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Application of Proliferation Resistance Barriers to Various Existing and Proposed Nuclear Fuel Cycles

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Executive Summary

The proliferation resistance attributes or "barriers" developed by the Technology Opportunities to improve the Proliferation resistance of nuclear power Systems (TOPS) task force of the U.S. Department of Energy (DOE) Nuclear Energy Research Advisory Committee (NERAC) provides a framework for the qualitative evaluation of the proliferation resistance of various candidate nuclear fuel cycles. This report summarizes such a qualitative assessment performed for ten current and proposed civilian nuclear fuel cycles.

Acronyms

BREST	A Russian Lead-Cooled Fast Reactor Concept
DOE	Department of Energy
ENHS	encapsulated heat source
H	high
HB	High Burnup
HTGR	High Temperature Gas-cooled Reactor
IFR	Integral Fast Reactor
IRIS	International Reactor Innovative & Secure
L	low
LEU	low-enriched uranium
LMR	Liquid-Metal (cooled) reactor
LWR	light-water reactor
MOX	Mixed Oxide (fuel)
MWD	MegaWatt-Day
NA	not applicable
OT	once-through
Pu	plutonium
PUREX	Plutonium-URanium EXtraction
RTF	Radkowski Thorium Fuel
STAR	small, transportable, autonomous reactor
Th02	Thorium Dioxide
TOPS	Technology Opportunities to improve the Proliferation resistance of nuclear power Systems
UF6	Uranium Hexafluoride
VH	very high

Application of Proliferation Resistance Barriers to Various Existing and Proposed Nuclear Fuel Cycles

Assessment of the proliferation resistance (or potential) of any fuel cycle requires the evaluation of many complex issues. The "Barriers Framework" developed by the TOPS task force[1,2] provides a framework for qualitatively evaluating the proliferation resistance of various fuel cycles[3]. This framework requires consideration of two important factors:

1) The effectiveness of a fuel cycle (and/or its supporting technologies) in supporting each of the barriers in the framework, and
2) The importance of that barrier to each of the particular threats.

It is a cumbersome process to consider both the barrier effectiveness and the barrier importance for barrier, fuel cycle step, and threat. However, the extent to which a particular fuel cycle and/or technology supports the effectiveness of a particular barrier (to an approximation) is dependent only on the fuel cycle and/or technology itself; it does not depend on the threat.

Conversely, the importance of a particularly barrier in the overall evaluation of proliferation resistance (to an approximation) depends primarily on the threat, and the capability of the threat to overcome that barrier. For example, the isotopic barrier is a very important barrier to subnational proliferation threats lacking the capability to separate weapons-useable isotopes, but it is not so important to a sophisticated country having enrichment capabilities. Indeed, most of the intrinsic barriers are more important impediments to less-sophisticated threats than to more-sophisticated threats, while the extrinsic barriers tend to be more important barriers for the more developed nations.

This "separation of variables" provides four important benefits. First, it provides a significant simplification of the overall evaluation process. Second, it allows us to evaluate the ability of a fuel cycle or technology to impact the "technical effectiveness" of the various barriers to proceed on a "purely technical" basis. Third, the "technical effectiveness" of the various barriers provides a convenient and easily understandable basis for comparing various fuel cycle alternatives. Fourth, separating the variables assists us in clarifying where technology can make an improvement in the barrier effectiveness and where such improvements can be considered significant, both important considerations for prioritizing research and development.

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[1] TOPS Task Force of the Nuclear Energy Research Advisory Committee, "Technological Opportunities To Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS)," US Department of Energy (DOE), January 2001. Available at: *http://www.nuclear.gov/nerac/FinalTOPSRpt.pdf*

[2] TOPS Task Force of the Nuclear Energy Research Advisory Committee. "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems," USDOE, October 2000. Available at: *http://www.nuclear.gov/nerac/FinalTOPSRptAnnex.pdf*

[3] For detailed descriptions of the fuel cycles described and additional information on the proliferation resistance attributes of each, the reader is referred to the report: "Report on Proliferation Resistance Technology Assessment of Nuclear Reactor Systems", USDOE June 15-16, 2000. Chicago, IL.

This assessment is a qualitative one, intended to accomplish two goals. It is first and foremost an illustration of how the TOPS proliferation resistance attributes can be used as a framework for evaluating proliferation resistance of nuclear power fuel cycles. It can also provide a preliminary assessment of the comparative proliferation resistance of several popular or proposed nuclear fuel cycles.

This assessment is not, nor is it intended to represent, an analysis of the absolute proliferation resistance of any nuclear fuel cycle or any component of such a fuel cycle. The assessment was performed by evaluating a set of reference cases [specifically the once-through (OT) and light-water reactor (LWR) mixed oxide (MOX) recycle fuel cycles] and then comparing alternative fuel cycles against those references to look for variations in specific barriers at specific points in the fuel cycle.

There has been no attempt to weight or otherwise assemble the various barriers into a single indicator of proliferation resistance. Such an attempt can be made only following significant dialogue and development of a more comprehensive approach to assessing proliferation resistance.

Although the results of this assessment are not surprising (for example, one can easily observe the proliferation resistance benefits resulting from increasing fuel burnup), this assessment has the particular benefit of clarifying the inherent trade-offs that are often involved in attempting to improve systems as complex as the nuclear fuel cycle.

A Note on Tabulated Entries

The results of the assessments are summarized in tabular form in the format used by the TOPS report. In addition, the entries for each of the individual fuel-cycle assessments are color-keyed to indicate how each is assessed relative to the LWR once-through fuel cycle (for other once-through options) or to the LWR-MOX recycle fuel cycle (for other recycle options). In this relative assessment:

- A blue entry signifies that that particular barrier is assessed as being qualitatively more effective (a better or higher barrier) than the reference.
- A red entry signifies that a particular barrier is assessed as being qualitatively less effective (a poorer or lower barrier) than the reference.

The rankings associated with the various barriers are taken from the TOPS report, and are intended to indicate qualitative assessments regarding the effectiveness of the barriers. These rankings range from ineffective to very high in order of increasing barrier effectiveness. Associations between the particular barriers and the ranking indicators are taken from the TOPS report.

1. Application of the Barrier Framework to the Once-Through LWR Fuel Cycle

Table 1. Barriers framework applied to the once-through LWR cycle.

	Material barriers					Technical barriers					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
Storage	VH	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH	I	M	H	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH	I	M	VH	M	VH	I	I	VH	VH	VH
Fuel handling	VH	I	M	VH	M	VH	L	I	VH	VH	VH
Reactor irradiation	L	VH	VH	VH	VH	L-H	VH	I	VH	M	H
Spent-fuel handling	L	VH	VH	VH	VH	VH	M	I	VH	VH	VH
Storage of spent fuel	L	VH	VH	VH	VH	VH	M	I	VH	VH	M
On-site dry storage	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	L-M
Back-end of the cycle											
Transport (of spent fuel)	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	VH
Storage (of spent fuel)	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Once-through:											
Processing for direct disposal	L	H-VH	VH	VH	VH	H-VH	H	I	VH	H-VH	H
Transport	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	VH
Pre-emplacement storage	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Repository emplacement	L	H-VH	VH	VH	VH	VH	VH	I	<VH-VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

VH	very high	L	low
H	high	I	ineffective
M	medium	NA	not applicable

The LWR-OT fuel cycle uses ordinary water-cooled, water-moderated reactors (either pressurized- or boiling-reactors) fueled with low-enriched uranium irradiated to moderate burnups, currently reaching about 45000 MWd/tonne without reprocessing or recycle of irradiated fuel. Table 1, taken from the "attributes" annex, summarizes the technical effectiveness of the barriers for the LWR-OT fuel cycle. This evaluation does not consider any particular threat. The sections that follow outline the logic used in assessing the effectiveness of the various barriers at each step in the fuel cycle.

1.1 Beginning of the Cycle

Evaluating the beginning of the LWR-OT fuel cycle is relatively straightforward. The materials are well defined, and the technologies involved (with the exception of enrichment) generally offer little to a potential proliferator.

1.1.1 Material Barriers

The beginning of the LWR-OT fuel cycle involves only natural, depleted, or low-enriched uranium (LEU). Thus, the isotopic barrier effectiveness is scored as a Very-High barrier throughout the front end of the fuel cycle.

Similarly, these materials have no significant radiological hazard and present an Ineffective barrier to proliferation throughout the front end of the fuel cycle.

The mining, milling, and associated transport of uranium ore generally involve raw ores, which can be considered mixed compounds, and present a Moderate barrier. Conversion transforms the ore to pure compounds that are considered to present a Low barrier to proliferation. This classification follows the material through the fuel cycle to fuel fabrication, where the process of fuel fabrication can be considered to transform the material to a mixed compound, because of the introduction of admixtures to the fuel matrix and the introduction of the clad itself. Thus, assembled fuel is considered a mixed compound, presenting a Moderate barrier to proliferation. It is recognized that this characterization involves some simplifications that mask several nuances in the effectiveness of the chemical barrier. For example, most analysts would consider that raw uranium ore (a mixed compound) is easier to reduce to metal than is uranium hexafluoride (a pure compound), given both the corrosive nature of the UF6 and the general availability of technologies and expertise for reducing ores.

The mass and bulk of all materials in the front end of the LWR-OT fuel cycle generally present a Moderate to High barrier to proliferation because of the low concentrations of fissile materials involved. Prior to enrichment, on the order of 10 tons of material must be obtained to yield roughly 50 kg of U235. This is generally in the form of bulk material, and it can be readily transported using common trucks, to represent a High barrier. After enrichment, this mass drops to on the order of a ton, increasing somewhat following fuel fabrication. Prior to fuel fabrication, the material is generally in a bulk form, so it could be transported in several trips, thus presenting a Moderate barrier to proliferation. After fuel fabrication, the bulk of the fuel assemblies, combined with the fact that several must be obtained to yield roughly 50-kg U235, increases the barrier effectiveness to High.

Accurate assay of natural, depleted, and LEU, and therefore reliable detection of theft, diversion, and misuse (such as enrichment to higher than intended levels) likely requires active means, and so presents a Moderate barrier throughout the front end of the fuel cycle.

1.1.2 Technical Barriers

For the most part, the technical barriers are associated with the facilities, processes, and operations associated with the fuel cycle. Not all countries having nuclear power possess all elements of the fuel cycle. Thus, any proliferation risk associated with a particular fuel cycle step can be associated only with a country having that fuel cycle step.

With the exception of enrichment facilities, the front end of LWR-OT fuel cycle facilities offers no significant attraction to potential proliferators for use in generating material for weapons applications or manufacturing a weapon. While these facilities deal with materials that may be considered attractive to some proliferators, the facilities themselves (except for enrichment) cannot be modified to convert material to a form more useful to a proliferator than the material already in those facilities. Similarly, the front end of the LWR-OT cycle lacks significant radiological hazards so processes and equipment do not have the shielding and remote access capabilities that may be of interest to a proliferator working with contaminated feedstocks such as plutonium. Thus, while processing equipment and other supporting technology may have limited application to processing materials potentially useful to a proliferator, such use offers little real advantage to a proliferator because of the cost, time, and complexity needed for modifications, as well as the relative availability of alternate approaches. Thus, all facilities (except enrichment) at the front end of the fuel cycle are scored as presenting a Very High “facility unattractiveness” barrier to proliferation.

Enrichment facilities are capable of producing high enriched uranium, and the effectiveness of the facility unattractiveness depends on specific facility design. However, all enrichment facilities can be operated in a batch mode (i.e., operated using pre-enriched feedstock to produce output enrichments higher than nominal) to produce HEU. Thus, even facilities that are designed to make it very difficult to reconfigure for HEU production have some inherent capability to produce HEU via batch processing. Thus, enrichment facilities are scored as having a facility unattractiveness barrier ranging from Ineffective (for facilities designed to produce HEU) to Moderate (for facilities designed to make HEU production difficult).

The facility access barrier describes how difficult it is to gain physical access to the materials and technologies within a facility to further proliferation goals—for example, to divert material or process technologies. This barrier depends only on the intrinsic qualities of the technologies involved, and not on the extrinsic barriers such as security and safeguards. For the LWR-OT fuel cycle, the lack of radiation barriers and the low toxicity of most of the materials minimize the need for remotely operated processes and systems, and many operations are performed "hands-on." Thus (with the exception of enrichment), we consider that essentially all LWR-OT front-end fuel cycle steps offer Ineffective intrinsic facility access barriers.

Enrichment is an exception. The nature of most enrichment processes requires the cascading of many stages. Because substantial material is needed to fill the cascade before product reaches the output stage, these processes are generally run relatively continually and relatively remotely. There are requirements for periodic hands-on maintenance, as well as various monitoring and sampling points where hands-on access may be considered routine. Thus, enrichment facilities are scored as providing facility access barriers ranging from Moderate to Very High, depending on specific design.

Generally, the front-end operations involved with the LWR-OT fuel cycle (with the possible exception of transport) process such large amounts of material that there is always sufficient fissile material that a critical mass of potentially weapons-useable material could be extracted (albeit requiring subsequent enrichment). Thus, all steps (except transport) are scored as providing an Ineffective available mass barrier to proliferation. Transportation at the front end involves only LEU-based materials and is scored as presenting either a Low or Moderate barrier, because most individual transportation shipments likely involve material quantities with less extractable potentially weapons-useable materials ranging from about 1 critical mass to a fraction of a critical mass).

The facility detectability barrier measures the extent to which facilities inherently support the detection of diversion and/or theft. This ability evolves from the type of materials processed and the accountability of the materials, as well as on the kinds of detection equipment required by the facility to process the materials. At the very front end of the fuel cycle, most operations handle large amounts of bulk material and no detection equipment is needed. Thus, there is an insignificant facility detectability barrier at the extreme front end of the LWR-OT fuel cycle. The situation changes somewhat during the conversion process. The need for additional quality control and the increased value of the product provide natural incentives for increasingly reliable inventory and process controls. Thus, most of the rest of the front-end steps are scored as providing a Moderate barrier for facility detectability. Enrichment processes require yet more stringent process controls and are scored as providing a Very High facility detectability barrier.

The extreme front end of the LWR-OT fuel cycle (mining and milling) provides no skills, knowledge, or expertise of particular benefit to a potential proliferator. Similarly, with the minor exception of avoiding criticality for enriched materials, transportation and storage offer no skills, knowledge, or expertise of particular use to a potential proliferator. Even the expertise needed to avoid criticality of LEU-containing materials is broadly available and of insignificant real benefit to a potential proliferator. Thus, most of the steps at the front end of the LWR fuel cycle are scored as presenting Very High barriers to proliferation.

Both conversion and fuel fabrication provide less effective barriers to proliferation because of the skills necessary to support those facilities and operations. Both involve expertise in uranium chemistry and materials processing which provides some utility for supporting a weapons program, and are thus scored as providing a Moderate barrier to proliferation.

Enrichment facility operation requires a high level of expertise that can be used directly in the development of a weapon, either through facilitating misuse of the enrichment facility for producing HEU, or through the development of an "out-of-system" enrichment facility. Thus, the enrichment step of the LWR-OT fuel cycle must be scored as presenting an Ineffective barrier to proliferation, although this score applies only to situations in which the facility exists in the country of concern. Clearly, the fact that enrichment is required for the LWR fuel cycle does not materially increase the proliferation risk for countries lacking enrichment facilities; it increases proliferation concerns only for countries having such facilities.

The time during which materials at the front end of the LWR-OT fuel cycle (and to some extent, equipment) is available to a potential proliferator tends to decrease as one moves from the extreme front end (mining) toward the later phases of the front end (fuel fabrication and transport). This is largely because of the increased value of the product and, therefore, an inherent desire to not allow materials to remain in unproductive store. Still, even though materials tend to flow quickly through each fuel cycle step, there is a need to maintain stores of feed materials at the front end of each of the major steps in the fuel cycle. Thus, the fact that specific materials tend to flow swiftly through the front end of the fuel cycle is somewhat mitigated by the fact that material storage itself may persist for long times. These issues are reflected in the scores of the time barrier ascribed to the various fuel cycle steps in Table 1. Mining tends to have material available for very long times and is scored as providing an Ineffective time barrier. The steps prior to enrichment tend to move materials relatively smoothly through processes, but maintain stores for longer times. The remaining steps have significant value added, tend to have less material in storage for shorter times, and are generally scored as supporting Very High time barriers. The enrichment and fuel fabrication steps are scored as supporting a High barrier (as opposed to a Very High barrier) because of the persistent nature of the processes and accompanying material stores.

1.2 Reactor Operations

Most proliferation concerns associated with the at-reactor LWR-OT fuel cycle operations focus on spent fuel. Fresh fuel has no directly useable materials and presents few concerns. There is potential for misuse of reactor facilities to produce potentially weapons-useable materials, but the nature of power reactor operations tends to make covert misuse difficult, although a nation abrogating safeguards could operate a power reactor in a manner that produces weapons-useable materials. Exploitation of such material (either material diverted from spent fuel, or that specially irradiated in a power reactor) would require reprocessing to separate weapons-usable material, so the proliferation potentials associated with at-reactor operations are not by themselves sufficient to fully support a proliferator's goals.

1.2.1 Material Barriers

Materials associated with at-reactor operations vary from LEU (representing a Very High isotopic barrier to spent fuel nominally containing around 60% plutonium-239, providing a Moderate isotopic barrier. Simultaneously, reactor irradiation dramatically increases the radiation barrier from that of fresh fuel (Ineffective) to that of fresh spent fuel (Very High), and also increases the chemical and detectability barriers from Moderate to Very High. Irradiation does not impact the mass and bulk of the fuel assemblies.

Note that on-site storage of spent fuel, both in the spent-fuel pool and in dry storage, is scored as providing a Very-High radiological barrier. In some cases, especially where lower burnup spent fuel has been stored for 30 years or more, this effect should result in some facilities being scored with a radiation barrier of High.

1.2.2 Technical Barriers

Of the facilities associated with the reactor operations portion of the LWR-OT fuel cycle, the reactor offers the most significant capabilities that might be applied to assist a proliferator's goals. Besides the reactor itself, which could be used to provide potentially weapons-useable materials (through irradiation of special target assemblies or short cycling to provide spent fuel of lower burnup), reactor facilities include hot cells and analytic facilities that can provide some ancillary benefit to a potential proliferator. The utility of the reactor for producing potentially weapons-useable material varies with the presumed scenario. Removing fuel after only a single irradiation cycle (to obtain spent fuel of lower burnup) or introducing special target assemblies (for production of weapons materials) is technically easy and incurs only the cost of purchasing additional spent fuel and a minor impact on fuel handling and storage. However, such an operation is observable (both directly through safeguards, and indirectly through fuel purchases and movements) and is scored as a Low barrier. Operating the reactor for short irradiation cycles to improve the isotopic qualities of plutonium in the spent fuel is also technically easy, but incurs significant costs in terms of operations, lost revenue, fuel supplies, etc. The associated power outage is highly observable, and the spent fuel obtained would still require substantial cooling time before it could be further processed and utilized. Such a scenario could result in a barrier effectiveness in the range of Low to High, depending on the specifics of the reactor design and on the resources of the potential proliferator. Most of the other steps and processes associated with reactor operation (fresh- and spent-fuel handling and storage) offer no significant utility to a potential proliferator and support a Very High barrier effectiveness.

The facility access barriers associated with at-reactor operations vary from Ineffective to Very High. The highly hands-on operations involved with fresh-fuel receiving and storage provide only an Ineffective barrier. Fresh-fuel handling, presumed to occur inside the reactor building, is rated as providing a Low barrier because it is routinely performed under careful administrative control for technical reasons. Once in the reactor, access is extremely difficult because of the need to shut the reactor down for access and the unusual nature of unscheduled access operations. Thus, the reactor irradiation step is scored as providing a Very High barrier to access. Spent-fuel handling and storage operations are scored as providing a Moderate barrier to access because of the special handling and safety requirements associated with the spent fuel.

Each of the at-reactor steps involves substantial quantities of materials, so the available mass barrier for each step is scored as Ineffective.

Each of the steps involved in the at-reactor operation involves materials and operations that are generally detectable and verifiable, and are thus scored as supporting a Very High facility detectability barrier.

Storage and handling of both fresh and spent fuel involve some degree of skill and knowledge, particularly in the areas of criticality safety and radiation safety. However, at the level of risk involved, the expertise associated with these operations offers few real advantages to a potential proliferator, and the practices and knowledge required to accomplish these steps are widely known and available. Thus, these steps are scored as supporting a Very High barrier to providing a potential proliferator with necessary skills, knowledge, and expertise. Actual reactor operations, however, require a broader skills set and a greater understanding of nuclear science. Such a skills set would assist a potential proliferator in the planning and implementation of short cycles or irradiating special assemblies and may assist in the development of other aspects of weapons development. Such skills are considered well short of those required to directly support design and development of a weapon itself. Thus, the reactor irradiation step of the LWR-OT fuel cycle is scored as providing a Moderate barrier to the spread of skills, knowledge, and expertise.

Fresh-fuel receiving and storage are scored as having a Very High time barrier because fresh fuel is generally stored on site for only very short times. Reactor irradiation is for intermediate times, but the time needed to access the fuel is long, so the irradiation step is scored as providing a High time barrier. Spent-fuel handling occurs infrequently and requires little time, so it is scored as supporting a Very High time barrier. Spent-fuel storage in the spent-fuel pool extends for some years and is scored as providing a Moderate barrier. On-site dry storage can extend from years to decades, and thus the associated barrier ranges from Low to Moderate.

1.3 Back End

1.3.1 Material Barriers

The material barriers associated with the back end of the LWR-OT fuel cycle are dominated by the characteristics of spent fuel. Without reprocessing, there is essentially no alteration of the material barriers. Thus, the back end is characterizing as having a Moderate isotopic barrier (LWR spent fuel generally contains about 60% Pu-239), and

Very High radiological, chemical, mass and bulk, and detectability barriers. The exception is the impact long-term storage and/or repository emplacement has on the effectiveness of the radiological barrier. The radiological barrier decays with time, and some existing spent fuel may, even now, no longer meet the "self-protection standard." Thus, the radiological barrier score varies between High and Very High. In the far future (beyond 100 years), spent fuel in the repository may decay to such an extent that the barrier degrades even lower.

1.3.2 Technological Barriers

The LWR-OT fuel cycle, with direct emplacement of spent fuel, offers few (if any) facilities and/or processes that may be characterized as providing "attractive" facilities or significant skills, knowledge, or expertise materially useful to a potential proliferator. Thus, the facilities unattractiveness barrier and the skills, knowledge, and expertise barriers are scored as Very High throughout the back end for the LWR-OT fuel cycle with direct emplacement. Should substantially more pre-emplacement processing of spent fuel be deemed advisable, these operations could provide a potential proliferator with some advantage, perhaps degrading the effectiveness of these barriers to High.

The access barriers associated with the back end of the LWR-OT fuel cycle are generally substantial. Transport access is scored as Moderate because the materials are assumed to be already "on the truck," although accessing the spent fuel itself may require special equipment not readily available. Storage and pre-emplacement processing are scored as having a High barrier because of the special equipment needed for safe handling of the materials. Emplacement ensures a Very High access barrier. In all cases, substantial quantities of materials are involved, so the available material barrier is scored as Ineffective. In all cases, the process and facilities involved are working with item-accountable materials and are considered highly detectable, so the facilities detectability barrier is considered Very High, although the detectability likely degrades with time for long times after emplacement in a repository. The time barrier is scored as Very High for transport and High for pre-emplacement processing. Material awaiting processing or emplacement may be stored for several years and is scored as a High barrier. Once emplaced, the material is available essentially forever, so the time barrier is assumed to be Ineffective.

2. Once-Through LWR Fuel Cycle with High Burnup

Table 2. Barriers framework applied to the once-through LWR fuel cycle with high burnup.

	Material barriers					**Technical barriers**					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
Storage	VH	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH	I	M	H	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH	I	M	H	M	VH	I	I	VH	VH	VH
Fuel handling	VH	I	M	H	M	VH	L+	I	VH	VH	VH
Reactor irradiation	L	VH	VH	VH	VH	L-H	VH	I	VH	M	H
Spent-fuel handling	L	VH	VH	VH	VH	VH	M+	I	VH	VH	VH
Storage of spent fuel	L	VH	VH	VH	VH	VH	M	I	VH	VH	M
On-site dry storage	L	H-VH	VH	VH	VH	VH	M+	I	VH	VH	L-M
Back –end of the cycle											
Transport (of spent fuel)	L	H-VH	VH	VH	VH	VH	M+	I	VH	VH	VH
Storage (of spent fuel)	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Once-through:											
Processing for direct disposal	L	H-VH	VH	VH	VH	H-VH	H	I	VH	H-VH	H
Transport	L	H-VH	VH	VH	VH	VH	M+	I	VH	VH	VH
Pre-emplacement storage	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Repository emplacement	L	H-VH	VH	VH	VH	VH	VH	I	<VH-VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

The LWR-OT fuel cycle with high burnup (LWR-OT-HB) is simply the LWR-OT cycle operating with improved uranium fuels to modestly higher burnups (perhaps approaching 75,000 MWD/tonne).

2.1 Isotopic Barriers

Higher burnups require slight increases in uranium enrichment, resulting in a negligible decrease in the isotopic barrier of the fresh fuel. Conversely, the higher burnups degrade the isotopics of plutonium found in spent fuel, resulting in a very slight increase in the isotopic barrier of the spent fuel. Neither effect is sufficient to materially impact the barrier classification.

2.2 Radiological Barriers

Higher burnup very slightly increases the radiation level of the spent fuel, but not enough to impact the barrier classification.

2.3 Facility Access Barriers

Higher burnup reduces the frequency of fresh- and spent-fuel handling and spent-fuel transportation requirements. By reducing spent-fuel inventories, it may reduce the need for on-site dry storage of spent fuel. Although the impact of these factors is not sufficient to alter the basic barrier categorization, a (+) is used to indicate that the impact is considered significant.

2.4 Available Mass Barriers

Higher burnup reduces the overall spent-fuel inventories and the total mass of associated plutonium. However, because high-burnup spent fuel still contains substantial quantities of plutonium, the effect is not considered significant.

3. LWR-OT Fuel Cycle with Homogeneously Mixed Thoria-Urania Fuel

Table 3. Barriers framework applied to the LWR-OT fuel cycle with homogeneously mixed thoria-urania fuel.

	Material barriers					Technical barriers					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH-	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH-	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH-	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH-	I	L	M	M	VH	I	I	M	M	H
Storage	VH-	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH-	I	M	H	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH-	I	M	H	M	VH	I	I	VH	VH	VH
Fuel handling	VH-	I	M	H	M	VH	L+	I	VH	VH	VH
Reactor irradiation	L	VH	VH	VH	VH	L-H	VH	I	VH	M	H
Spent-uel handling	L	VH	VH	VH	VH	VH	M+	I+	VH	VH	VH
Storage of spent fuel	L	VH	VH	VH	VH	VH	M	I+	VH	VH	M
On-site dry storage	L	H-VH	VH	VH	VH	VH	M+	I+	VH	VH	L-M
Back-end of the cycle											
Transport (of spent fuel)	L	H-VH	VH	VH	VH	VH	M+	I+	VH	VH	VH
Storage (of spent fuel)	L	H-VH	VH	VH	VH	VH	H	I+	VH	VH	H
Once-through:											
Processing for direct disposal	L	H-VH	VH	VH	VH	H-VH	H	I+	VH	H-VH	H
Transport	L	H-VH	VH	VH	VH	VH	M+	I+	VH	VH	VH
Pre-emplacement storage	L	H-VH	VH	VH	VH	VH	H	I+	VH	VH	H
Repository emplacement	L	H-VH	VH	VH	VH	VH	VH	I+	<VH-VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

The LWR using homogeneously mixed thoria-urania fuel (LWR-Th02) is similar to the LWR-OT-HB cycle but offers promise for achieving higher levels of burnup and significantly reducing the buildup of plutonium in spent fuel. Use of thoria fuels reduces plutonium buildup by reducing the quantities of U238 (the fertile material that breeds plutonium) in the core. However, as thorium is not a fissile material, the initial enrichment of uranium must be increased, and the fresh uranium component of the fuel is enriched to nearly 20%. As the fuel is burned, the thorium is converted to U233. The fuel mix is designed to ensure that the concentration of the mixture of U233+U235 remains below the "HEU" limit (nominally 20% U235 equivalent).

3.1 Isotopic Barriers

This concept uses uranium enriched to nearly 20%, the limit of LEU. Thus, the isotopic barrier of the fresh fuel is rated at the lower end of the category, VH(-). Conversely, the higher burnups degrade the isotopics of plutonium found in the spent fuel. At the higher burnups suggested for this concept, the Pu239 content is reduced to below 50%, resulting in a moderate increase in the isotopic barrier of the spent fuel, although the effect is not sufficient to materially impact the barrier classification.

3.2 Radiological Barriers

Higher burnup slightly increases the radiation level of the spent fuel, but not enough to impact the barrier classification.

3.3 Chemical Barriers

Thoria is considered chemically more difficult to reprocess than urania. Some modest increase in the effectiveness of the chemical barriers of the spent fuel is warranted.

3.4 Facility Access Barriers

Higher burnup reduces the frequency of fresh- and spent-fuel handling and spent-fuel transportation requirements. By reducing spent-fuel inventories, it may reduce the need for on-site dry storage of spent fuel. Although the impact of these factors is not sufficient to alter the basic barrier categorization, a (+) is used to indicate that the impact is considered significant.

3.5 Available Mass Barriers

Substitution of thoria for urania reduces the amount of U238 available for plutonium generation and reduces the plutonium buildup (by as much as 2/3.) Higher burnup reduces the overall spent-fuel inventories and further reduces the total mass of associated plutonium. The overall effect is significant, as indicated by the (+). However, because there will still be substantial quantities of plutonium, the basic categorization of the available mass barriers does not change.

4. LWR-OT Fuel Cycle with a Heterogeneous Thorium Seed-Blanket Core

Table 4. Barriers framework applied to the LWR-OT fuel cycle with a heterogeneous thorium seed-blanket core.

	Material barriers					Technical barriers					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH-	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH-	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH-	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH-	I	L	M	M	VH	I	I	M	M	H
Storage	VH-	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH-	I	M	H	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH-	I	M	H	M	VH	I	I	VH	VH	VH
Fuel handling	VH-	I	M	H	M	VH	L+	I	VH	VH	VH
Reactor irradiation	L	VH	VH-	VH	VH	L-H	VH	I	VH	M	H
Spent-fuel handling	L	VH	VH-	VH	VH	VH	M+	I+	VH	VH	VH
Storage of spent fuel	L	VH	VH-	VH	VH	VH	M	I+	VH	VH	M
On-site dry storage	L	H-VH	VH-	VH	VH	VH	M+	I+	VH	VH	L-M
Back-end of the cycle											
Transport (of spent fuel)	L	H-VH	VH-	VH	VH	VH	M+	I+	VH	VH	VH
Storage (of spent fuel)	L	H-VH	VH-	VH	VH	VH	H	I+	VH	VH	H
Once-through:											
Processing for direct disposal	L	H-VH	VH-	VH	VH	H-VH	H	I+	VH	H-VH	H
Transport	L	H-VH	VH-	VH	VH	VH	M+	I+	VH	VH	VH
Pre-emplacement storage	L	H-VH	VH-	VH	VH	VH	H	I+	VH	VH	H
Repository emplacement	L	H-VH	VH-	VH	VH	VH	VH	I+	<VH- VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

The LWR using a heterogeneous thorium seed-blanket core (also called the Radkowski Thorium Fuel, or RTF) is similar to the LWR-Th02 cycle in terms of proliferation resistance, and most of the scoring and underlying rationale are taken directly from the preceding. In terms of the proliferation resistance, the only notable differences between the two are:

1) The differences in fuel handling introduced by the heterogeneous design, and
2) The fact that some variations use metal fuel.

The differences among the various fuel-handling options are insignificant at the level of detail attempted here, and indistinguishable from the description for the homogeneous thoria case. Metal fuel is considered easier to reprocess and results in a slight reduction in the chemical barriers associated with spent fuel compared with other LWR options. Options using oxide fuels are considered indistinguishable from the homogeneous thoria case.

5. LWR – MOX Fuel Cycle

Table 5. Barriers framework applied to the LWR–MOX fuel cycle.

Stage of the fuel cycle	Material barriers					Technical barriers					
	Isotopic	Radiological	Chemical	Mass and bulk	Detectability	Facility unattractiveness	Facility access	Available mass	Facility detectability	Skills, knowledge, expertise	Time
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
Storage	VH	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH	I	M	H	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	L	I	M	H	M	VH	I	I	VH	VH	VH
Fuel handling	L	I	M	H	M	VH	L	I	VH	VH	VH
Reactor irradiation	L	VH	VH	VH	VH	L-H	VH	I	VH	M	H
Spent-fuel handling	L	VH	VH	VH	VH	VH	M	I	VH	VH	VH
Storage of spent fuel	L	VH	VH	VH	VH	VH	M	I	VH	VH	M
On-site dry storage	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	L-M
Back-end of the cycle											
Transport (of spent fuel)	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	VH
Storage (of spent fuel)	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Once-through:											
Processing for direct disposal	L	H-VH	VH	VH	VH	H-VH	H	I	VH	H-VH	H
Transport	L	H-VH	VH	VH	VH	VH	M	I	VH	VH	VH
Pre-emplacement storage	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Repository emplacement	L	H-VH	VH	VH	VH	VH	VH	I	<VH-VH	VH	I
Closed cycles:											
Reprocessing	L	L	L	I	M	I	M	I	VH	I	H
Storage of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Transport of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Storage of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Fuel fabrication	L	L	M	I	M	I	L	I	M	M(-)	H
Storage	L	L	M	H	M	VH	I	I	M	VH	VH
Transport	L	L	M	H	M	VH	I	I	M	VH	VH
Transport of wastes (actinide)	L	VH	VH	VH	VH	VH	M	VH	VH	VH	VH
Disposal of wastes (actinide)	L	VH	VH	VH	VH	VH	VH	VH	VH	VH	I
(return to reactor operations)											

The LWR-MOX fuel cycle described here is essentially the same as the LWR-OT fuel cycle except that the fuel is a mixture of uranium and plutonium oxides (MOX) and the uranium portion of irradiated fuel is reprocessed and recycled. The LWR-MOX fuel cycle considered here discusses the so-called 1/3-core option, wherein 1/3 of the fuel assemblies in the core contain MOX and 2/3 contain normal urania fuel. We also assume that aqueous (PUREX) reprocessing is used. This is the type of MOX recycle currently practiced in a number of reactors in the world, most notably several in France. Much of the fuel cycle is identical to the LWR-OT system, with the obvious introduction of reprocessing. The spent MOX fuel, in terms of its proliferation resistance, is essentially identical to spent fuel from the high-burnup LWR case. In the case considered here, the MOX component of the fuel cycle is assumed NOT to be recycled.

In this 1/3-core MOX case, without reprocessing of the spent MOX, the front end of the fuel cycle is treated as dealing only with the 2/3 of the core material that is uranium based. The MOX portion of "fresh fuel" is treated as coming from the back end of the fuel cycle. The back end of the MOX fuel cycle has two distinct portions. The "Direct Disposal" path associated with the LWR-OT fuel cycle carries into the MOX fuel cycle here, because the spent MOX fuel is assumed to be directly disposed. The "Reprocessing" path is new and represents fuel cycle steps not directly comparable with those of the LWR-OT fuel cycle.

5.1 Isotopic Barriers

Spent MOX fuel has plutonium isotopics similar to those of high-burnup fuel, so the isotopic barrier of the spent fuel is slightly enhanced. In the 1/3-core MOX design, 2/3 of the spent fuel is normal uranium-based fuel, with isotopics identical to those of normal once-through spent fuel. Thus, the overall impact of MOX fuel on spent-fuel isotopics is generally positive, but negligibly so. This also holds for the spent MOX, here assumed to be destined for direct disposal.

The major impact MOX fuel cycles have relative to the LWR-OT fuel cycle is the existence of chemically separated materials, with relatively low isotopic barriers. The materials recycled have isotopic barriers equivalent to normal LWR-OT fuel cycle materials. The portion of the fresh fuel that is MOX has a reduced isotopic barrier; thus, storage and handling of fresh fuel is scored as presenting a Low barrier.

5.2 Radiological Barriers

For most of the LWR-MOX fuel cycle, the radiological barriers are the same as those for the LWR-OT fuel cycle. The fact that MOX contains reactor-grade Pu could be a basis for increasing the radiological barrier of fresh MOX fuel, but the additional radiation associated with the Pu in MOX is 1) dilute, 2) effectively shielded by the fuel clad, and 3) represents only 1/3 of the fresh fuel. Thus, the radiological barrier of fresh MOX is considered equivalent to that of fresh uranium fuel. There is a slight increase in the radiological barriers associated with the spent MOX part of the spent fuel, but on the whole they are not considered significant. The radiological barrier associated with reprocessing wastes (which contain a small amount of actinides) is Very High.

5.3 Chemical Barriers

The introduction of MOX fuel does not significantly impact the chemical barriers associated with either the front end or the reactor operations portions of the fuel cycle. The introduction of reprocessing, with its associated separation of plutonium (as oxide) results in a Low chemical barrier effectiveness for much of the recycle portion of the fuel cycle. This barrier is increased somewhat (to Moderate) when the separated plutonium is refabricated as mixed-oxide fuel.

5.4 Mass and Bulk Barriers

The introduction of MOX does not alter the mass and bulk barriers associated with either the front end or reactor-operations portions of the LWR fuel cycle, nor of the direct-disposal path for spent MOX. The introduction of reprocessing, however, results in separated plutonium (usually as powdered oxide) that, for criticality concerns, is packaged in relatively small containers that represent an Insignificant barrier to proliferation. The fuel-fabrication process converts this material to the high-barrier form of complete fuel assemblies. Actinide-containing wastes resulting from the reprocessing step are packaged in very bulky forms that cannot be handled without additional shielding, making the overall package massive and bulky.

5.5 Detectability Barriers

Again, the introduction of MOX does not alter the effectiveness of the detectability barrier at the front end of the fuel cycle and probably does not affect the detectability significantly for at-reactor operations involving MOX; nor does it affect the detectability of most operations involving spent fuel. The material separated in the reprocessing step has distinctive radiation signatures, but the dominant alpha radiation is easily shielded, so active detection measures are probably required for reliable detection. Thus, the separated materials, as well as MOX fuel assemblies, are considered to support a moderate detectability barrier.

5.6 Facility Unattractiveness Barriers

The most significant impact the introduction of MOX has on facility unattractiveness is on the reprocessing facility itself. Reprocessing facilities routinely process potentially weapons-useable materials and thus represent an Insignificant barrier to proliferation. To the extent that the related storage and transport steps associated with recovered material routinely handle significant quantities of potentially weapons-useable materials, these steps are also scored as having an Insignificant barrier to proliferation. Because MOX fuel fabrication facilities must also routinely handle directly useable weapons materials, they are also scored as representing an Insignificant barrier. The transportation, storage, and handling steps involving fabricated MOX fuel do not involve directly useable materials, so are considered Unattractive.

5.7 Facility Access Barriers

Reprocessing facilities are highly automated and highly remote; they offer relatively little direct access to material in the process. There can be considerable requirements for hand-on maintenance, but at infrequent intervals. Thus, the facility access barrier is considered Moderate for reprocessing facilities. The storage and transport steps involving separated plutonium are considered to support a Low barrier to proliferation. In particular, concerns for criticality introduce storage constraints that help impede access to some degree. Once fabricated into MOX fuel assemblies, these constraints are relaxed, and the associated intrinsic access barriers are considered less effective.

5.8 Available Mass Barriers

The introduction of MOX does not alter the available mass barriers for most of the fuel cycle. All steps associated with MOX involve significant quantities of plutonium, so represent insignificant available mass barriers to proliferation. MOX has two positive impacts on available mass, however. First, because only the MOX portion of spent fuel is destined for direct disposal, the total amount of plutonium directly disposed decreases, even though the overall processes involved deal with very large quantities of plutonium. Second, the reprocessing wastes contain very little plutonium, so much of the overall waste has a Very High available mass barrier.

5.9 Facility Detectability Barriers

Reprocessing facilities use highly automated, and therefore highly instrumented, operations. This affords reprocessing facilities a Very High level of facility detectability. The remaining operations associated with the plutonium recycle appear to offer about the same degree of facility detectability as similar operations (material storage, transport, and fuel fabrication) at the front end of the fuel cycle. Processing, transportation, and disposal of reprocessing wastes are similar to those of spent-fuel disposal and are Very Highly detectable.

5.10 Skills, Knowledge, and Expertise Barriers

Reprocessing requires a set of skills, knowledge, expertise, and technologies that are directly useable by a potential proliferator for the purposes of obtaining weapons-useable material, and it presents an Ineffective barrier to proliferation. MOX fabrication is similar to fabrication of uranium fuel and uses similar technologies and skills. The addition of plutonium requires some additional skills and knowledge; thus, MOX fuel fabrication presents a slightly lower barrier to proliferation than uranium fuel fabrication, as indicated by the (-). Other operations associated with recycling offer no significant advantages to a proliferator and are scored as supporting a Very High barrier to proliferation.

5.11 Time Barriers

The time barriers associated with reprocessing and recycle are similar to those associated with the enrichment, fuel fabrication (and associated steps) at the front end of the fuel cycle. This is because the processes are similar in terms of materials flows (i.e., they are essentially continuous, with only short-time opportunities for access and/or diversion); storage times of separated materials can be very short. (Although current practice stores separated materials for long times, this is caused by the imbalance between the rates of plutonium separation and utilization. The technical imperative inherent in the system is to utilize the plutonium as soon as possible after separation.)

6. Prismatic Fuel High-Temperature Gas-Cooled Reactors

Table 6. Barriers framework applied to the prismatic fuel high-temperature gas-cooled reactors.

Stage of the fuel cycle	Material barriers					Technical barriers					
	Isotopic	Radiological	Chemical	Mass and bulk	Detectability	Facility unattractiveness	Facility access	Available mass	Facility detectability	Skills, knowledge, expertise	Time
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH-	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH-	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH-	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH-	I	L	M	M	VH	I	I	M	M	H
Storage	VH-	I	M+	M+	M	VH	I	I	M	VH	VH
Transport	VH-	I	M+	M+	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH-	I	M+	M+	M	VH	I	I	VH	VH	VH
Fuel handling	VH-	I	M+	M+	M	VH	L+	I	VH	VH	VH
Reactor irradiation	L+	VH	VH+	VH+	VH	L-H	VH	L	VH	M	H
Spent-fuel handling	L+	VH	VH+	VH+	VH	VH	M+	L	VH	VH	VH
Storage of spent fuel	L+	VH	VH+	VH+	VH	VH	M	L	VH	VH	M
On-site dry storage	L+	H-VH	VH+	VH+	VH	VH	M	L	VH	VH	L-M
Back end of the cycle											
Transport (of spent fuel)	L+	H-VH	VH+	VH+	VH	VH	M	L	VH	VH	VH
Storage (of spent fuel)	L+	H-VH	VH+	VH+	VH	VH	H	L	VH	VH	H
Once-through:											
Processing for direct disposal	L+	H-VH	VH+	VH+	VH	H-VH	H	L	VH	H-VH	H
Transport	L+	H-VH	VH+	VH+	VH	VH	M	L	VH	VH	VH
Pre-emplacement storage	L+	H-VH	VH+	VH+	VH	VH	H	L	VH	VH	H
Repository emplacement	L+	H-VH	VH+	VH+	VH	VH	VH	L	<VH-VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

The high-temperature gas-cooled reactor (HTGR), as the name implies, is cooled by gas (current designs use helium) heated to higher pressures than achievable in water-cooled designs. Since the gas is not an effective moderator, a separate moderator is required,

and in the case of the reactors considered here, the moderator (carbon) is part of the fuel design itself. By achieving higher temperatures than water-cooled reactors, the HTGR can achieve higher thermal efficiencies, and since the moderator is part of the fuel and cannot leak out (or boil away), HTGR's claim potential safety advantages over the LWRs. Prismatic fuel HTGRs use a once-through, high burnup fuel using a low-fissile-density carbide fuel blocks inserted into hexagonal carbide structures arranged and handled similarly to fuel assemblies in common LWRs. The major proliferation advantages (relative to the previously discussed cases) include higher burnup, chemically more stable fuel, and lower fissile material density. This is achieved at the cost of requiring nearly 20% initial uranium enrichment.
As in the previous cases, we will primarily discuss those barriers that differ from the assessment of the LWR-OT fuel cycle.

6.1 Isotopic Barriers

The Prismatic-high-temperature gas-cooled reactor (HTGR) isotopics are similar to either of the thorium cases discussed earlier and achieve similar very high burnups, but require nearly 20% initial enrichment. The core has two zones (similar to the heterogeneous thorium case). The Pu-239 content of spent fissile fuel is on the order of 40% and scores at the upper end of the Low classification (L+); that of the fertile material contains some 50% Pu-239. Overall, the spent fuel isotopics appear to contain less Pu-239 than options considered above, so are scored as L+.

6.2 Radiological Barriers

The Prismatic-HTGR produces similar radiological barriers for spent fuel as the previous high burnup cases. The smaller size of individual fuel assemblies implies a lower level of radiation, but that is partly compensated by the increased radiation from the higher burnup. Overall the combined effects are not considered significantly different than those for other spent fuel.

6.3 Chemical Barriers

The chemical barriers associated with the prismatic fuel appear substantially improved relative to cases considered previously. The combination of the chemical processing required for the carbide forms, the mechanical processing required, the dilute nature of both fresh and spent fuel, and the fact that there is currently no commercially demonstrated technology for processing the fuel suggests the higher chemical barrier noted here.

6.4 Mass and Bulk Barriers

Fresh fuel assemblies for the prismatic-HTGR weigh approximately 260 pounds and can be handled with only a few people or a single person with a handcart, but nearly 100 are required to obtain a significant amount of U235. Thus, the mass and bulk barrier for fresh fuel is rated at the higher end of the Moderate category. Because of the very low plutonium density in the spent fuel, nearly the entire core must be diverted to obtain roughly a critical mass of plutonium. This contributes to a higher barrier mass and bulk barrier for spent fuel, characterized here as VH+.

6.5 Facility Access Barrier

The Prismatic-HTGR features a higher level of remote fuel handling than that of the LWR, and is therefore scored as having the slightly more effective barriers as indicated by +.

6.6 Available Mass Barriers

An entire core of fresh fuel, although relatively dilute in uranium, still contains some 10 critical masses of U-235, so is scored as representing an Insignificant barrier to proliferation. Spent fuel, in contrast, is very dilute in plutonium, and an entire spent core contains only on the order of a critical mass. Thus, the available mass barrier for this concept is scored as presenting a Low barrier to proliferation.

7. Pebble-Bed Fuel High-Temperature Gas-Cooled Reactors

Table 7. Barriers framework applied to the pebble-bed fuel high-temperature gas-cooled reactors.

	Material barriers					Technical barriers					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
Storage	VH	I	M+	M+	M	VH	I	I	M	VH	VH
Transport	VH	I	M+	M+	M	VH	I	L-M	M	VH	VH
Reactor operations											
Storage of fresh fuel	VH	I	M+	M+	M	VH	I	I	VH	VH	VH
Fuel handling	VH	I	M+	M+	M	VH	L-	I	VH	VH	VH
Reactor irradiation	L+, L++	VH	VH+	VH+	VH-	L	M	L	VH	M	H
Spent-fuel handling	L+, L++	VH	VH+	VH+	VH-	VH	M-	L	VH	VH	VH
Storage of spent fuel	L+, L++	VH	VH+	VH+	VH-	VH	M-	L	VH	VH	M
On-site dry storage	L+, L++	H-VH	VH+	VH+	VH-	VH	M	L	VH	VH	L-M
Back –end of the cycle											
Transport (of spent fuel)	L+, L++	H-VH	VH+	VH+	VH-	VH	M	L	VH	VH	VH
Storage (of spent fuel)	L+, L++	H-VH	VH+	VH+	VH-	VH	H	L	VH	VH	H
Once-through:											
Processing for direct disposal	L+, L++	H-VH	VH+	VH+	VH-	H-VH	H	L	VH	H-VH	H
Transport	L+, L++	H-VH	VH+	VH+	VH-	VH	M	L	VH	VH	VH
Pre-emplacement storage	L+, L++	H-VH	VH+	VH+	VH-	VH	H	L	VH	VH	H
Repository emplacement	L+, L++	H-VH	VH+	VH+	VH-	VH	VH	L	<VH-VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

The pebble-bed HTGR is very similar in many aspects to the prismatic HTGR, with the main difference being that the fuel is in the form of thousands of individual billiard-ball-sized spheres that slowly move downward through the reactor similar to the motion of grains of sand in an hourglass. The reactor is refuled on-line. The pebble-bed fueled HTGR uses a low-density carbide-based fuel using approximately 8% enriched U235 and achieves very high burnups (slightly higher than the prismatic-HTGR). The reactor features a higher degree of automatic refueling, but is refueled continuously and on line. Two variants of this concept have been described: one using uranium fuel, the other using a mixed uranium-thorium fuel. We will primarily discuss the uranium case here. The thorium case would be similar, but both the isotopic and available mass barriers of the spent fuel would be further improved through the use of a mixed uranium-thorium fuel. The differences, where appreciable, are shown as a range in the table (separated by a comma).

Because of the many similarities to the prismatic-HTGR case, we will refer many of the barriers discussions to that case.

7.1 Isotopic Barriers

The spent fuel from this concept has only some 40% Pu-235, so rates a Low+ barrier for all its spent fuel. Use of uranium-thorium fuel may reduce the Pu-239 content to as low as 25%, as indicated by the L++ rating applied here.

7.2 Radiological Barriers

(See Prismatic-HTGR discussion)

7.3 Chemical Barriers

(See Prismatic-HTGR discussion)

7.4 Mass and Bulk Barriers

(See Prismatic-HTGR discussion)

7.5 Detectability Barriers

The small size of the individual pebbles suggests that individual spent pebbles may be more easily shielded than other spent-fuel forms. Thus, the detectability barrier for spent pebbles is shown as slightly less effective than that for other spent-fuel forms.

7.6 Facility Unattractiveness Barriers

Individual fuel pebbles move through the reactor relatively quickly and remain in the reactor for only about 60 days. Particles make many passes through the reactor before being fully spent. There is a sophisticated automatic fuel monitoring and handling system that routes individual pebbles either back to the reactor for additional irradiation, to a spent-fuel holding tank, or to a defective fuel holding tank. The rapid transit through the reactor suggests that the system, if modified, could provide an attractive vehicle for producing weapons-useable material. Thus, the facility unattractiveness barrier for the reactor is scored as Low.

7.7 Facility Access Barriers

The facilities access barriers associated with the at-reactor operations offer competing issues. On the one hand, the relative lack of hands-on operation suggests higher barriers than the reference LWR case. On the other hand, the small pebble size, the fact that the system is continuously refueled, and the system for sorting various pebbles (especially "defective" pebbles) suggest that a lower set of access barriers may be appropriate. In the final analysis, we believe the fact that the system is continuously refueled represents the major access issue, and rate the facility access barriers as slightly lower than those of the reference LWR case.

7.8 Available Mass Barriers

(See Prismatic-HTGR discussion)

8. Small, Transportable, Autonomous Reactor (STAR)

Table 8. Barriers framework applied to the small, transportable, autonomous reactor (STAR).

Stage of the fuel cycle	Material barriers					Technical barriers					
	Isotopic	Radiological	Chemical	Mass and bulk	Detectability	Facility unattractiveness	Facility access	Available mass	Facility detectability	Skills, knowledge, expertise	Time
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
Storage	VH	I	M	H	M	VH	I	I	M	VH	VH
Transport	VH	I	M	VH	M	VH	I	I - L	M	VH	VH
Reactor operations											
Storage of fresh fuel	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel handling	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Reactor irradiation	L+	VH	VH	VH	VH	VH+	VH+	I - L	VH	VH	H
Spent-fuel handling	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of spent fuel	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
On-site dry storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Back–end of the cycle											
Transport (of spent fuel)	L+	H-VH	VH	VH	VH	VH	M+	I	VH	VH	VH
Storage (of spent fuel)	L+	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Once-through:											
Processing for direct disposal	L+	H-VH	VH	VH	VH	H-VH	H	I	VH	H-VH	H
Transport	L+	H-VH	VH	VH	VH	VH	M+	I	VH	VH	VH
Pre-emplacement storage	L+	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Repository emplacement	L+	H-VH	VH	VH	VH	VH	VH	I	<VH- VH	VH	I
Closed cycles:											
Reprocessing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage of recovered materials	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of recovered material	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Disposal of wastes (actinide)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage (of recovered materials)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
(return to reactor operations)											

While there are many concepts for small, transportable autonomous reactors (STAR) (including different coolants, fuels and so on), they all tend to share several important features, including long core life with no on-site refuelling, LEU fuel, highly autonomous operation and reduced maintenance. The long-life core designs eliminate the need to refuel the reactor, thus eliminating all “in-country” fuel handling and storage operations. Fresh and spent-fuel handling is limited to the actual installation and replacement of the entire reactor unit, presumably under strict international control. The concepts also strive to eliminate reactor maintenance, simplify reactor operations, and severely restrict access to the reactor itself. Of particular note is the assumption that all fuel-cycle operations occur under strict international control, presumably in a trusted, stable location. These combine to improve the skills and access barriers relative to the reference OLWR-OT case.

The encapsulated heat-source (ENHS) reactor is considered a variant of STAR, and it has very similar proliferation resistance characteristics.

The front-end and back-end operations normally associated with the fuel cycle are presumed to be provided by a major industrial nation under strict international control. Although shown as scored here, these elements of the fuel cycle are considered not to contribute to the proliferation risk in the country where the reactor is located (and indicated by the dark background in Table 8. Because there is no in-country storage of fresh or spent fuel, and no related fuel handling operations, these fuel cycle steps are considered not applicable (NA).

Because of the similarity with other high-burnup cases, many of the barriers discussions are referenced to the LWR-High burnup case [recognizing that STAR concepts include LWR, liquid-metal (cooled) reactor (LMR), HTGR, and other variants].

8.1 Isotopics Barriers

Fresh fuel for the STAR concepts and variants likely uses enrichments approaching 20%, and thus the score is at the low end of the Very High barrier. In contrast, the long-life, high-burnup core design means that the plutonium content of the spent fuel is low, possibly as low as 40%, so is scored at the high end of the Low scale.

8.2 Radiological Barriers

(See other high-burnup cases)

8.3 Mass and Bulk Barriers

The fact that the entire reactor is transported fully fueled makes the mass and bulk barriers associated with fresh and spent-fuel transport Very High.

8.4 Facility Unattractiveness and Facility Access Barriers

Because the core is designed for unrefueled operation and the reactor systems are designed to inhibit access (in principle, the reactor can be designed with a nonremovable head, and does not require an in-containment crane or handling equipment), both of these barriers must be considered at the higher end of the Very High category.

8.5 Available Mass Barriers

The small size of these systems may result in lower overall available masses, suggesting a possible increase in this barrier compared to the reference OLWR-OT case. Even so, the fact that the entire fresh core is transported as a unit suggests a slightly lower available mass barrier for that operation (as compared to the reference LWR case).

8.6 Skills, Knowledge, and Expertise Barriers

The design specifically adopts features minimizing the requirements for the specialized skills needed to operate more conventional nuclear plants. Thus, this barrier is considered to be Very High.

9. IRIS–MOX Fueled Concept

Table 9. Barriers framework applied to the IRIS–MOX fueled concept.

	Material barriers					Technical barriers					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
Storage	VH	I	L	M	M	VH	I	I	M	VH	VH
Transport	VH	I	L	M	M	VH	I	L-M	M	VH	VH
Fuel fabrication	NA	I	L	M	M	VH	I	I	M	M	H
Storage	NA	I	M	H	M	VH	I	I	M	VH	VH
Transport	L	I	M	VH	M	VH	I	I - L	M	VH	VH
Reactor operations											
Storage of fresh fuel	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel handling	L	I	M	VH	M	VH	H	I - L	VH	VH	VH
Reactor irradiation	L+	VH	VH	VH	VH	VH	VH	I - L	VH	VH	H
Spent-fuel handling	L+	VH	VH	VH	VH	VH	H	I - L	VH	VH	VH
Storage of spent fuel	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
On-site dry storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Back–end of the cycle											
Transport (of spent fuel)	L+	H-VH	VH	VH	VH	VH	M	I	VH	VH	VH
Storage (of spent fuel)	L+	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
Once-through:											
Processing for direct disposal	L+	H-VH	VH	VH	VH	H-VH	H	I - L	VH	H-VH	H
Transport	L+	H-VH	VH	VH	VH	VH	M	I - L	VH	VH	VH
Pre-emplacement storage	L+	H-VH	VH	VH	VH	VH	H	I - L	VH	VH	H
Repository emplacement	L+	H-VH	VH	VH	VH	VH	VH	I - L	<VH-VH	VH	I
Closed cycles:											
Reprocessing	L	L	L	I	M	I	M	I	VH	I	H
Storage of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Transport of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Storage of recovered materials	L	L	L	I	M	I	L	I	M	VH	VH
Fuel fabrication	L	L	M	I	M	I	L	I	M	M(-)	H
Storage	L	L	M	H	M	VH	I	I	M	VH	VH
Transport	L	L	M	H	M	VH	I	I	M	VH	VH
Transport of wastes (actinide)	L	VH	VH	VH	VH	VH	M	VH	VH	VH	VH
Disposal of wastes (actinide)	L	VH	VH	VH	VH	VH	VH	VH	VH	VH	I
(return to reactor operations)											

The IRIS reactor is similar to the STAR concept, but looks at a specific small LWR design using a tight fuel lattice to achieve a high burnup and a long life core. Although dissimilar from conventional LWRs in its longer core life, it does include the probability of on-site refueling (although the design calls for no on-site storage of either fresh or spent fuel). Thus, while accomplishing many of the goals of the STAR concepts, IRIS arrears to not reap all the benefits of avoiding on-site refuelling. Both uranium and MOX fueling options have been considered, and both options appear to require in-country refueling. Both options use nearly 20% enriched uranium. The MOX option is the developer's current preferred option, so that is the option discussed here.

Because the IRIS-MOX reactor uses MOX, it relies on reprocessing for its fuel supply. Thus, Table 9 is based on the LWR-MOX case, although (as for the STAR case) reprocessing is shown with a dark background, indicating that these steps in the fuel cycle occur "out of country." IRIS-MOX uses an all-MOX core, so the "uranium fuel fabrication" steps at the front end of the fuel cycle are considered "not applicable," and fuel fabrication is considered part of the recycled materials portion of the fuel cycle.

Spent IRIS-MOX fuel is presumed to go to direct disposal.

9.1 Isotopic Barriers

IRIS uses 20% uranium in its MOX, so the enrichment step and associated transport step are scored at the low end of the Very High barrier range. The MOX itself uses reactor-grade plutonium, so scores as a Low barrier, similar to that of other MOXs. The spent fuel from the IRIS-MOX reactor has slightly less total plutonium and less Pu-239 content than comparable LWR-MOX spent fuel because of the higher uranium enrichment and full MOX core.

9.2 Radiological, Chemical, and Material Detectability Barriers

The radiological, chemical, and material detectability barriers are assumed to be similar to those in the LWR-MOX case.

9.3 Mass and Bulk Barriers

The IRIS design considers that refueling of the core involves either full cores or large integral sections of the core, such that the mass and bulk barriers associated with in-country operations are similar to those of STAR. Those associated with the front and back ends of the remainder of the fuel cycle are considered the same as in the LWR-MOX case.

9.4 Facility Unattractiveness and Facility Access Barriers

Because IRIS includes provisions for on-site refueling, these barriers are not as high as those of STAR. On the other hand, refueling is very rare, so the barriers are clearly higher than for more conventional LWR cases.

9.5 Available Mass, Facility Detectability, Skills, Knowledge, and Expertise, and Time Barriers

The in-country available mass, facility detectability, skills, knowledge, and expertise, and time barriers are considered equivalent to those of the STAR concept. The rest are considered equivalent to the LWR-MOX case.

10. IFR/PRISM/BREST Fuel Cycle

Table 10. Barriers framework applied to the IFR/PRISM/BREST fuel cycle.

	Material barriers					**Technical barriers**					
Stage of the fuel cycle	**Isotopic**	**Radiological**	**Chemical**	**Mass and bulk**	**Detectability**	**Facility unattractiveness**	**Facility access**	**Available mass**	**Facility detectability**	**Skills, knowledge, expertise**	**Time**
Beginning of the cycle											
Mining	VH	I	M	H	M	VH	I	I	I	VH	I
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Milling	VH	I	M	H	M	VH	I	I	I	VH	M
Transport	VH	I	M	H	M	VH	I	L-M	I	VH	M
Conversion	VH	I	L	H	M	VH	I	I	M	M	M
Storage	VH	I	L	H	M	VH	I	I	M	VH	M
Transport	VH	I	L	H	M	VH	I	L-M	M	VH	M
Uranium enrichment	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel fabrication	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	L	L	L-H	H	M	VH	I	I	M	VH	VH
Reactor operations											
Storage of fresh fuel	L+	M - H	M-H	H+	H	VH	M	I	VH	VH	VH
Fuel handling	L+	M - H	M-H	H+	H	VH	M	I	VH	VH	VH
Reactor irradiation	L+	VH	M-VH	VH	VH	I-M	VH	I	VH	L	H
Spent-fuel handling	L+	VH	M-VH	VH	VH	VH	H	I	VH	VH	VH
Storage of spent fuel	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
On-site dry storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Back –end of the cycle											
Transport (of spent fuel)	L+	H-VH	M-VH	VH	VH	VH	H	I	VH	VH	VH+
Storage (of spent fuel)	L+	H-VH	M-VH	VH	VH	VH	H	I	VH	VH	VH
Once-through:											
Processing for direct disposal	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pre-emplacement storage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Repository emplacement	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Closed cycles:											
Reprocessing	L+	M - H	L-H	M	H	L-M	M	I	VH	I	H
Storage of recovered materials	L+	M - H	L-H	M	H	L-M	M	I	H	VH	VH
Transport of recovered materials	L+	M - H	L-H	M	H	L-M	M	I	H	VH	VH+
Storage of recovered materials	L+	M - H	L-H	M	H	L-M	M	I	H	VH	VH
Fuel fabrication	L+	M - H	M-H	H+	H	L-M	M	I	H	M(-)	H
Storage	L+	M - H	M-H	H+	H	VH	M	I	H	VH	VH
Transport	L+	M - H	M-H	H+	H	VH	M	I	H	VH	VH+
Transport of wastes (actinide)	L+	VH	VH	VH	VH	VH	M	VH	VH	VH	VH
Disposal of wastes (actinide)	L+	VH	VH	VH	VH	VH	VH	VH	VH	VH	I
(return to reactor operations)											

The IFR, PRISM, and BREST fuel cycles are all similar. They all feature liquid-metal cooled reactors and closed equilibrium fuel cycles using dry (electrochemical) reprocessing, and all eliminate the need for enrichment. Differences include the actual coolant (unimportant for proliferation resistance), fuel form and chemistry (may have a minor impact, but not considered significant), and refueling scheme (BREST features on-line refueling). The back end of the fuel cycle, including fuel fabrication, is colocated with the reactor facilities, eliminating all off-site transport of fuel (with the exception of the initial fuel load—shown as a front-end fuel cycle step.)

Because these fuel cycles feature reprocessing, they are compared to the LWR-MOX case.

In the near term, these fuel cycles may operate on depleted uranium already in inventory. However, in the longer term, the front end of the fuel cycle (up to enrichment) would be required and is shown here. As in the LWR-MOX case, fuel fabrication is treated as part of the back end of this fuel cycle.

In contrast to the LWR-MOX case, all spent fuel is reprocessed, and none goes to direct disposal. The only actinides reaching a repository are those contained as trace elements in reprocessing wastes.

10.1 Isotopic Barriers

Relative to the LWR-OT fuel cycle, the IFR fresh fuel contains plutonium and has a lower isotopic barrier than fresh LWR-OT fuel. Relative to LWR-MOX fuel, however, IFR plutonium fuel (at equilibrium) comes from higher burnup material and has a higher isotopic barrier than LWR-MOX.

10.2 Radiological Barriers

The initial core of these systems is presumed to be fueled with "clean" reactor-grade plutonium and therefore has a Low radiological barrier. Equilibrium fuel is not fully separated from its fission products and rates a Moderate to High radiological barrier. Spent fuel has a radiation barrier equivalent to other high burnup fuels. At the back end of the cycle, because the separated plutonium is not fully isolated from fission products, the Moderate-to-High barrier is presumed to persist.

10.3 Chemical Barriers

Fresh initial cores are assumed to be equivalent to fresh LWR-MOX fuel. Because fresh equilibrium fuel contains substantial fission products, its chemical barrier is considered somewhat higher than that of comparable MOX fuels. However, the underlying chemical form of the fuel varies among the concepts, ranging from metal fuel to oxide and nitride fuels. Thus, the overall chemical barriers associated with fresh fuel may range from Low (for metal alloys) to High (mixed compounds), and for equilibrium fuel from Moderate (for metal alloys with fission products) to High (mixed compounds with fission products). These ranges are assumed to be appropriate for the partially separated materials also. (Because the processed material has had many of the fission products removed, it is inappropriate to consider the chemical barrier of partially separated materials to be very high).

Spent fuel is scored as ranging from Moderate (assuming spent alloy fuel) to Very High.

10.4 Mass and Bulk Barriers

The mass and bulk barriers of initial fuel assemblies are assumed to be equivalent to those for LWR-MOX fuel assemblies. These barriers for separated reprocessed materials are assumed to be slightly higher than those for separated MOX materials because of the additional shielding required. Similarly, the mass and bulk of "fresh" equilibrium fuel are somewhat higher than those for comparable MOX because of the additional shielding required, but they are considered lower than those of the spent fuel.

10.5 Detectability Barriers

The detectability of initial fuel is equivalent to that of fresh MOX because the fission products in the separated materials and equilibrium fresh fuel exceed those of MOX, and the detectability is considered to be High.

10.6 Facility Unattractiveness Barriers

Fast reactors effectively burn the even isotopes of plutonium, making it possible to configure the core to produce very desirable plutonium isotopics. Thus, there is an inherently lower facility unattractiveness barrier for a fast reactor than for a LWR. This concern may be compounded in the case of Brest, which includes on-line refueling.

However, the back end of the fuel cycle does not completely separate plutonium from its fission products, and the reprocessing schemes proposed appear to be more proliferation resistant than aqueous (PUREX) reprocessing. In addition, because of the high radiation burden of the partially separated materials, the balance of the back-end operations, including fuel fabrication, are carried out with a higher degree of automation and remote procedures than equivalent LWR-MOX facilities. Thus, these steps are considered to have higher facility unattractiveness barriers than the LWR-MOX fuel cycle.

10.7 Facility Access Barriers

Because of the radiation level of the materials throughout most of the fuel cycle, both at-reactor and back-end operations are performed with a higher degree of automation than many of the similar LWR-MOX operations. In addition, because these fuel cycles feature collocated back-end operations, there is less access associated with transportation and storage steps.

10.8 Available Mass Barriers

Each of these concepts involves ample fissile materials in all phases of the fuel cycle except waste disposal, where only trace amounts of fissile materials are expected in the waste streams.

10.9 Facility Detectability Barriers

The highly automated and remote nature of most of the at-reactor and back-end fuel cycle steps suggests that the facility detectability barriers may be higher than those for the equivalent LWR-MOX fuel cycle steps.

10.10 Skills, Knowledge, and Expertise Barriers

These barriers are considered equivalent to those of the LWR-MOX case except for those associated with reactor operations. Because the fast reactor has some inherently better capability for producing weapons-grade plutonium than a LWR, the associated skills, knowledge, and expertise are also considered of greater interest to a potential proliferator.

10.11 Time Barriers

The time barriers are considered similar to those of the LWR-MOX fuel cycle, with perhaps somewhat shorter storage times throughout the back end of the fuel cycle. Because no off-site transport of material (other than receipt of the initial fuel charge) is anticipated, the time barriers associated with on-site transport are at the upper end of the Very High category.