontaneous neutrons can affect the design, yield, and reliability of a device. The lower the spontaneous neutron generation rate, the lower the barrier. For plutonium, this depends strongly on the concentrations of Pu^{240} and Pu^{242}.

It should be noted that the definition of LEU for mixtures of U^{233} and U^{235} has not been established in law or in international agreements. The LEU limit for U^{235} in U^{238} is 20%, and that for U^{233} in U^{238} is generally accepted at 12%. A recent study by Forsberg, et al. (*Definition of Weapons-Usable Uranium-233*, Oak Ridge National Laboratory, ORNL/TM-13517, March 1998) shows that 12% U^{233} is "critically equivalent" to 20% U^{235} (in mixture with U^{238}), and that the "criticality equivalency" of LEU for mixtures of U^{233} + U^{235} in U^{238} can be expressed by the relationship:

$$\left(\frac{1.67U^{233} + U^{235}}{U^{tot}}\right) < 20\%$$

Heat-generation rate. Heat produced by the nuclear decay of the material complicates the weapon's operation and therefore the design. A lower heat-generation rate represents a lower barrier than a higher rate. For plutonium, this depends strongly on the concentration of Pu^{238}.

Radiation. The radiation (especially gamma radiation) released by the isotope itself interferes with the handling, processing, and design of a nuclear device. This is different from the radiological hazard discussed later, as it deals with the difficulty of weapons design and not the dose to humans. However, the two may be related. A lower radiation level represents a lower barrier than a higher level. For plutonium, this depends on the concentration of Pu^{240} and Pu^{242}; for U^{233}, on U^{232}.

These attributes are not easily aggregated into a single measure of the effectiveness of the overall isotopic barrier. However, various national and international classifications of material attractiveness provide some guidance. HEU and all plutonium isotopic mixes[7] are considered "directly usable" in weapons (although the technical sophistication required to design and produce such a weapon clearly varies with the isotopic mix). HEU[8] can be used to make a "gun-type" device, but plutonium requires an implosion design. Because the technical sophistication required to produce a gun-type device is considered less than that required to produce an implosion device, very highly enriched uranium presents a lower barrier to proliferation than plutonium.

The effectiveness of the isotopic barrier associated with HEU, as well as that associated with LEU, clearly depends on the level of enrichment. This fact is recognized in DOE Order 5633.31 where safeguard categories for various special nuclear materials are defined (i.e., plutonium, U^{233} and U^{235} with enrichments of 20% or greater). This order differentiates between high-grade U^{235} (enrichment 50% or greater) and low-grade U^{235} (enrichment <50%). We extend this distinction to the evaluation of the isotopic barrier of HEU, and consider HEU having an enrichment 50% or greater to represent an insignificant barrier, and HEU with enrichment between 20% and 50% to represent a low to medium barrier to proliferation. This distinction recognizes that uranium enriched to less than 50% U^{235} can be used in a nuclear weapon, but that more effort is needed to produce such a weapon than for enrichments at 50% or greater.

For plutonium, the critical mass varies less among the different isotopes. "Weapons-grade" plutonium has a critical mass of about 11 kg (alpha phase), while "reactor-grade"[9] (containing 60% Pu^{239}) has a critical mass of about 13 kg. However, the heat-generation rate and the spontaneous neutron-generation rate associated with reactor-grade plutonium can have a deleterious effect on the design and performance that increases with increasing burnup in a reactor. Thus, it is appropriate, for these classes of materials, to subdivide these categories to reflect these important issues. In the barrier summary, we have indicated 60% and 40% Pu^{239} content as illustrative of the range of plutonium isotopics that may be achievable with current and near-term LWR fuels. Other reactor and fuel concepts may achieve markedly higher burnups with further reductions in Pu^{239} content. As in the discussion of HEU, the distinction between different classes of plutonium is not intended to imply that it is greatly more difficult

[7] Except plutonium mixes with 80% (or greater) concentration of the isotope Pu^{238}, which under IAEA guidelines are not subject to safeguards.
[8] Both U.S. and international practice considers uranium containing 20% or more U^{235} to be "High Enriched Uranium" requiring a higher degree of safeguards oversight. This distinction between HEU and low-enriched or LEU is arbitrary and results in an artificial discontinuity in the isotopic barrier for uranium.
[9] The isotopic content of reactor-grade plutonium varies with burnup (among other things.) Nominal burnup of uranium oxide fuels (in the range of 33 to 45 MWd/kg) yield plutonium with slightly under 60% Pu^{239} content. Higher burnups of uranium fuels (75 to 100 MWd/kg) can reduce the Pu^{239} content to nearly 50%. Alternate fuel compositions, such as uranium–thorium mixes, taken to burnups as high as 100 MWd/kg, may reduce the Pu^{239} content to nearly 40%. Besides reducing the Pu^{239} content, increasing the burnup in all these fuels increases the content of Pu^{238}, which further exacerbates weapons design.

to make a nuclear weapon from reactor-grade plutonium.[10] The degree to which the various aspects of the isotopic barrier can be overcome depends on the technical sophistication of the state or group attempting to produce a nuclear weapon.

Other materials (primarily LEU, natural, and depleted uranium) are unsuitable for weapons and require considerable enrichment to produce weapons-usable material. These classes of materials can best be characterized by the effort required to enrich them to some weapons-usable form. As the sidebar on this page notes, the enrichment effort necessary to convert LEU to HEU is considerably less than that needed to generate HEU from natural uranium. Thus, LEU presents a slightly lower barrier to proliferation than does natural or depleted uranium.

Examples of Uranium Enrichment for 1-kg Product

Product Enrichment (%)	Feed Assay (%)	Feed Required (kg)	Tails Assay (%)	SWU
3.25	0.71	7.2	0.3	3.9
5.0	0.71	11.5	0.3	7.2
93	0.71	226	0.3	200
93	5.0	20	0.5	50
93	5.0	23	1.0	40
93	20	4.8	1.0	15.5
93	20	5.9	5.0	10.2

Fissionable materials commonly considered attractive to potential proliferators can thus be classified as follows:

Insignificant:	I (-)	Weapons-grade HEU (approximately 80% or greater U^{235})
	I (+)	HEU between about 50 and 80% U^{235}
Low:	L (-)	Weapons-grade Pu (>90% Pu^{239})
	L	Typical reactor-grade Pu (approximately 60% Pu^{239})
	L (+)	HEU between about 35 and 50% U^{235}; very-high-burnup reactor-grade Pu (approximately 40% or less Pu^{239})
Medium:	M	HEU between about 20 and 35% U^{235}
High:	H	Low-enriched U [$(1.67\ U^{233} + U^{235})/U^{tot} < 20\%$]
Very High:	VH	Natural, depleted U

Other fissionable materials (such as Np, Cm, and Am) can be brought into this basic HEU or plutonium classification by comparing their critical masses, spontaneous neutron generation rates, and heating rates with those of HEU and plutonium (see Table 1).

Chemical Barrier

The chemical barrier refers to the extent and difficulty of chemical processing required to separate the weapons-usable material(s) from accompanying diluents and contaminants. The presence of a significant radiological barrier renders chemical processing much more difficult and the chemical barrier therefore much more effective. Conversely, in the absence of a significant radiological barrier, the chemical barrier is much less effective. Attributes of the chemical barrier generally relate to the degree of technical difficulty needed to refine materials into the appropriate form, be they metals or

[10] *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, U.S. Dept. of Energy Report DOE/NN-0007, January 1997, pp. 37–39.

compounds. Other possible attributes include the existence of admixtures (such as those incorporated to frustrate chemical separation or denaturing), the number of separate processing steps needed to obtain materials of sufficient purity for weapons applications, and the general availability of the necessary processing techniques.

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

- I Pure metals
- L Single compounds (including oxides, nitrides, etc.; e.g., requiring relatively few and simple chemical steps to extract a pure metal)
- M Mixed compounds (in particular MOX fuel, and including diluents and burnable poisons, but not including fission products or other radiation barriers)
- H Spent fuel and vitrified wastes

While this classification is quite broad, the range of difficulty implied by this classification may be rather narrow. Most chemical processes involved in the separation, extraction, and refining of fissile materials are well known and available.

Radiological Barrier

This barrier affects both the ease of theft or diversion and can complicate chemical processing. One might select many attributes to describe the effectiveness of radiological barriers, among them the specific dose rates (for example, at the surface of the material or container) or the time required to accumulate a significant dose (say, the mean lethal dose). Other possible attributes could categorize the materials by the degree of remote handling required: for example (in order of increasing severity), unlimited hands-on access, limited or occasionally hands-on, long-handled tools and/or isolation and/or remote manipulation (such as in glove boxes), and fully remote and/or shielded facilities.

It is important to recognize that some materials have a high radiation barrier in their elemental form, while other materials have a radiation barrier only due to admixtures. The radiation barrier generally attributed to U^{233} is primarily due to the decay of U^{232}, for example, a contaminant that can only be eliminated by subsequent isotopic separation.[11] On the other hand, the radiation barrier associated with spent fuel can be substantially eliminated through chemical processing. Although important for materials such as U^{233}, this does not constitute an additional barrier, but represents the interaction of the radiological barrier with the isotopic and/or chemical barriers.

Beginning with the National Academy of Sciences (1995) description, and noting no effective difference in the radiation from uranium of any enrichment, we may describe the radiological-barrier effectiveness as follows:

[11] To be precise, the radiation associated with U^{232} contamination actually comes from its daughter products. In theory, chemical processing could remove these daughter products, minimizing the associated radiation hazard for the brief period of time required for their concentration to rebuild as a result of subsequent U^{232} decay.

- I Material with no significant radiation hazard, and capable of unlimited hands-on access; includes natural, depleted, and enriched uranium
- M Material with moderate radiation hazards, normally requiring glove-box handling; includes separated plutonium
- H Material with dangerous radiation hazards, but whose radiation level falls below the "self-protection standard" (IAEA and Nuclear Regulatory Commission self-protection radiation standard = 100 R/hr at 1 meter); includes aged spent reactor fuel and mixtures of spent reactor fuel with high-level waste
- VH Material with lethal levels of radiation meeting the self-protection standard; includes most spent reactor fuel and high-level waste.

Because the radiological barrier decays with time, after a few tens of years, the radiation barrier of spent fuel has decayed to a level where it may be reasonably shielded or handled with less sophisticated techniques. Furthermore, the radiological barrier is largely a health and safety issue and the importance of the radiological barrier may be less for proliferators willing to sacrifice their personnel.

Mass and Bulk Barrier

If the material is dilute, then the total amount of material to obtain, transport, and process in order to have sufficient material for a weapon is large, and the mass barrier would be significant. Conversely, if the material is concentrated, then less bulk is needed and the barrier is considerably lower. Other attributes besides the concentration of the material itself are important. Although fissile material is often in relatively concentrated forms, it is frequently incorporated into bulky items or configurations that are themselves not easy to obtain or transport (for example, MOX fuel in a complete fuel assembly). The shear bulk and unwieldy character of the MOX fuel assembly acts as a barrier to theft or diversion. Another attribute of the mass and bulk barrier is the ease of concealing the material being diverted or stolen. Materials that are easily transported and concealed represent a significant risk.

The following characterization is suggested:

- I Small amounts of weapons-usable materials are easily concealed and transported, with sufficient concentration that a significant quantity can be accumulated in a few trips.
- L Similar to I, but significantly more difficult to conceal.
- M Large quantities of materials must be transported, requiring a significant number of multiple trips and/or several individuals.
- H Large quantities of materials must be transported, requiring commonly available vehicles and equipment.
- VH Large quantities of materials must be transported, requiring specialized equipment and/or vehicles, and/or large quantities of materials of low concentration, requiring many trips using readily available vehicle and equipment.

Detectability Barrier

Nuclear materials are inherently detectable, and this detectability facilitates proliferation resistance through various safeguards and security arrangements. The easier a material is to detect and identify, the more difficult it is to remove without detection, thus a greater level of proliferation resistance. For intrinsic detectability to be meaningful, it must be supported by a safeguards and security system (extrinsic barrier) capable of detecting specific materials.

Some of the attributes that contribute to detectability include:

- the degree to which materials can be passively detected (i.e., the type and intensity of its spontaneous emissions).
- the degree to which active methods (such as neutron stimulation) are necessary.
- the hardness of the radiation signatures (i.e., the difficulty in masking or shielding signatures from detectors).
- the uniqueness of the materials' signatures.
- uncertainties in detection equipment, including screening for dummy items.

The effectiveness of the detectability barrier may be characterized as:

I Materials with no reliable signature allowing for remote detection.
L Materials requiring active and/or intrusive means of detection, but with only moderate detection probabilities.
M Materials that can be reliably detected, but require active means.
VH Materials easily detected by passive means, with unique radiation signatures that are difficult to shield.

Attributes of Technical Barriers

Technical barriers are the intrinsic technical elements of the fuel cycle, its facilities, processes, and equipment that serve to make it difficult to gain access to materials and/or to use or misuse facilities to obtain weapons-usable materials. Misuse of facilities includes the replication of facilities, processes, and technologies to support weapons development. 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.

Facility Unattractiveness

The extent to which facilities, equipment, and processes are resistant to the production of weapons-usable materials is an important intrinsic 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, material, 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.

The facility unattractiveness barrier can roughly be characterized as follows:

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

Facility Accessibility

The extent to which facilities and equipment inherently restrict access to fissile materials represents an important barrier independent from institutional barriers including security and access controls that limit access. For example, reactors with on-line refueling (especially those involving manual fuel-handling) have a lower proliferation barrier than those designed for un-refueled operations throughout their lifetime. Similarly, facilities with a high degree of remote, autonomous processes and operations present a higher barrier to proliferation than those with more hands-on operations.

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

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

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

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

Available Mass

To construct a nuclear weapon, proliferators must obtain at least a critical mass of an appropriate weapons-usable material. If there is insufficient material available in a process or at a facility to represent an attractive target for diversion, theft, or other misuse, then there is a larger barrier to proliferation than for cases where large amounts of materials are available. Material availability in general is affected by the physical characteristics of the process, technology, and facility, and by the security and safeguards measures implemented. These aspects of availability are discussed under the intrinsic facility barriers and the extrinsic institutional barriers described later. The “available mass” barrier specifically treats the amount of material in existence at a point in the nuclear fuel cycle.

The attribute associated with available mass is the amount of potentially weapons-usable material, expressed in terms of critical masses (see Table 1). For the purposes of this barrier, the available mass must be considered the material potentially extractable from diluents or other materials present.

The following characterization is suggested:

- I Very large quantities (multiple critical masses) of potentially weapons-usable materials are present or can be extracted.
- L A significant quantity (on the order of a critical mass) of potentially weapons-usable material is present or can be extracted.
- H Small quantities (small fractions of a critical mass, less than 10%) of potentially weapons-usable material are present or can be extracted.
- VH Very small quantities (small fractions of a critical mass, less than 1%) of potentially weapons-usable material are present or can be extracted.

Diversion Detectability

Diversion detectability is a measure of the extent to which diversion or theft of materials from processes and facilities can be detected. This concept differs from material detectability because diversion detectability accounts for the barriers that the various facilities, technologies, and processes themselves present to diversion and theft. Diversion detectability differs from safeguards in that it relates to those features intrinsic to a technology, process, or facility that make diversion (and/or theft) inherently detectable, whereas safeguards are extrinsic features added institutionally to assist in the detection of diversion. Facility detectability describes the extent to which undesirable modifications to the facilities can themselves be detected and is included in the definition of the attributes for facility unattractiveness.

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

Attributes that characterize the materials detectability barrier include:

- the type of material and processes involved and the extent to which the process supports accurate materials accountability.
- uncertainties in detection equipment, including screening for dummy items.
- the form of the material is amenable to item counting.

The effectiveness of the diversion detectability barrier covers a wide range of possibilities. Limiting conditions are characterized as:

I Facilities with no or minimal detection equipment. Procedures that allow material to easily move without detection.

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

Skills, Expertise, and Knowledge

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

- The level of specialized skills and knowledge necessary to support specific elements of the fuel cycle (the availability of “dual-use” skills—skills that can serve both peaceful and weapons programs). In general, the absence of specialized skills represents a higher barrier than the existence of such skills.
- The extent to which such information is directly applicable to weapons development and the applicability of dual-use skills. A lack of applicable skills represents a higher barrier than the existence of such skills.
- The extent to which such information is generally available (alternate sources of skills). The time required to achieve some level of expertise from available sources may be part of this attribute. General availability and alternate sources of applicable skills represent a lower barrier to proliferation than lack of such sources.

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

I The process, technology, or facility provides significant and unique technical expertise having direct application to a weapons-development program.
M Existence of skills, knowledge, and expertise provide support or insights valuable to a weapons program, or shortens the time required to obtain expertise through training, etc.
VH Only general industrial skills are needed to support the technology or facility and they are well known and readily available from a number of common sources.

Time

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

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

I Long storage time (decades) with opportunity for access to materials and/or equipment
L Long storage time but with low opportunity for access
M Intermediate storage time (years) and low opportunity for access
H Short or no storage time (days to months) and low opportunity for access

Attributes of 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 other aspects of the nuclear energy system to contribute to proliferation. These include international safeguards, MPC&A, highly effective and well-integrated safeguards measures based substantially on real-time monitoring, and other measures such as controls over sensitive information, export controls, etc. Additional extrinsic barriers may be considered institutional in nature, such as the economic and political stability of the region or nation where the nuclear system (or its elements) is located and the commitment of the country to nonproliferation goals.

We are interested in identifying technology opportunities for enhancing proliferation resistance. Thus, we will discuss those institutional barriers that technology can directly affect. Examples of 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 to 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 strong 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 are 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 the future. Moreover, the development of technical options for improved proliferation resistance must be compatible with and supportive of these factors.

Safeguards

Safeguards are those extrinsic measures implemented to assist in the monitoring, detection, and deterrence of facility misuse and/or of material diversion or theft. Because safeguards specifically relate to extrinsic measures, the are materially different from the intrinsic "diversion detection" or "materials detectability" attributes. Safeguards are effective to the extent that they can:

- provide a credible and effective deterrent to proliferation,
- provide effective transparency, and
- reliably detect illicit activities as early as possible.

Attributes that describe the effectiveness of safeguards include:

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

There are many attributes to consider. Here, we will only describe the extremes of the safeguards barrier ranges as:

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

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

Access Control and Security

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

- administrative steps necessary to obtain access.

- physical protection and security arrangements.
- existence of effective backup support.
- how effectively access control and security are implemented and supported if needed, e.g., whether the technology supports co-location of sensitive activities.

The effectiveness of this barrier may be characterized as:

I Material could be easily removed without detection by one knowledgeable insider, or could easily be stolen covertly by one person or small group of outsiders.

L With some prior planning, material could be removed with a small probability of detection by a knowledgeable insider, or could be stolen by a small group of lightly armed outsiders.

M At most times, theft attempts by a single insider would be detected, but the system still has exploitable vulnerabilities in extraordinary circumstances (such as during emergency evacuations or power outages); theft by outsiders would require a group of well-trained, well-armed individuals equipped with explosives and relevant equipment that could be carried on foot.

H Theft attempts by single insiders or small groups of armed outsiders, or both working together, can be blocked with good confidence; design basis threat includes possible use of equipment brought in vehicles.

VH Theft attempts by multiple insiders, or by larger groups of armed outsiders, even if working together, can be blocked with high confidence; design basis threat also includes the possible use of helicopters.

Location

Location represents a problematic barrier in several ways. For example, site remoteness may make a facility harder to attack, but it can also make it difficult to defend and increase the defenders' response time. Operations at widely dispersed locations require transport of materials between them, and transport involves increased risk. On the other hand, co-located facilities may only require on-site transport and represent reduced risk.

The effectiveness of the location barrier will require careful evaluation of the threat and location implications to determine the net value of the location barrier. For these reasons, we do not characterize the barrier here.

Importance of the Various Barriers to the Different Threats

Implementation of this framework requires a very large number of evaluations, particularly when considering a large number of threats. To an approximation, the major features of this threat envelope can be addressed by considering a few selected threats. This will assist in reducing the level of effort required to provide initial, qualitative assessments of technologies and options. **Table 3** summarizes the importance of the various barriers to a selected set of represented threats. This table is intended to serve only as a guide for prioritizing the overall assessment effort. Initial attention should be given to those barriers considered highly important to deterring particular threats, and little initial effort be spent evaluating those barriers seen as having little or no importance to a particular threat.

Table 3 is considered a work-in-progress, the broad judgments are context dependent, and are subject to change as further analyses clarify issues.

Table 3. Relative Importance of Various Barriers to a Selected Threat Sample				
	Sophisticated State, Overt	**Sophisticated State, Covert**	**Unsophisticated State, Covert**	**Subnational Group**
Material Barriers				
Isotopic	Low	Low	High	High
Chemical	Very low	Very low	High	High
Radiological	Very low	Low	Moderate	High
Mass and Bulk	Very low	Low	Low	Moderate
Detectability	Very low	Low	Moderate	High
Technical Barriers				
Facility Unattractiveness	Moderate	High	Moderate	Very high
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
Institutional Barriers				
Safeguards	Moderate	High	High	Moderate
Access Control and Security	Very low	Low	Moderate	Moderate
Location	Very low	Very low	Low	Low

Retrospective

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

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

Several related key issues should also be resolved:

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

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