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Proliferation Vulnerability Red Team Report

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ABSTRACT

This report is the product of a four-month independent technical assessment of potential proliferation vulnerabilities associated with the plutonium disposition alternatives currently under review by DOE/MD. The scope of this MD-chartered/Sandia-led study was limited to technical considerations that could reduce proliferation resistance during various stages of the disposition processes below the Stored Weapon/Spent Fuel standards. Both overt and covert threats from host nation and unauthorized parties were considered. The results of this study will be integrated with complementary work by others into an overall Nonproliferation and Arms Control Assessment in support of a Secretarial Record of Decision later this year for disposition of surplus U.S. weapons plutonium.

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ES1. EXECUTIVE SUMMARY

The Proliferation Vulnerability Red Team (PVRT) was chartered by DOE's Office of Fissile Materials Disposition (DOE/MD) for a four-month independent technical assessment of potential proliferation vulnerabilities associated with the plutonium disposition options under evaluation within the Fissile Materials Disposition Program. Proliferation vulnerabilities are features of lower proliferation resistance that provide the greatest opportunities for illicit removal and recovery of plutonium for use in nuclear weapons.

The PVRT performed a broad, systems-level assessment of potential proliferation vulnerabilities associated with the processes that were under investigation within the FMDP for disposing of surplus U.S. weapons plutonium. The scope of this assessment, although spanning a broad range of issues, was limited by the customer to technical considerations that can cause shortfalls in the proliferation resistance of the alternatives for disposing of U.S. surplus weapons plutonium. Threat scenarios of interest included not only illicit removal by unauthorized parties by either forcible or covert means, but also removal by the host nation for reuse in nuclear weapons thereby contravening international agreements and/or reversing the disarmament process.

This was not a traditional site or facility vulnerability assessment in which various attack scenarios from specified threats against a well-characterized system are developed and evaluated. Such assessments help establish the detailed requirements and performance for security systems and will be performed later in the development of the chosen disposition system. Rather, the disposition concepts were broadly examined in order to determine the most relevant proliferation resistance factors, and to identify features that represent potentially significant shortfalls from goals if not adequately compensated during system design and implementation.

Proliferation resistance can be generally thought of as the net barrier that must be overcome in order to acquire nuclear weapons. Larger barriers impose greater risks, resources, timelines, and/or levels of effort upon the threat. It is not a measurable or unambiguously calculable quantity, nor are there unequivocal techniques for determining the adequacy of a system's proliferation resistance. The PVRT developed a framework that decomposes proliferation resistance from several perspectives: the types of barriers that contribute to proliferation resistance, the measures and features that provide these barriers, and the relative reliance upon intrinsic versus institutional means.

Two complementary "standards" were used as references against which shortfalls, i.e., proliferation vulnerabilities, were assessed: the Stored Weapons Standard (SWS) and the Spent Fuel Standard (SFS). The SWS and SFS were assumed to represent equally acceptable, not necessarily equal, levels of proliferation resistance. The SWS means that, to the extent possible, the high standards of security and accounting applied to storage of intact nuclear weapons and pits should be maintained for excess weapons-usable plutonium throughout the disposition process. This does not imply that the same measures and features must be applied throughout the process. The PVRT identified features of the disposition processes that would significantly challenge the ability to maintain these high standards as the form and states of the material change during disposition. The SFS means that the disposition processes should be able to make the plutonium roughly as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors. It does not imply that the particular properties of spent fuel are required to meet the standard. The PVRT considered whether features of the disposition options result in end state conditions that are less proliferation resistant than the SFS.

The plutonium disposition options were considered stage-by-stage to identify features that could potentially reduce the proliferation resistance of that stage to a level below the standards. The stages were examined at varying levels of detail, depending upon the available descriptions and the identification of relevant issues.

All plutonium from all stages of all alternatives can be made weapons usable, should sufficient material be successfully removed. Although weapons-grade plutonium is preferable for the development and fabrication of nuclear weapons and nuclear explosive devices, reactor grade plutonium can be used. The technology for recovering Pu from spent fuel is in the open literature and can be easily adapted for the material forms within the alternatives. The resources required for the recovery of a significant quantity of plutonium are estimated to be relatively modest. The presence of a radiation barrier sufficient to require shielding and the need for chemical processing during recovery provide the greatest discrimination among the material forms. However, a small, well-prepared group could recover sufficient plutonium for a device within perhaps two months. Keeping Pu inaccessible is the key to proliferation resistance.

Transportation and bulk processing are stages of lower proliferation resistant, which are common to all the disposition alternatives. The frequent and long-term transport of very attractive materials for this program increases its exposure. The disposition options should be configured to minimize this exposure, such as through collocation of facilities, and utilizing SSTs for domestic intersite legs. Limitations in materials accountancy during bulk processing of material, especially in concentrated form, provide a window of opportunity for covert diversion by careful and resourceful adversaries, and trends in the security environment raise challenges to maintaining effective protection-in-depth over the duration of the disposition campaign. Since continued storage minimizes these stages, it is the most proliferation resistant of the options considered against unauthorized threats, although it provides essentially no resistance to host diversion.

One of the primary goals of the disposition program is to put the plutonium in a form that is roughly as unattractive and inaccessible for retrieval and weapons use as the much larger and growing stock of plutonium in civilian spent fuel. However, the intrinsic features of spent fuel are insufficient to protect it from sufficiently dedicated adversaries with modest resources. The institutional protection provided by domestic safeguards are necessary to augment the intrinsic barriers. The intrinsic barriers for the immobilized end forms are currently somewhat less than those implied by the SFS due to lower dilution and the rapid separability of cans from the surrounding radioactive matrix, although these can likely be mitigated and/or the security posture can be graded accordingly. Sealing any of the end forms in a geologic repository imposes very long and observable access requirements, and enables the institutional measures to be greatly relaxed.

Even with IAEA monitoring, covert diversion by a nuclear nation host of multiple Significant Quantities of plutonium a year during disposition is a possibility within the large MUF resulting from high throughput bulk-processing operations, the long campaign times, and the host country control of the security and accountancy infrastructure. However, diversion of such quantities during disposition seems implausible because of the large strategic reserves possessed by both the

United States and Russia and the fact that there is no international observability before the output of the conversion facility. Rather than attempt diversion within MUF and risk being caught by the IAEA through its complementary containment/surveillance features, the host could simply withhold material from the program. Removal of quantities sufficient for rearmament (hundreds of weapons) should be internationally observable because of item accountable final forms and/or the relative ease of monitoring a sealed repository or borehole.

1. INTRODUCTION

1.1 PVRT OBJECTIVES

Sandia was chartered by DOE's Office of Fissile Materials Disposition (DOE/MD) to lead a four-month independent technical assessment of potential proliferation resistance issues associated with the plutonium disposition options under evaluation within the Fissile Materials Disposition Program (FMDP). Proliferation vulnerabilities are features of lower proliferation resistance that provide the greatest opportunities for illicit removal and recovery of plutonium for use in nuclear weapons, thereby reducing the effectiveness of the disposition process. The objective of the Proliferation Vulnerability Red Team (PVRT) assessment was to identify such features of greatest significance. This report summarizes the assessments and findings.

The FMDP is part of the national strategy initiated by Presidential Decision Directive (PDD-13) in 1993 to address the growing stockpiles of fissile material and their national security implications, and has included an ongoing series of evaluations and refinements of alternative means for disposing of surplus weapons-usable plutonium. The National Academy of Sciences published seminal works on plutonium disposition that provides excellent reference and guidance for subsequent analysis.[1,2] More recently within the FMDP, development and analysis of plutonium disposition technologies and issues has been performed by a collection of teams drawn from the national laboratories and contractors. These include three "Alternative" teams focused on each of the three basic disposition approaches (immobilization, deep boreholes, and reactors), and a number of teams focused on cross-cutting topics such as Safeguards & Security, Transportation & Packaging, and Systems Analysis. A variety of criteria, including proliferation resistance criteria, have been considered in these evaluations. Indeed proliferation resistance has been the prominent consideration of the Safeguards & Security team.

The purpose of the PVRT assessment is to provide the customer, the program management at DOE/MD, with a fresh perspective, independent of the ongoing programmatic efforts, focused on potential shortfalls in proliferation resistance of the plutonium disposition options. The findings of this assessment will be integrated with complementary work by others into an overall Nonproliferation and Arms Control Assessment in support of a Secretarial Record of Decision for nuclear materials disposition later this year.

1.2 GENERAL APPROACH

The PVRT performed a broad, systems-level assessment of potential proliferation vulnerabilities associated with the processes that were under investigation within the FMDP for disposing of surplus U.S. weapons plutonium. Figure 1-1 provides an overview of the principal elements for consideration in the assessment. The weapons-usable plutonium that is expected to be declared surplus to U.S. national security needs and undergo disposition currently exists in a variety of material forms ranging from pits and clean metal to rich scrap at a number of DOE facilities.[3] Each of the FMDP plutonium disposition alternatives and variants represents an end-to-end system of operations intended to transition ~50 metric tons of surplus plutonium to more proliferation resistant forms and/or locations while maintaining high standards of security and accounting. Threat scenarios of interest included not only illicit removal by unauthorized parties by either forcible or covert means, but also removal by the host nation for reuse in nuclear weapons thereby contravening international agreements and/or reversing the disarmament process. The PVRT examined each stage of the disposition processes for features that could significantly reduce the proliferation resistance below generally accepted, although ambiguously defined, standards. Such features—termed proliferation vulnerabilities—were identified and their significance evaluated within a common system-level framework. A number of steps were identified for mitigating some of these concerns and strengthening the proliferation resistance of the selected disposition paths.

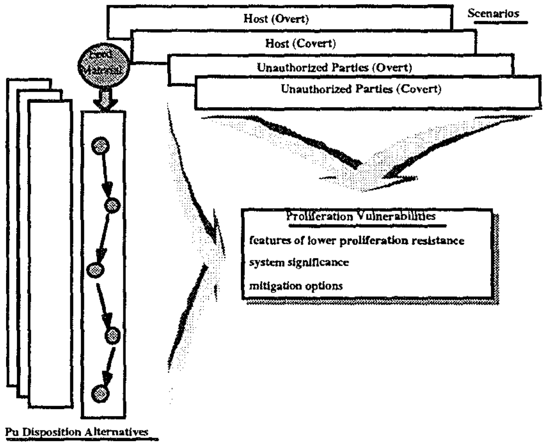

Figure 1-1. Pu Disposition Systems were Broadly Assessed for Proliferation Vulnerabilities

1.3 SCOPE

The scope of the PVRT assessment, although spanning a broad range of issues, was limited by the customer to technical considerations that can cause shortfalls in the proliferation resistance of the alternatives for disposing of U.S. surplus weapons plutonium. There are other important issues that affect proliferation resistance and the relative attractiveness of the various disposition alternatives.

Although beyond the scope of the PVRT, there are many relevant international considerations. It is important to note that the disposition of U.S. plutonium is not being considered in isolation of other nations. The security and accounting of plutonium and other weapons-usable material within Russia and other former Soviet states are of paramount and acute concern to national and international security as their institutional infrastructures degrade. Concerns over their ability to sustain strong enduring institutional controls, interest in the U.S. providing an exemplary model for plutonium management, differing economic priorities and perspectives, and the desire to avoid future asymmetries in strategic posture are examples of the linkages between foreign and U.S. plutonium disposition decisions that can impact proliferation resistance. There are also other international facets to the U.S. disposition options being considered. Implicit to all of them are currently undefined international agreements to dispose of plutonium. There will be mutual influences between the eventual terms of these agreements and the technical capabilities and requirements for monitoring the disposition processes. Some of the disposition alternatives have stages that involve the transfer (both temporary and permanent) of U.S. weapons plutonium to other nations. It is recognized that the protection against illicit removal of plutonium-bearing material by unauthorized (non-host) parties is the responsibility of the host/custodian nation, and assumed that their domestic safeguards requirements and implementation will be satisfactory.

The PVRT also did not address non-technical issues that can influence proliferation resistance, nor were tradeoffs between proliferation resistance and other criteria evaluated. There are numerous policy issues intertwined with proliferation resistance that were beyond the scope of this assessment. Examples include how to provide a motivating example for plutonium management that other nations might embrace, and implications of relinquishing U.S. weapons plutonium for the protection and/or use by others. The assessment of policy and international factors, and their integration with technical considerations will be performed by DOE's Office of Arms Control and Nonproliferation.[4] In addition to proliferation resistance, the FMDP has been evaluating the disposition options against other criteria such as technical viability, cost effectiveness, and timeliness. The PVRT did not attempt to perform any tradeoffs or balancing between these criteria and the technical factors directly affecting proliferation resistance.

The assessment of the Proliferation Vulnerability Red Team is not a traditional site or facility vulnerability assessment in which various attack scenarios from specified threats against a well-characterized facility are developed and evaluated. Such assessments help establish the detailed requirements and performance for security systems and would be performed later in the development of the chosen disposition system. The current conceptual states of definition for the disposition alternatives do not support such an approach. Rather, the disposition concepts were broadly examined from a variety of perspectives within a systematic framework in order to determine the most relevant factors and relationships, and to identify operations and features that represent potentially significant shortfalls from goals for proliferation resistance.

The descriptions of the various disposition options were provided, through documents, briefings, and responses to follow-up questions, by the FMDP alternative teams that are developing and championing the concepts. It's important to note that many of these conceptual descriptions were evolving during and subsequent to the PVRT assessment, which underscores their fluidity and flexibility to adapt. Thus, some of the proliferation vulnerabilities in this report do not necessarily reflect invariant features associated with some disposition alternatives, and indeed many can likely be mitigated. Rather, they flag areas of concern that have been raised regarding proliferation resistance based upon the descriptions provided, and represent opportunities for strengthening the effectiveness of the disposition options. The PVRT was not requested, nor did it attempt, to rank-order the alternatives based on the issues considered. The fluidity and conceptual nature of the alternative descriptions would raise into question any attempt at doing so. The proliferation resistance of a disposition alternative will depend in part upon how the recommendations presented here are integrated with others assessments and balanced with competing program objectives and implemented.

1.4 PARTICIPANTS

PVRT participants represented diverse organizations and expertise affiliated with Sandia National Laboratories, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Savannah River Site. None were recent participants in the FMDP, nor represented technical areas for which their organizations were viewed as having vested interests in the outcomes of the assessments. In addition to technical backgrounds and programmatic independence, selection of the team was guided by their availability to participate at a high level of effort for a short duration on short notice.

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[1] "Management and Disposition of Excess Weapons Plutonium," National Academy of Sciences, 1994.

[2] "Management and Disposition of Excess Weapons Plutonium: Reactor Related Options", National Academy of Sciences, 1995.

[3] "Plutonium-Bearing Materials Feed Report For The Fissile Materials Disposition Program Alternatives," W. G. Brough and S. T. Boerigter, Lawrence Livermore National Laboratory, UCRL-ID-120749, 6 April, 1995.

[4] Memorandum for the Secretary Approving Nonproliferation Study Plan, Kenneth Luongo and Greg Rudy, 10 May, 1996.

2. PROBLEM AND ASSESSMENT FRAMEWORK

This chapter summarizes the foundational issues and perspectives underlying the assessment of proliferation vulnerabilities for the plutonium disposition options. The proliferation threats and scenarios are discussed in the section below. A framework that examines the components of proliferation resistance from three different perspectives was developed over the course of this assessment. Each stage of the various plutonium disposition options was considered for features that might result in proliferation resistance shortfalls relative to the Stored Weapons Standard and Spent Fuel Standard. These standards and the manner in which they were applied for this assessment are then presented. This chapter concludes with an overview of how these elements were applied by the PVRT.

2.1 PROLIFERATION THREATS AND SCENARIOS

The potential threats considered here include illicit removal, either overtly or covertly, of plutonium-bearing material for use in nuclear weapons by unauthorized parties as well as by the host nation. The scope of these threats was established by two of the assessment criteria used by the FMDP for evaluating plutonium disposition options: (1) resistance to theft or diversion by unauthorized parties, and (2) resistance to retrieval, extraction, and reuse by the host nation.

2.1.1 Unauthorized

The threats from unauthorized parties were considered by the PVRT to pose the greater near-term concern. Unauthorized parties include criminals, terrorists, subnational groups, aspiring nuclear states, and insiders within the facilities and institutions that are implementing plutonium disposition.[1] The acquisition of plutonium sufficient for a nuclear explosive device by those that currently do not possess such capability is the primary proliferation concern.

The threat of unauthorized parties attempting to illicitly acquire plutonium-bearing material from within a disposition process, whether by overt forcible theft or covert diversion, and to recover plutonium metal sufficient for nuclear explosive devices was considered by the PVRT to be quite credible. Many of the non-weapons states have long declared their desire to acquire nuclear power status. Global political and religious realignments have disrupted long-standing balances of power and increased the resolve of some states and groups to acquire nuclear weapons. Economic and social disruptions that have accompanied some of this political realignment have improved the conditions for an illicit global market for weapons-usable fissile material and nuclear terrorism. Weapons-usable plutonium has undeniably great value to a variety of potential threats. The existence of seemingly more attractive or potentially more vulnerable sources for weapons-usable material, such as SNM in other countries, was not considered to be a protective factor for these plutonium disposition options, and does not diminish the need to assure adequate proliferation resistance for them.

A range of potential scenario characteristics were considered to be well within the purview of many credible threats by unauthorized parties. Access to billions of dollars to fund the acquisition of weapons material using increasingly sophisticated resources and methods are now within the means not only of aspiring nuclear nations but of subnational groups as well. The ever-increasing proliferation of information has helped elevate the technical sophistication of many terrorist activities. Tools that have been demonstrated to be credible by use in terrorist and criminal actions include all types and sizes of explosive devices, chemical and biological agents, night vision equipment, a broad range of military weapons, helicopters and other aircraft, and large well-coordinated and highly trained teams. Attempts to acquire plutonium by unauthorized parties could be driven by any number of motivations, and willingness to both die and kill for a cause has been frequently demonstrated. Insiders—personnel with authorized access to parts of the disposition process—must be considered as part of the adversarial potential. Insiders were considered to be the primary threat for covert diversions, and were assumed to be sources of information or other support in overt scenarios. Because of the potential use of insiders and the increasing proliferation of information, lack of knowledge is not considered to be an enduring barrier to unauthorized threats.

The increasing availability of sophisticated technical information has also reinforced the critical importance of denying weapons-usable fissile material to those seeking to acquire it. The PVRT considered the removal by unauthorized parties of material bearing sufficient plutonium for a single nuclear explosive device to be unacceptable, whether it occurs in a single incident or by covert diversion of smaller amounts over extended periods of time.

2.1.2 Host

The second FMDP assessment criterion listed above reflects the desire to make it difficult for the host nation to reuse plutonium for weapons once it has been declared surplus and entered into the disposition process. This is consistent with two of the objectives identified by the NAS toward minimizing the security risks posed by excess fissile materials: (1) minimizing the risks that the materials could be reintroduced back into the arsenals from which they came, thereby halting or reversing the arms reduction process, and (2) strengthening the national and international control mechanisms designed to ensure continued arms reduction.[2]

In contrast to the threats from unauthorized parties, host nation diversion of plutonium-bearing material was not considered to be a near-term threat. The two nations of primary consideration for plutonium disposition, the United States and Russia, are nuclear weapons states. Although sizable reductions in the nuclear arsenals and dismantlement of nuclear weapons are occurring, both nations were assumed to retain significant stockpiles containing many hundreds to several thousands of nuclear weapons for the foreseeable future. In addition, each nation will have unverified quantities of plutonium in strategic reserves that are not declared excess to national security needs. For these reasons, covert diversion by a weapons state host nation of plutonium during the disposition process was considered by the PVRT to not be very plausible. Simply not declaring plutonium as excess to national security needs and withholding it from the disposition process would accomplish the same end without it being subject to international scrutiny.

Should nuclear disarmament proceed to the point that there are no strategic reserves with which to replenish a weapons state's diminished nuclear arsenal, then breakout from a disposition agreement by retrieving disposed plutonium for rearmament would become a more plausible scenario. For this scenario, it was assumed that retrieval of approximately one metric ton of plutonium would represent a breakout for rearming a nuclear weapons state's military stockpile.

It is recognized that there may be significant political value in implementing a process that is under safeguards by the international community in which it can be verified that weapons plutonium is indeed being disposed of according to terms of agreement. Thus, host diversion of small quantities was given some consideration. It should be noted that some of the initial stages of disposition and much of the upstream dismantlement process are currently beyond the purview of acceptable international monitoring capabilities due to concerns about revealing classified information. A key programmatic assumption of the FMDP is that all operations involving surplus plutonium will be performed under IAEA safeguards, except those involved with classified parts, shapes, and information.

Although it is not the primary focus of current interest, some non-weapons states also have stockpiles of plutonium that might someday undergo disposition. However, consideration of plutonium other than that declared excess by the U.S. is beyond the scope of this assessment. Although the term "proliferation resistance" is loosely applied to both unauthorized and host nation "threats," it is important to note that for the U.S. as host, "breakout resistance" might be a more appropriate designation. For some of the alternatives considered here, a non-weapons state (Canada) does host some stages of the disposition process, so "proliferation resistance" is not necessarily inappropriate, and will be used throughout this report.

2.2 PROLIFERATION RESISTANCE

Proliferation resistance can be generally thought of as the net barrier that must be overcome in order to acquire nuclear weapons. Larger barriers impose greater risks, resources, timelines, and/or levels of effort upon the threat. The relevant obstacles that are presented and factors that contribute to them will depend upon the scenarios, systems, and context under consideration. Only technical aspects of features that are directly associated with the various stages of the plutonium disposition processes, and the barriers that they provide were considered here. Other contextual or infrastructural features, such as commerce controls, intelligence capabilities, emergency response readiness, etc., contribute to the overall proliferation resistance posture but are beyond the scope of this treatment.

Proliferation resistance is not a measurable or unambiguously calculable quantity, nor are there unequivocal techniques for determining the adequacy of a system's proliferation resistance. In order to satisfy the objectives of this assessment to independently assess potential proliferation vulnerabilities, the PVRT developed a framework for proliferation resistance. This framework, represented generically in Figure 2-1 and described in the remainder of this section, decomposes proliferation resistance from several perspectives: the types of barriers that contribute to proliferation resistance, the measures and features that provide these barriers, and the relative reliance upon intrinsic versus institutional means.

2.2.1 Types of Barriers

For this assessment, proliferation resistance was considered to be the collection of three types of barriers represented by the three columns in Figure 2-1, and designated for convenience as ACCESSIBILITY, OBSERVABILITY, and UTILITY. ACCESSIBILITY barriers make it difficult to access and remove plutonium bearing material from within a disposition process. OBSERVABILITY barriers make it difficult to do so without being detected and recognized, and can also increase the likelihood of recapture and recovery. UTILITY barriers make it difficult to

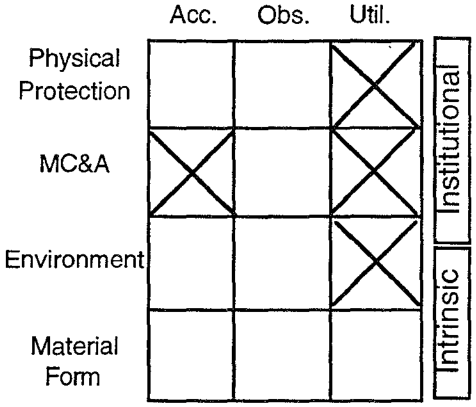


Figure 2-1. Proliferation Resistance Framework

recover weapons-usable plutonium from material that is successfully removed from within a disposition process. As will be discussed later in this section, the relative significance of these depends in large part upon the type of threat scenario under consideration.

2.2.2 Categories of Contributing Measures and Features

There is a wide range of diverse features and measures associated with the plutonium disposition processes that contribute to the various components of proliferation resistance. These have been grouped into the four broad categories represented by the rows in the figure above: physical protection, MC&A, environment, and material form. The relative significance of these categories and the particular features within a category also depend upon the type of threat scenario being considered.

The measures in the “physical protection” category provide the functions of deterrence, detection, delay, and denial by the host against threats from unauthorized parties, and contribute only to the ACCESSIBILITY and OBSERVABILITY barriers. Physical protection measures are provided by and under the direct control of the host nation, and therefore have no bearing upon considerations of host diversion. International safeguards have no protective role in limiting access to the material.

The category that was designated “MC&A” includes the domestic material control and accounting (MC&A) measures that along with physical protection measures constitutes domestic safeguards. Both DOE and NRC regulations call for graded domestic safeguards based upon material attractiveness (quantity and form), with the most severe requirements applied to materials of greatest strategic value. The “MC&A” category also includes the material accountancy and complementary containment/surveillance measures that constitute international safeguards. The international safeguards provide a means for the international community to verify the host’s system of accounting for plutonium-bearing material, and thus a means of detecting illicit diversion by the host nation. This category of measures contributes only to the OBSERVABILITY component of proliferation resistance.

The “environment” category represents a diverse set of features inherently associated with the conditions under which the material is located within a particular stage of the disposition process that can have significant impacts upon proliferation resistance. These features contribute most directly and strongly to the ACCESSIBILITY component of proliferation resistance, in terms of its exposure to opportunities for illicit removal. For example, the exposure of material stored in sealed containers within a continuously monitored vault that is infrequently accessed is inherently less than material being handled by technicians within a processing facility. Some features within the "environment" category can also contribute to the OBSERVABILITY barrier. For example, material sealed within an underground repository is not only inherently difficult to reach, but the access operations may require the use of heavy equipment over long periods of time, making them difficult to conceal. All of the features in this category are relevant to the proliferation resistance against threats from unauthorized parties, although not necessarily to both covert and overt types of scenarios. Some features, such as geologic depth, can also provide significant resistance against host diversion.

The final category of features that influence proliferation resistance is "material form." These are intrinsic properties associated with the plutonium-bearing material. The properties of primary relevance include plutonium dilution, size and mass, chemical form, and the presence and intensity of an ionizing radiation barrier. Collectively, these can contribute to all of the barriers, as indicated in Figure 2.1. Plutonium in the form of pits or cans of concentrated plutonium oxide contribute essentially nothing to proliferation resistance. These are significant quantities of plutonium in packages that are relatively easy to carry and conceal, and that require minimal processing to be usable for weapons. In the immobilization and reactor disposition options, the material form properties listed above are all altered for the effect of significantly increasing their contribution to proliferation resistance. Their significance to proliferation resistance is sensitive to the type of threat being considered.

2.2.3 Institutional vs. Intrinsic Contributions

The third perspective from which proliferation resistance is considered in this assessment is the relative reliance upon institutional versus intrinsic contributions to proliferation resistance. Institutional measures are those contributors to proliferation resistance that require the effective performance of people and institutions. As indicated in Figure 2-1, the measures within the physical protection, MC&A, and part of the environment categories are institutional measures. Intrinsic features of a disposition process are those that still contribute to proliferation resistance if the performance of people is removed from consideration. The material form and much of the environment categories are intrinsic contributors to proliferation resistance.

The excess plutonium entering the disposition processes is in a condition that relies primarily upon institutional measures for proliferation resistance against threats from unauthorized parties. However, these provide essentially no barriers to the ability of the host to rapidly reuse this material in nuclear weapons. All of the plutonium disposition processes result in end states for which intrinsic properties contribute significantly to proliferation resistance, and for which there is less reliance upon institutional measures.

The fundamental issues considered here are whether these end states are at acceptable levels of proliferation resistance, and whether, in the process of reaching those end states, shortfalls from current acceptable levels occur along the way.

2.2.4 Notional Representation of Proliferation Resistance

In order to identify potential proliferation vulnerabilities, the PVRT analyzed the various factors relevant to proliferation resistance at each stage of the disposition processes from the perspectives of the framework described above. Proliferation resistance is not a measurable or unambiguously calculable quantity. Its components are diverse, and their impacts upon the risks, resources, timelines, and/or levels of effort for a potential threat are complex. However, approximations of the relative contributions and relationships of these components to proliferation resistance of a given stage can be represented graphically, as shown notionally in Figure 2-2. Such representations were developed by the PVRT and are utilized here to provide aggregated summary views that reflect some of the conclusions drawn from the PVRT analyses.

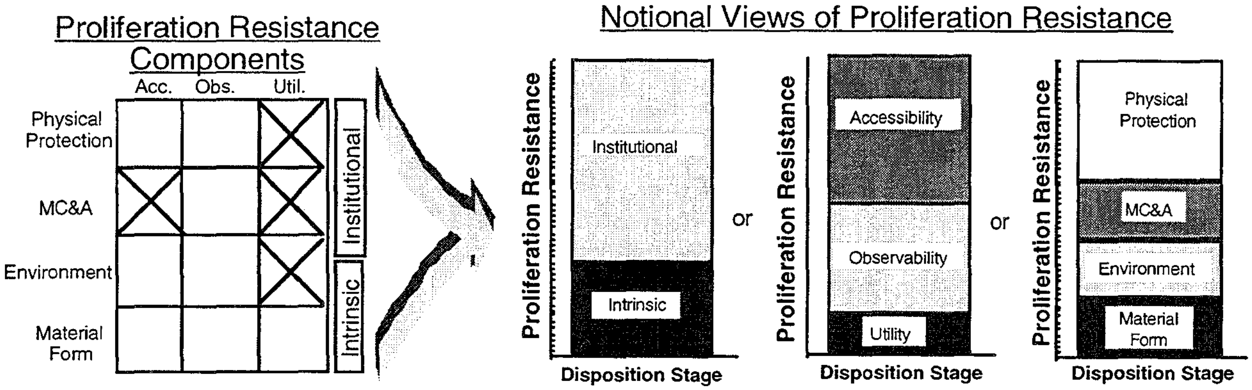


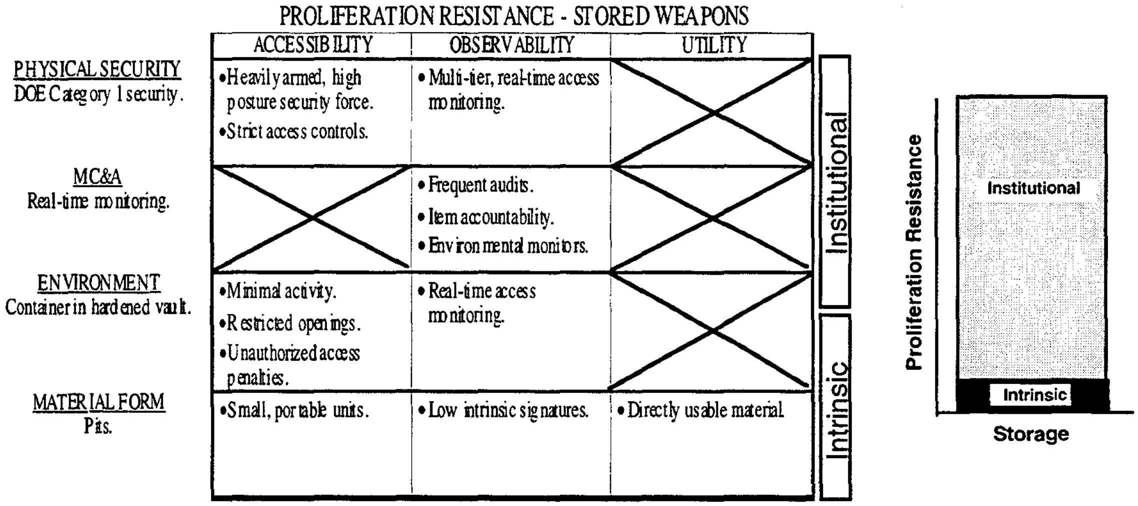
Figure 2-2. Notional Representation of Proliferation Resistance Components

2.3 PROLIFERATION RESISTANCE STANDARDS

Two complementary "standards" were used as references against which shortfalls in proliferation resistance, i.e., proliferation vulnerabilities, were assessed: the Stored Weapons Standard (SWS) and the Spent Fuel Standard (SFS). These terms were initially coined by the NAS, and subsequently refined by DOE. They have been proposed as references against which the security risks associated with plutonium disposition might be judged. Neither of these are truly measurable standards, but rather refer to situations that reflect generally acceptable levels of proliferation resistance. Particularly for the SFS, there has been considerable debate on what features or measures are necessary for conditions to be at equivalent levels of proliferation resistance.

2.3.1 Stored Weapons Standard

The SWS means that, to the extent possible, the high standards of security and accounting applied to storage of intact nuclear weapons should be maintained for excess weapons-usable plutonium throughout the disposition process. Figure 2-3 depicts some of the components contributing to proliferation resistance for such conditions. High proliferation resistance against threats by unauthorized parties is provided primarily by institutional measures, such as the strict access controls and real-time monitoring associated with the multi-tiered, high security posture. It is important to note that this does not imply that the same measures and features must be applied throughout the process. It is standard practice to grade the security posture according to the form and quantity of material present. A fundamental issue for the PVRT assessment was to identify features of the disposition processes that would significantly challenge, though not necessarily preclude, the ability to maintain these high standards of security and accounting as the form and states of the material change during disposition. The SWS provides no barrier to host nation diversion.



PROLIFERATION RESISTANCE - STORED WEAPONS

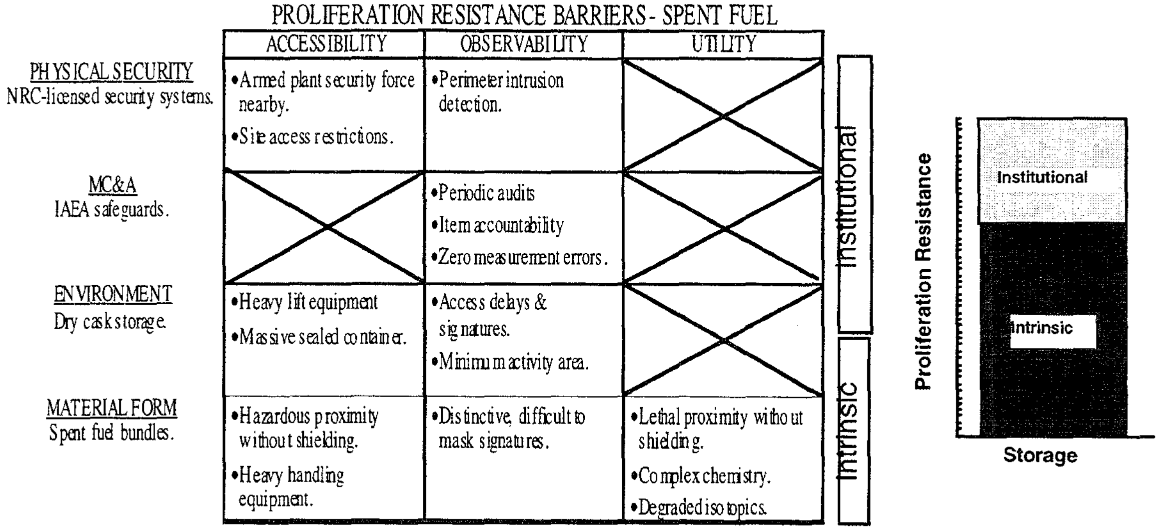
	ACCESSIBILITY	OBSERVABILITY	UTILITY
PHYSICAL SECURITY DOE Category 1 security.	•Heavily armed, high posture security force. •Strict access controls.	• Multi-tier, real-time access monitoring.	
MC&A Real-time monitoring.		• Frequent audits. • Item accountability. • Environmental monitors.	
ENVIRONMENT Container in hardened vault.	•Minimal activity. •Restricted openings. •Unauthorized access penalties.	• Real-time access monitoring.	
MATERIAL FORM Pits.	•Small, portable units.	• Low intrinsic signatures.	• Directly usable material

Figure 2-3. Proliferation Resistance of Stored Weapons

2.3.2 Spent Fuel Standard

The SFS has been generally established as the national objective for the disposition of excess weapons-usable plutonium. It means that the disposition processes should be able to make the plutonium roughly as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors.[3] It does not imply that the particular properties of spent fuel are required to meet the standard. The rationale underlying the original NAS proposal for such a standard were that the intrinsic material properties of spent fuel pose significant barriers to theft or diversion and recovery of weapons-usable plutonium, and that by meeting this standard, the excess weapons-usable plutonium would no longer pose a unique security risk relative to the large stock of plutonium in civilian spent fuel.

A fundamental issue for the PVRT was to assess whether features of the disposition options result in end state conditions that are less proliferation resistant than the SFS. In order to do this, the proliferation resistance of U.S. commercial spent fuel in dry cask storage was decomposed into the framework described above. As illustrated in Figure 2-4, the intrinsic properties of spent fuel provide a significant component of proliferation resistance. It should be emphasized that institutional measures also provide significant contributions to the proliferation resistance of spent fuel. For example, proximity of a reactor site security force contributes significantly to the ACCESSIBILITY barrier against unauthorized theft, and IAEA safeguards provide a mechanism for international OBSERVABILITY of diversion by the host.



PROLIFERATION RESISTANCE BARRIERS - SPENT FUEL

	ACCESSIBILITY	OBSERVABILITY	UTILITY
PHYSICAL SECURITY NRC-licensed security systems.	•Armed plant security force nearby. •Site access restrictions.	•Perimeter intrusion detection.	
MC&A IAEA safeguards.		•Periodic audits •Item accountability •Zero measurement errors.	
ENVIRONMENT Dry cask storage.	•Heavy lift equipment •Massive sealed container.	•Access delays & signatures. •Minimum activity area.	
MATERIAL FORM Spent fuel bundles.	•Hazardous proximity without shielding. •Heavy handling equipment.	•Distinctive, difficult to mask signatures.	•Lethal proximity without shielding. •Complex chemistry. •Degraded isotopics.

Figure 2-4. Proliferation Resistance of Spent Fuel

2.4 ASSESSMENT METHODOLOGY

The plutonium disposition options, briefly described in the following chapter, were considered stage-by-stage to identify features that could potentially reduce the proliferation resistance of that stage to a level below the standards described above. Although the stages were examined at varying levels of detail, depending upon the available descriptions, they are aggregated here into series of storage, transportation, and processing steps.

Separate consideration was given to each of the overt and covert manifestations of both unauthorized and host threats. For unauthorized proliferation threats, the SWS was used as the reference throughout each disposition process up to the stage at which the intrinsic features are intended to satisfy the SFS. When considering host diversion, the SFS was also used beyond that point. Prior to that, OBSERVABILITY with respect to international safeguards is the only relevant factor, so that component of the SFS was also used as the reference. The SWS represents no barrier at all to host diversion.

It is important to note that the SWS and SFS were assumed to represent equally acceptable levels of proliferation resistance with respect to threats from unauthorized parties, and this is depicted in the graphical summaries that follow. This does not imply that there is no difference between them, nor that the disposition processes result in no more desirable conditions than the starting point. It simply reflects that no judgment was made as to whether the barriers presented to a threat by the SWS were greater or less than those presented by the SFS. They were assumed to be equally acceptable, not necessarily equivalent.

The general factors that emerged from this analysis as potential proliferation vulnerabilities, and the bases for comparison against the standards are presented in this report (Chapter 4) in four topical areas, as indicated in Figure 2-5. The first area, *UTILITY*, examines the issues of how usable for nuclear weapons is material that might be removed from within the disposition processes. This primarily includes the processing required to recover plutonium metal and its isotopics. The focus in *INTRINSIC ACCESSIBILITY & OBSERVABILITY* is the application of the intrinsic components of the SFS to the range of end states reflected in the disposition options. The primary issues of *INSTITUTIONAL OBSERVABILITY* are the limitations in the ability to measure and account for material throughout the disposition processes. The issues discussed in *INSTITUTIONAL ACCESSIBILITY* are the factors that reduce confidence in the security posture, increase opportunities for theft or diversion, or present greater security system challenges relative to the SWS.

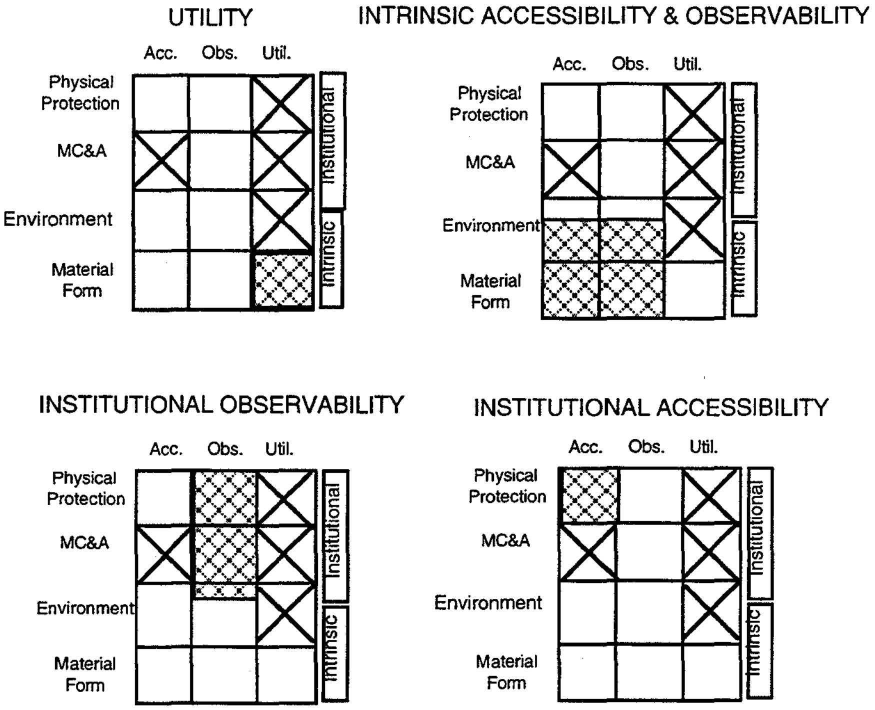


Figure 2-5. Areas of Focus

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[1] "Fissile Material Disposition Program Statement of Threat," paper by the FMDP Safeguards and Security Team, 1995.

[2] "Management and Disposition of Excess Weapons Plutonium," National Academy of Sciences, 1994.

[3] "Technical Summary Report For Surplus Weapons-Usable Plutonium Disposition," DOE Office of Fissile Materials Disposition, 17 July, 1996.

3. ALTERNATIVE DESCRIPTIONS

This section briefly summarizes features of the plutonium disposition alternatives available at the time of the PVRT investigation that are relevant to this report. Because of continuing development of the disposition concepts within the FMDP program, these may not accurately reflect recent modifications and refinements. Except where noted in this report, the PVRT is unaware of changes that would substantively impact the findings presented here. For full and complete descriptions, the reader should consult the most recent Technical Summary Reports of the FMDP.

3.1 COMMON STAGES

3.1.1 Transportation

Multiple transportation segments are common elements to all of the plutonium disposition options. The geographical locations of the facilities at which the intermediate processes for each of disposition options are performed are scattered across the country, and all of them are significantly distant from the sources of the feed materials, namely pits and parts. This diversity of location requires intersite transportation of special nuclear material in various forms and concentrations. **Intersite transport**, also referred to as off-site transport, is defined by the DOE as the movement of materials in "areas outside the boundaries and jurisdiction of a DOE facility to which the general public has free and unlimited access." Some of the options will also involve intrasite transport among processing facilities co-located at a single site. **Intrasite transport** (on-site) is the movement of materials in "any area within the boundaries of a DOE site or facility that is fenced or otherwise access-controlled." Different regulations and security requirements apply to these two transportation environments.

The reason for considering transportation issues is that there are major differences among the disposition options in the numbers of intersite and intrasite transportation segments and the mileage involved. There are also differences in the population densities and urban industrial settings encountered along the routes traveled. The routes are determined by the geographical locations of processing centers that are not yet established and vary widely among the various alternatives. These differences in exposure, and hence to the risk of proliferation, present themselves as proliferation discriminators among the disposition options. Some of the alternatives, for example, require the transport of material on foreign soil during which control of the material is relinquished. Consequently, these alternatives involve more proliferation vulnerability than those in which our control and sovereignty are maintained.

3.1.1.1 Cargo Types

There are six cargo types that were considered when examining the transportation segments of the various options and assessing the potential for proliferation. It should be kept in mind that all of these cargoes contain weapons-useable plutonium, regardless of form or concentration. In order of decreasing attractiveness they are:

1. **Pits and Parts**: This segment is common to all of the disposition options. The fissile material is in the forms of pits, clean metals, impure metals, clean oxides, impure oxides,

alloys, compounds, rich scrap, miscellaneous plutonium-bearing materials, and reactor fuel. These materials are stored at a number of DOE facilities around the country.

- In this segment the surplus plutonium is transported from current locations to a single plutonium conversion facility, the location of which will be determined by the selected option.
- The cargo will be in the most attractive form for diversion or theft during this segment.
- Pits will, by definition, be in classified configuration during this segment, which makes the cargo most attractive and directly useable for weapons.
- These shipments will have very high plutonium concentration per load.

2. **High Quality Oxides:** The material being moved is the plutonium dioxide output of the plutonium conversion facility. Depending on the chosen disposition option and where the conversion facility is located, this segment will be either an intersite or an intrasite transport mode

   - This material is undiluted PuO_2 in powdered form. The plutonium is weapons grade material and is therefore highly attractive for theft or diversion.
   - For the Eurofab option, this segment would include a trans-oceanic leg and transport on foreign soil under custody of a foreign government.
   - These shipments will have very high plutonium quantities per load.

3. **Immobilized Unirradiated Material:** This mode does not apply to the reactor options since all plutonium purification and subsequent blending is confined to the MOX fuel fabrication facility.

   - For the Immobilization option, this segment is an intrasite mode involving the movement of borosilicate glass frit containing 10% plutonium in sealed stainless steel containers.
   - For the Immobilized Borehole option, this segment may be either intersite or intrasite depending on the eventual location of processing facilities. The material transported from the processing facility to the borehole wellhead will be coated ceramic pellets containing 1% Pu as plutonium dioxide.

4. **Fresh (unirradiated) MOX Fuel Assemblies:** This transport case applies only to the reactor options. The MOX fuel is about 4% plutonium as PuO_2 in an unenriched UO_2 matrix. The fuel is shipped only as reactor fuel assemblies.

   - A single BWR fuel assembly is 5.5 in. square by 15 ft. long and weighs 600 lbs. Four assemblies per SST in a single Westinghouse MO-1 shipping container.
   - A single PWR fuel assembly is 8 in. square by 13 ft. long and weighs 1,365 lbs. Two assemblies per SST in a single Westinghouse MO-1 shipping container.
   - A single CANDU fuel assembly is 4 in. diameter by 20 in. long and weighs 55 lbs. 168 assemblies per SST in 24 shipping containers holding seven assemblies each.

5. **Immobilized DHLW Glass/Ceramic in Stainless Steel Canisters ("Logs"):** This mode applies only to the set of immobilized variants in which the PuO_2 is blended or encased in a matrix of borosilicate glass or ceramic material containing defense high level waste (DHLW) or gamma-emitting ^{137}Cs as a previously recovered isotope.

    - The plutonium loading of these logs will be about 5% by weight.
    - The container used in this option is the 2 ft diameter by 10 ft high stainless steel DWPF canister. The loaded weight of this package is 4,400 lbs.
    - The radiation field associated with this package will be in the range of 100 to 1,000 R/hr at 3 ft from the canister for 30 years.
    - Special remote handling gear with high weight capacity will be required to move and manipulate these canisters.
    - The size, weight, and radiation field of these canisters will require the use of a rail car shipping cask to move them from the processing facility to the geological repository.
    - The conceptual design of the rail shipping cask has a capacity of five canisters and a total loaded weight of 192,000 lbs. However, it is anticipated that four of the canisters will contain only DHLW glass; the remaining canister will contain the Pu-glass plus DHLW glass.

6. **Spent Fuel:** This mode applies only to the reactor variants. The shipping from the reactor sites to the repository will occur after many years of residence in the reactor spent fuel pool and subsequent onsite storage in convection cooled dry storage vaults.

    - The spent MOX fuel assemblies become a small part of the much larger commercial spent fuel inventory containing plutonium.
    - The spent fuel assemblies are large, heavy, and highly radioactive.
    - NRC licensed spent fuel shipping casks will be required for this segment.

3.1.1.2 Transportation Modes

SST:
Cargo types 1, 2, 3, and 4 will require shipment by SST. The SST (Safe Secure Trailer) fleet is a transportation system owned and operated by the DOE Transportation Safeguards Division (TSD).

The system consists not only of the armored tractor-trailer fleet, but includes a fleet of special escort vehicles. All vehicles are continuously monitored by a state-of-the-art satellite-based tracking and reporting system based at TSD headquarters in Albuquerque. The position, route adherence, and on-board systems status is displayed and recorded at this command and control center. The couriers operating the trucks and escort vehicles are heavily armed and combat trained federal agents authorized to employ deadly force to protect and maintain control of the cargo.

Sea-going Vessels and Foreign Land Transport:
If the Eurofab MOX option is chosen, cargo types 2 and 4 would be transported by these modes.

Licensed Common Carrier:
Since the type 3 cargo transported in the borehole option from the processing facility to the wellhead is 1% plutonium by weight, transportation by common carrier is an option.

NRC Licensed Shipping Casks:
Cargo types 5 and 6 must be transported by either rail or heavy truck casks because of radioactive shielding requirements and the size and weight of the items to be transported.

3.1.2 Conversion

3.1.2.1 Feed Materials

The surplus plutonium disposition program will receive plutonium as pits from retired nuclear weapons, and in various stabilized forms resulting from the remediation program recommended by the Defense Nuclear Facility Safety Board (Recommendation 94-1).

The following material forms are expected to be declared excess to the national defense needs and available to the plutonium disposition program.

- Pits
- Impure plutonium metal
- Plutonium alloys
- Alloy reactor fuels (unirradiated)
- Oxide reactor fuels (unirradiated)
- Impure oxide
- Uranium/Plutonium oxide
- Oxide-like materials
- Sand, slag and crucibles*
- Halide salts/oxides*

* These materials categories are expected to be converted to impure oxides as part of the DNFSB Recommendation 94-1 Stabilization Program.

The approximate distribution of plutonium from the various feed materials is expected to be 65% from pits and clean metal, 14% from impure oxide, 7% from alloy reactor fuel, 5% from impure metal, 3% from oxide reactor fuel, and 2% each from U/Pu oxide, alloys, and clean plutonium oxide.[1]

In all disposition alternatives the plutonium feed materials will be processed in a Disassembly and Conversion Facility into forms suitable for incorporation into the disposition end-forms. The Facility will process nominally 5MT of plutonium per year. Pits will be disassembled and converted to plutonium metal or oxide in the Advanced Recovery and Integrated Extraction System (ARIES). The remaining plutonium forms will be processed in a Material Conversion facility, consisting of a combination of aqueous and pyrochemical processing steps.

3.1.2.2 ARIES

In the ARIES process, the incoming pits will be assayed for plutonium and bisected into two hemishells, then the various components will be physically separated. Plutonium will be removed from pits in a hydride-oxidation cycle that produces plutonium oxide suitable for MOX fuel preparation or for immobilization in glass or ceramic end-forms. The plutonium oxide powder will be packaged for interim storage in sealed metal containers, and nondestructively assayed for plutonium content. The external surfaces of the containers will be decontaminated in an electrolytic process.

3.1.2.3 Material Conversion

The Disassembly and Conversion facility accepts plutonium in various forms (pits, oxides, scrap, reactor fuel, and plutonium-bearing wastes) and converts them to oxides. Input materials are generally controlled under DOE item-accountable procedures, and the output product (PuO_2 in sealed cans) is similarly under item accountability. During the chemical and mechanical processing stages, work is done in glove boxes; bulk accountability of the material stream is provided. The entire facility is protected by DOE Category-I security measures. It is anticipated that little intra-site transportation of weapons-usable fissile materials will be done.
A variety of chemical and physical steps will be required to convert the plutonium from the various stabilized forms to forms suitable for feed to the disposition alternatives. The detailed nature and sequence of these steps will be determined in future development work.

3.1.3 Mined Geologic Repository

The high-level waste repository described in the Alternative Descriptions as being located somewhere in the western U.S. will undoubtedly be located in a remote, arid region with sufficient geological structural relief to allow a minimum of 200 m of overburden and 200 m of separation between the emplaced waste and the water table. Conceptual design of a high-level waste repository has waste emplaced about 400 m beneath the surface in mined drifts. Repository layout includes a total of approximately 250 km of drifts on two emplacement levels, covering 3 to 4 km^2. Highly radioactive spent nuclear fuel assemblies will be permanently sealed in multi-purpose canisters (designed for safety and ease of handling during interim storage and transportation), inserted into a disposal container then a waste package prior to emplacement in the drifts. Repository design options include backfilling the drifts with crushed rock; after the waste packages are emplaced, the drifts will be sealed. The currently planned disposal operational period is 2010 to 2033; however, in recent Senate testimony (December 1995) Secretary O'Leary said the opening may be delayed until 2015. Lifetime of the facility is indefinite.

Disposal of 50 metric tons of excess plutonium from weapons as MOX spent fuel will require approximately 500 waste packages. But since the MOX fuel would be replacing LEU fuel in reactors, the number of waste packages generated by reactors each year would be the same whether or not reactors are used for plutonium disposition. Disposal of plutonium in the immobilized forms varies from about 600 to 1000 canisters; since the can-in-canister variants displace glass from the HLW canisters, only about 200 addition canisters over what is necessary for the HLW mission will be produced. The HLW repository is designed to accommodate a total of 12,000 waste packages. Of the expected 23 years of HLW Repository operation, emplacement of the excess weapons plutonium is estimated to range from 10 years for the immobilization variants to 17 years for the reactor variants. It is assumed that the plutonium waste packages will be indistinguishable and interspersed with the commercial spent fuel during normal operations. Heat from the waste packages will result in repository temperatures exceeding 100°C for hundreds to thousands of years depending on the packing density of the waste.

The NRC requires that the waste be retrievable for a period of 50 years. Site performance for environmental concerns will be assessed for 100 years, after which the repository will be sealed and have minimal institutional controls and monitoring. The repository is being designed to accommodate IAEA inspections and monitoring, and an offer has already been made to involve the IAEA.

3.2 IMMOBILIZATION ALTERNATIVES

'Immobilization' is proposed to convert plutonium into a 'stable' form meeting the spent fuel standard prior to geologic disposal. This proposal is based on the extensive development of radioactive waste disposal processes developed to assure isolation of radioactive materials from the biosphere. All alternatives isolate the plutonium in a very low solubility matrix and place the material in a canister ≤ 2 ft diameter x 10 ft long weighing less than 5000 lb. The canisters are placed in rail shipping casks intermingled with HLW glass canisters. Although the conceptual shipping cask will hold five canisters, for ease of criticality control in the repository, only one of the five per cask will contain plutonium. The casks are then shipped to a HLW Repository for final disposal.

It is assumed that the feed material for all variants is the product of the conversion processes described earlier that will be sealed in metal containers holding ≈ 4.5 kg PuO_2. These will be subject to item accountability and probably IAEA oversight.

Glass and ceramic forms are being considered for plutonium disposal because of their success as waste forms. Neither form, however, was designed to preclude plutonium recovery by humans.

The Vitrification alternatives are:

Vitrification; Adjunct melter at SRS

Vitrification; "Can"-in-Canister at SRS

Vitrification; Greenfield melter at a new site

The first two are assumed to operate at SRS using the 221-F canyon facility to process PuO_2 into Pu-glass. For the adjunct melter variant the prepared Pu-glass frit is blended with additional frit and ^{137}Cs from the SRS HLW tanks to prepare the final product with a radiation barrier. For the "can-in-canister" variant, cans of vitrified plutonium are loaded into a Defense Waste Processing Facility (DWPF) canister and Defense High Level Waste (DHLW) glass is used to encapsulate the cans inside the DWPF canister; the DHLW provides the radiation barrier. The Greenfield variant is similar to the adjunct in that Pu-glass frit is first prepared, which is then further blended with additional frit and ^{137}Cs from the Hanford $^{137}CsCl$ capsules to prepare the final product with a radiation barrier.

In the "Can-in-Canister" variant 20 "cans" each containing about 2.56 kg plutonium vitrified in about 25.6kg of plutonium glass are inserted and fixed in empty DWPF canisters each 2 ft diameter x 10 ft long. At this point, while still in F canyon, the canisters contain 51.2 kg of plutonium without an radiation barrier. The Can loaded canisters are then transported, on-site, to the DWPF and filled with DHLW glass to provide the radiation barrier. They are then moved to sub-surface storage nearby to await rail transport to a geologic repository somewhere in the west.

In the Adjunct Melter Variant the Pu-glass frit is placed in shipping cans that are transported, on-site, to the adjunct melter's lag storage. These shipping cans contain a glass frit with 10% plutonium without a radiation barrier and accumulate at the output end of 221-F canyon and the input lag storage at the adjunct melter. From there they are withdrawn and the Pu-glass frit melted and blended with ^{137}Cs and addition glass frit and then poured into the canisters. A total of 1660 kg of glass containing 5% plutonium are placed in each canister. The ^{137}Cs provides a radiation barrier.

The third variant Vitrification; Greenfield is similar to the Adjunct melter except for location and the source of ^{137}Cs loaded glass is the Hanford ^{137}CsCl capsules instead of the SRS HLW supernate. The final form is the same 1660 kg of 5% Pu glass in a 2 ft diameter x 10 ft long canister weighing ≈ 2200 Kg.

There are two Immobilization variants using ceramics to tie up the plutonium. A zirconolite-based ceramic is extremely stable in geologic media and is proposed as a matrix to chemically bind the plutonium. The ceramic Greenfield variant takes the impure PuO_2 feed and blends it with ceramic precursors, neutron absorbers, and a ^{137}Cs radiation barrier. Although the final concentration of plutonium in the form is yet to be prescribed, the initial assumptions is that a batch of 33 kg of this material is hot pressed in a metal bellows to produce a dense bellows (12 in. diameter x 4 in high) containing 12% or 4 kg of plutonium. Twenty of these bellows are placed in a stainless steel canister 14 in diameter x 8 ft long. The canister is then filled with rutile. The total amount of plutonium per canister is 80 kg.

The ceramic Can-in Canister variant would use DWPF at SRS to add the radiation barrier similar to the vitrification can-in-canister. The ceramic would be formed via a cold-press-and-sinter technique and loaded into cans. The cans have not yet been designed but could be similar to the vitrification cans or could resemble fuel tubes. The amount of plutonium per canister is assumed to be the same as that in the vitrification can-in-canister, i.e., about 51 Kg. DHLW glass would be poured around the cans to provide the radiation barrier, instead of the ^{137}Cs used in the Greenfield case.

The target level for the radiation barrier is >100R/h at 1 m from the surface of the DWPF canister's centerline at 30 years after fabrication. This can be obtained by adding about 10,800 Curies of ^{137}Cs; the average loading for DWPF canisters is expected to be about 13,000 Curies according to the latest SRS batching memos.

Table 3.2-1 summarizes pertinent data on the immobilization alternatives.

3.3 BOREHOLE ALTERNATIVES

Disposal of surplus weapons-usable plutonium in deep boreholes is intended to effectively isolate the material in a manner that, among other attributes, attains a high degree of proliferation resistance. By emplacing the plutonium at depths of greater than 2 km, the isolation provided by the overburden rock is sufficient to make the plutonium at least as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in spent fuel from commercial nuclear reactors (i.e., the disposal method meets or exceeds the Spent Fuel Standard).

Table 3.2-1. Immobilization Alternatives Process Summary

Immobilization Alternatives Process Summary

Alternative	Pu Feed	1 st stage Immobilization *	Can/Bellows	Containers per Canister	Canister Fill	Canister Contents	Pu Content
Adjunct Melter	PuO_2	10% Pu in Glass			*^{137}Cs*	1680 kg 5% Pu loaded DHLW glass	**84 kg Pu**
Glass Can-in-Canister	PuO_2	10% Pu in Glass	25.6 kg glass/can 2.56 kg Pu/can	20 Cans in Canister	*DHLW glass*	20 Cans suspended in DHLW glass	**51.2 kg Pu**
Glass Greenfield	PuO_2	10% Pu in Glass			*^{137}Cs loaded glass*	1680 kg 5% Pu loaded ^{137}Cs glass	**84 kg Pu**
Ceramic Greenfield	PuO_2	12% Pu in ceramic	33 kg Bellows 4 kg Pu	20 Bellows in Canister	TiO_2 Fill	660 kg ceramic in 20 bellows containing 1 kg Cs (87,000 Ci)	**80 kg Pu**
Ceramic Can-in-Canister	PuO_2	10% Pu in ceramic	2.56 kg Pu/can	20 Cans in Canister	*DHLW glass*	20 Cans suspended in DHLW glass	**84 kg Pu**

*** Gd is mixed with Pu for criticality control in all alternatives. It has no Impact on Proliferation Resistance.**

The location described for the borehole-disposal facility is crystalline rock that is seismically stable with no nearby faults and has a low geothermal gradient. At the emplacement depth of 2 to 4 km there will be few fractures and the minor amount of connate water will be ancient and highly saline. The four holes that comprise the facility will be vertically drilled on a square with 500 m surface separation. Casing will be installed down to a depth of approximately 2 km. In the uncased emplacement zone the holes will be 0.9 m in diameter down to 3 km and 0.7 m in diameter from there to total depth. The linear loading of the emplaced plutonium in the boreholes is 6.0 kg/m, giving a total plutonium content of each borehole of 12.5 tonnes. Above the emplacement zone the hole is filled and sealed with engineered hydraulic barriers, while the surrounding rock serves as a natural barrier to fluid movement.

3.3.1 Variants

This disposal alternative considers two material forms for the emplacement of the weapons-usable fissile materials in the borehole: (1) minimally converted fissile materials – plutonium metal and plutonium oxides ("direct-disposal" variant), and (2) plutonium dioxide "immobilized" in ceramic pellets.

The "direct-disposal" variant requires less processing of surplus weapons materials than any other disposal alternative being considered. The rationale for the immobilized variant is that by incorporating the weapons-usable plutonium in a ceramic matrix at 1% concentration, the possibility of nuclear criticality after emplacement is extremely low, and the utility of the emplaced material is further reduced from that of the direct method.

3.3.2 Process Steps Relevant to PVRT Assessment

3.3.2.1 Aspects Common to Both Variants

The Disassembly and Conversion facility accepts plutonium in various forms (pits, oxides, scrap, reactor fuel, and plutonium-bearing wastes) and converts them to oxides. Input materials are generally controlled under DOE item-accountability procedures, and the output product (PuO_2 in sealed cans) is similarly under item accountability. During the chemical and mechanical processing stages, work is done in glove boxes with bulk accountability of the material stream. The entire facility is protected by DOE Category-I security measures. It is anticipated that there will be little intra-site transportation of weapons-usable fissile materials.

Disposal sites will be characterized by various surface and subsurface investigation techniques to ensure that the sites are tectonically stable, with very slow groundwater flow and transport characteristics. This will ensure that there are no nearby faults, that there are few fractures in the emplacement zone, that the site has a low geothermal gradient at depth, and that the formation fluid is relatively stagnant and saline. The groundwater is expected to be concentrated brines at temperatures of 75° – 150°C. Lithostatic pressures are of the order of 10,000 psi.

Although the emplacement containers used in the direct-disposal variant will soon degrade, the emplacement environment is such that the materials will not speciate or migrate either laterally or vertically. Similarly, the emplacement design of the immobilized variant with the pellet–grout mixture at depth is intended to provide a high resistance to mobilization of the fissile materials. Drilling will be performed with minimal formation damage to enhance interaction with formation water. The upper 2 km of the boreholes are backfilled with grout, and engineered devices have been proposed to impede efforts by anyone to redrill the holes for recovery of the plutonium.

The institutional protective environment can rely to a large extent on remote sensors to detect retrieval attempts by both unauthorized parties or the host nation. The nature of the emplacement environment may permit minimal physical protection of the emplacement site and wellhead. The wellheads at the surface will be sealed, and an exclusion area will be established around the facility. Visual (TV cameras, satellites) and seismic sensors can be employed to provide remote surveillance of the site.

3.3.2.2 Unique to Direct Disposal

At the Disassembly & Conversion facility, plutonium metal, plutonium oxide, and other plutonium-bearing materials are packed into product cans, which are encapsulated in primary containment vessels (PCVs) that are ~0.14 m in diameter and ~0.51 m long; each PCV holds 4.5 kg of fissile material. At the emplacement facility, nine PCVs are placed into a ~0.41 m-diameter, ~6.1 m-long emplacement canister. Twenty-five emplacement canisters are assembled at the emplacement wellhead into a 150-m-long canister string, which is lowered into the borehole. Plutonium product cans are not opened after they are sealed at the Disassembly & Conversion facility. Physical security for the operations at the emplacement facility is all DOE Category-I protection.

At the wellhead, the 150 m canister strings are lowered individually into the borehole and then grouted in place. The grout prevents extensive settling or collapse of the product cans when the supporting canisters degrade due to the emplacement environment; canister corrosion in the brine may result in some minor material movement after a considerable period of time.

3.3.2.3 Unique to Immobilized Disposal

At the Disassembly & Conversion facility, all of the surplus-plutonium feedstock (i.e., pits, metal, scrap, etc.) is converted to oxide. The converted oxide and oxide feedstock is then formed into ceramic pellets by a sintering process. The ceramic pellet matrix consists of calcium–titanium oxides; the plutonium loading is 1%, and 0.7% gadolinium (neutron absorber) is also added. This fabrication step involves bulk handling of the plutonium oxide.

Pellets are packed in shipping containers and transported to the surface processing facility at the Deep Borehole Disposal facility from the Disassembly & Conversion facility. Shipping containers are approximately the size of 55-gal drums, and hold 500 kg of ceramic (representing 5.1 kg of plutonium). Assuming the pellets are not produced at the Deep Borehole site, transport may either be by SST or by licensed commercial carrier. In the latter case the quantity of plutonium must be less than 16 kg per shipment.

The pellets are transferred from the surface processing facility to the emplacement facility by truck. At the emplacement facility, plutonium-loaded pellets are mixed with similar-sized ceramic filler pellets. The resultant average plutonium loading is therefore 0.5%. The ceramic pellet mixture is then metered and mixed at the wellhead with grout in preparation for emplacement in the borehole. This operation involves bulk handling of the plutonium-bearing pellets. At this point there is limited MC&A control of the fissile material.

The pellet–grout mixture is emplaced by one of two batch methods: (1) pumped down a delivery pipe from the surface to the emplacement zone, or (2) lowered to the emplacement zone in a dump bucket. For environmental reasons, effort will be expended to ensure the material stays essentially in place, and that the emplaced material has no voids. The design will incorporate engineered transport barriers such as sealing plugs of "nearly natural" materials installed at strategic locations, and take advantage of the relative insolubility of the ceramic waste form itself.

Although drilling-type rigs and similar equipment is used for the emplacement operation, the activity is not a standard drill-hole grouting procedure. There is no drilling-mud circulating equipment or other processes that could transport the plutonium-bearing pellets to the surface after being inserted into the borehole.

3.4 REACTOR ALTERNATIVES

The reactor options seek to convert weapons plutonium to a form comparable to the much larger and growing inventory of plutonium in civilian spent fuel. Although the end forms of these alternatives are spent fuel, the characteristics across the alternatives do vary.

The scope of the PVRT assessment encompassed four reactor alternatives (comprised of ten variants) as listed in Table 3.B.2-1 of the Reactor Alternative Summary Report[2], which is reproduced in part below as Table 3.4-1. The distinguishing feature between the alternatives was the type of reactor considered; existing light water reactors, partially complete reactors, evolutionary reactors and Canadian Deuterium-Uranium (CANDU) reactors. The distinguishing features of the variants in the alternatives included differences in location of facilities, ownership of facilities, specific reactor, and fuel cycle.

The reactor options listed in Table 3.4-1 are from the FMDP Phase II studies. Our understanding is that the relevant features of the options retained in the Phase III studies are bounded by those of the Phase II options.

A schematic of a generic reactor alternative is shown in Figure 3-1. For a detailed description of each of the reactor variants, see the Reactor Alternative Summary Report.[2] In the figure, the rectangles represent the locations were plutonium resides during the disposition process. The small arrows indicate onsite transfers that are performed behind security barriers and under the protection of the facility security forces. The large arrows indicate offsite transportation of material where the material leaves a secure facility and passes into areas where the public has access.

The baseline existing LWR variant (R2.0) assumed the use of existing, privately-owned, light water reactors in the U.S. to perform the disposition mission. The reactors would have full-core MOX loadings. The plutonium content of the fresh fuel is 3% and of the spent fuel is about 2%. The federally-owned plutonium conversion facility was assumed to be located in the western U.S. and the privately-owned MOX fabrication facility was assumed to be located in the southeastern U.S. Transfers X1, X2, and X3 shown in Figure 3-1 are offsite transfers of unirradiated plutonium-bearing materials and were assumed to be done using SSTs. After irradiation and cooling, the spent fuel is transferred to the federally-owned geologic repository in the western U.S. in a transfer cask carried by rail.

Table 3.4-1. Description of the Reactor Variants

ID Number	Category	Description
R2.0	Existing LWR Base Case	• All Pu feed forms except lean scrap and irradiated fuel. • Separate Pu processing & fuel fab facilities • Federally-owned Pu processing facility in western U.S. • New domestic, privately-owned fuel fab facility located in southeast U.S. • Complete fuel assembly fabrication • No Ga or Am removal • Full MOX core loads • Four privately-owned BWRs located in mid-west U.S.* • Spent fuel to federally-owned geological repository in western U.S.
R2.1	Existing LWR Variant 1	• Same as R2.0 except: • Federally-owned cofunctional Pu processing & fuel fab facilities located in western U.S.
R2.2	Existing LWR Variant 2	• Same as R2.0 except: • Privately-owned European fuel fab facility • PuO_2/MOX fuel lag storage facility
R2A.0	Partially Complete LWR Base Case	• Same as R2.0 except: • Two federally-owned PWRs located in southeast
R3.0	Evolutionary LWR Base Case	• Same as R2.0 except: • Two privately-owned ABB-CE System 80+ reactors
R3.1	Evolutionary LWR Variant 1	• Same as R3.0 except: • Four PDR-600 reactors
R3.2	Evolutionary LWR Variant 2	• Same as R3.0 except: • Federally-owned cofunctional Pu processing & fuel fab facilities located in western U.S. • Federally-owned reactors located in southeast U.S.
R6.0	CANDU Base Case	• Same as R2.0 except: • Two Bruce A CANDU reactors • Spent fuel to Canadian geological repository
R6.1	CANDU Variant 1	• Same as R6.0 except: • Hybrid reference MOX/CANFLEX fuel loading protocol (two reactors with reference MOX for 5 years, then four reactors with CANFLEX for 10 years)

** Four privately-owned BWRs are a surrogate for all existing LWRs (both BWR and PWRs). In general, the throughput of four BWRs is equivalent to two PWRs.*

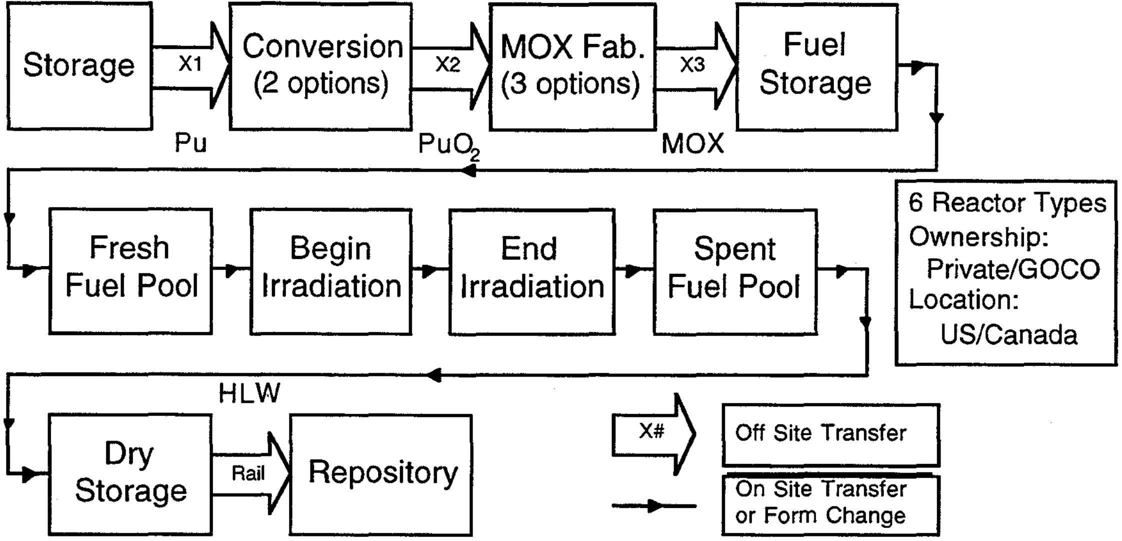

Figure 3-1. Schematic of a Reactor Option

Existing LWR variant 1 (R2.1) is the same as R2.0 except that the plutonium conversion and MOX fabrication functions are located at the same facility. The combined facility is owned by the federal government. This makes transfer X2 of Figure 3-1 an onsite transfer of plutonium dioxide.

Existing LWR variant 2 (R2.2) is the same as R2.0 except that the MOX fabrication is done at an existing, privately-owned facility in Europe. This takes advantage of an existing fabrication capability to allow an earlier start of the disposition process. In this variant, transfers X2 and X3 of Figure 3-1 involve shipboard movements from the U.S. to Europe and back as well as land transport in Europe. Custody of the U.S. weapons-grade plutonium is transferred to a foreign country for the out-bound sea transportation and back to the U.S. on the arrival of the MOX fuel. Secure lag storage facilities on both sides of the Atlantic will be required to support the plutonium transfers.

The baseline partially complete LWR variant (R2A.0) is the same as R2.0 except that the federal government was assumed to purchase two partially complete reactors, finish them, and use them for the disposition mission. The reactors would then be federally owned. The plutonium content of the fresh fuel is 4.5% and of the spent fuel is about 3.5%.

The evolutionary LWR base case (R3.0) is the same as R2.0 except that ABB-CE System 80+ (an improvement of a current design) would be used. The plutonium content of the fresh fuel is 6.8% and of the spent fuel is about 5%.

Evolutionary LWR variant 1 is the same as R3.0 except that Westinghouse PDR-600 reactors are used. The plutonium content of the fresh fuel is 6.6 percent and of the spent fuel is about 5%.

Evolutionary LWR variant 2 is the same as R3.0 except that the reactors are federally-owned and the plutonium conversion and MOX fabrication facilities were located at the same site. Transfer X2 of Figure 3-1, as in R2.1, is an onsite transfer.

The CANDU base case (R6.0) is the same as R2.0 except that privately-owned CANDU reactors are used and the spent fuel remains in Canada to be placed in the Canadian geologic repository. Transfer X3 of Figure 3-1 involves the crossing of the border between the U.S. and Canada. The custody of the U.S. weapons plutonium transfers to Canada at that point. The plutonium content of the fresh fuel is 1.5% and of the spent fuel is about 0.8%.

CANDU variant 1 (R6.1) is the same as R6.0 except that most of the disposition mission is done using an advanced fuel in the reactors with higher plutonium loading. The plutonium content of the fresh fuel is 2.7% and of the spent fuel is about 1.4%.

3.5 LONG-TERM STORAGE

Whether storage is considered as an intermediate step between dismantlement and disposition or as an alternative to disposition, plutonium and HEU will have to be stored for tens of years. The four primary long-term storage alternatives for fissile materials are: (1) upgrade or replacement of current plutonium or HEU storage facilities at multiple DOE sites, (2) consolidation of plutonium at a single DOE site, (3) collocation of plutonium and HEU at a single DOE site, and (4) no action, i.e., continued storage of fissile materials at existing sites in existing storage configurations. The six candidate storage sites are: the Hanford Site, the Idaho National Engineering Laboratory (INEL), the Nevada Test Site (NTS), the Oak Ridge Reservation (ORR), the Pantex Plant, and the Savannah River Site (SRS). The Safeguards and Security systems must address the needs and requirements as defined by DOE Orders and design basis threat guidance regardless of whether new facilities are built or existing facilities are modified. New storage facility designs are being driven by a desire to provide at least the present level of Safeguards and Security while reducing total life-cycle costs and reducing personnel radiation exposures through technology/manpower trade-offs.

To accommodate the pits from continued weapon dismantlement, DOE and the operators of Pantex have developed plans to increase the storage capacity at Pantex by using igloos not previously used for pit storage and by modifying the stacking arrangements within the igloos. DOE has also contracted with an architect/engineer to develop a Reference Site Conceptual Design for a Consolidated Special Nuclear Material Storage Plant (CSNMSP). This grew out of a Preconceptual Design for the Complex-21 Plutonium Storage Plant completed in July of 1993. The CSNMSP will provide for safe, secure, long-term (up to 50 years) storage of the inventory of surplus and strategic reserve plutonium at a single DOE site.

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[1] Mark C. Bronson, "Front End Processing for Immobilization," LLNL, April 24-25, 1996. Immobilization Program Peer Review.

[2] S. R. Greene, et al., Reactor Alternative Summary Report Rev. 3, ORNL/MD/LTR-43, Oak Ridge National Laboratory, Oak Ridge, TN, January 12, 1996.

4. GENERAL PROLIFERATION VULNERABILITY FACTOR ASSESSMENTS

In this section we summarize potential proliferation vulnerability issues in four topical areas: (1) Utility; (2) Intrinsic accessibility and observability; (3) Institutional observability; (4) Institutional accessibility.

4.1 UTILITY

Utility is the proliferation resistance barrier that makes it difficult to recover weapons-usable plutonium from material that is successfully removed from within a disposition process. The utility of a plutonium-bearing material may be measured by the resources (manpower, equipment, and technology) and time required to recover a significant quantity of weapons-usable plutonium. An analysis was made of the utility of plutonium forms that might be stolen or diverted from disposition processes and converted to nuclear explosive devices. The analysis consisted of two parts:

(1) An assessment of the resources and time required to recover one significant quantity (1 SQ = 8 kg) of plutonium metal from the various plutonium-bearing forms in the disposition program, including the plutonium feed materials, forms in the conversion and intermediate processing steps, and the end forms proposed for disposition.

(2) A review of the usefulness of "reactor-grade" plutonium in nuclear weapons.

4.1.1 Plutonium Recovery from Forms in Alternative Disposition Processes

4.1.1.1 Summary

The PVRT assessed the feasibility and difficulty of recovering plutonium from plutonium-bearing forms in the disposition program, including the plutonium feed materials, the forms in the conversion and intermediate processing steps, and the end forms proposed for disposition. The following discussion of the relative resistance to plutonium recovery of the various feed, intermediate and end-forms evaluates the scenario involving a subnational or terrorist group attempting to quickly recover sufficient plutonium to fabricate one or two weapons. The study evaluates the resources required to recover a significant quantity (SQ) as defined by the IAEA. The study estimated the time and manpower to recover plutonium metal, not to fabricate complete nuclear weapons. The resources required to fabricate weapons would be the same in all cases studied, and would probably add days, not weeks, to the estimates.

The team concluded that plutonium in weapons-useful quantities could be recovered from any of the forms in the disposition program. Furthermore, the resources required for the recovery of a significant quantity of plutonium, including the manpower, materials, equipment, and time, would be relatively modest.

Most of the technology required for the recovery process is available in the unclassified, technical literature. An exception is the lack of technology for the dissolution of plutonium immobilized in ceramic forms, such as SYNROC. Although methods have not been developed for these steps, it was judged by the team that either aqueous or non-aqueous recovery techniques could be developed for plutonium ceramic forms with relatively modest effort. Based upon the known chemistry of Ti and Zr oxides and other compounds, it is likely that these techniques will be more difficult than the dissolution of heavy metal from spent nuclear fuels.

The two major discriminators in ranking the relative difficulty of recovering plutonium metal from the various intermediate and end-forms are the presence of a radiation barrier and the complexity of the mechanical and chemical processing steps, especially in the front end of the recovery process. The radiation barrier complicates the recovery by requiring shielding and remote operations. The dose rates were found to be high enough to be life threatening over the course of the recovery operation if shielding were not provided. The complexity and difficulty of the mechanical and chemical processing steps varies with the different plutonium forms, especially the steps in the front end of the recovery process, including disassembly, cutting, shearing, pulverizing, and grinding of the end forms, and the dissolution or leaching of plutonium from the forms.

4.1.1.2 Plutonium Forms

All of the disposition alternatives would receive the following plutonium material forms that are expected to be declared excess to the national defense needs:

4.1.1.2.1 Feed Materials

- Pits
- Pu metal
- Pu alloys
- Pu alloy reactor fuels (unirradiated)
- Halide salts/oxides
- Pu oxide
- U/Pu oxide
- Sand, slag and crucibles (SS&C)
- Pu oxide reactor fuels (unirradiated)

4.1.1.2.2 Intermediate Forms

In the proposed disposition alternatives, the feed would be processed to various intermediate forms. Some of the more attractive targets for theft would be the following intermediate forms:

- PuO_2 Powder. Most feed would be processed to PuO_2 powder and stored in ≈ 4.5 kg quantities in sealed metal containers awaiting processing to end forms.
- "Cans" with 25.6 kg glass containing 10% Pu for the Vitrification Can-in Canister alternative
- Canisters containing 20 of the "cans" mentioned above. In the Vitrification Can-in Canister alternative 20 of the "cans" will be located in empty canisters (2 ft dia x 10 ft long) and stored prior to filling with DHLW glass.
- "Cans" with 25.6 kg ceramic containing 10% plutonium for the Ceramic Can-in-Canister alternative.
- Fresh MOX fuel pins containing 2 to 7% plutonium. In the reactor alternatives, fuel pins containing mixed oxide pellets with 2 to 7% plutonium would be produced, stored and transported.

After conversion and processing, the following plutonium end-forms would be produced:

4.1.1.2.3 End Forms

- Pu in glass containing Gd and ^{137}Cs from HLW tanks (Vitrification Adjunct Melter)
- Pu in glass containing Gd and ^{137}Cs(Vitrification Greenfield)
- Pu in ceramic containing Gd and ^{137}Cs (Ceramic Greenfield)
- Pu-glass in can containing Gd (Vitrification Can-in-Canister)
- Pu-ceramic in can containing Gd (Ceramic Can-in-Canister)
- Pu in ceramic pellets containing Gd (Immobilized Borehole)
- Pu in spent MOX fuel (Reactor Alternatives)

The assessment considered the time and effort required to recover 1 SQ of plutonium from each of these materials, in comparison with the effort required to recover 1 SQ from spent LWR fuel.

4.1.1.3 Recovery Process for LWR or MOX Spent Fuel

A simplified flow diagram for a process to recover plutonium from LWR or MOX spent fuel is shown in Figure 4-1. The process steps were chosen from a number of alternatives that are reported in the technical literature,[1,2] they represent a relatively simple process that might be operated by an adversarial group in makeshift or temporary facilities such as a remotely located warehouse or a small industrial plant.

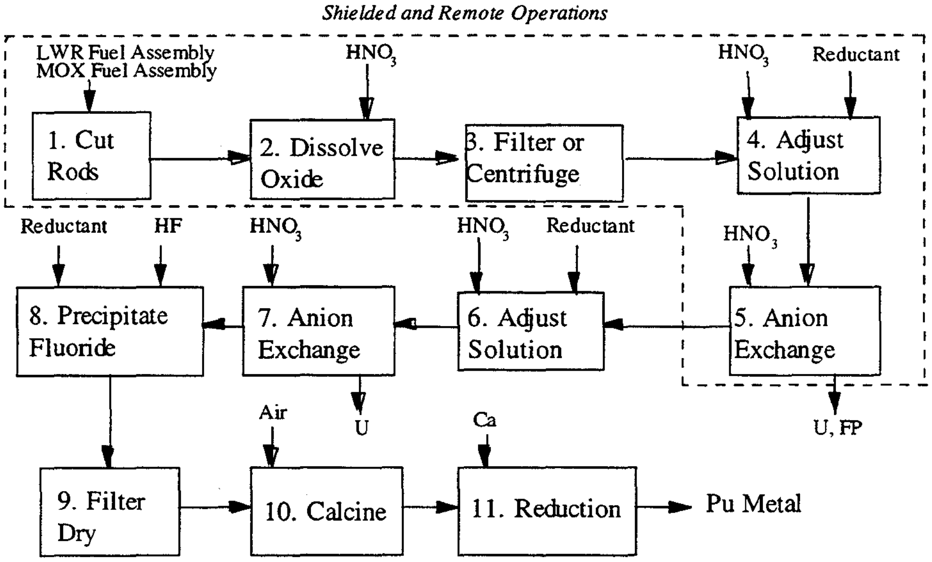

Figure 4-1. A Process for Recovering Plutonium from Spent Fuel

4.1.1.4 Adaptation of Recovery Process to Other Forms

The plutonium in all of the intermediate and end-forms can be recovered by some adaptation of the reference process shown in Figure 4-1. The main variations are (1) the treatment of the material (Step 1) to prepare it for dissolution, and (2) the need for shielding and remote operations.

Because technology for the recovery of plutonium from SYNROC forms has not been developed and demonstrated, the PVRT attributed a somewhat higher proliferation resistance to the ceramic form with a radiation barrier (Ceramic Greenfield) than to spent LWR fuel. However, as knowledge of the possible use of ceramic forms for plutonium disposition becomes more widespread, technical means for plutonium recovery will undoubtedly be developed. Based upon the known chemistry of titanium and zirconium compounds, it is likely that the recovery of plutonium from SYNROC will be more difficult than the recovery from spent fuel. However, this advantage in proliferation resistance may be temporary and must be balanced against other factors in choosing the disposition end form.

4.1.1.5 Resource Requirements

Shielding required for processing plutonium forms containing DHLW or ^{137}Cs could be provided by a water-filled pool or by shadow-shields of concrete, steel or lead. Remote manipulation could be done with long-handled tools; and pumps and electrically activated valves could be operated remotely. Cutting of spent fuel or steel canisters could be done with explosives, power hacksaws or abrasive disks. Containment for the process equipment could be provided by painted plywood boxes with windows of transparent plastic with gloves attached. A crude off-gas treatment system would use fans to ventilate the boxes, discharging the air to limestone and sand-filled drums or pits to conceal volatile fission products and actinide particulates that might provide an external detectable signal to surveillance/retrieval forces. The process equipment would be designed to prevent accidental criticality, using a combination of geometric and concentration control. Radioactive waste could be stored in drums or underground in cribs.

The equipment and materials required for the processing are not unique or unusual, and could be acquired from conventional industrial supply sources.

The PVRT estimated the numbers of personnel and the types of skills that would be required to successfully carry out a clandestine recovery operation. These are summarized in Figure 4-2. For the forms with a radiation barrier, it was judged that six skilled people could complete the operation. For the forms without a radiation barrier, only about four people would be required. An appropriate mix of skills would be required. It is likely that experienced people could be obtained from nuclear weapons states or from states with nuclear power plants, or from disgruntled employees in this country.

The team estimated the length of time that would be required to prepare and test a processing facility, and the time after acquiring the plutonium material to produce 1 SQ of plutonium metal. The preparation lead-time varied from six months for a facility requiring shielding and remote operations to about three months for a facility requiring only containment. The time to produce 1 SQ varied from eight weeks for materials with a radiation barrier to four weeks for plutonium oxide that required purification, and less than one week for pure plutonium oxide that could be directly reduced to plutonium metal. The PVRT recognized that there are considerable uncertainties in attempting to estimate teams that would be required to produce 1SQ of plutonium metal from the various forms. The time would depend strongly on the skill and knowledge of the operators, the complexity of the process chosen, the reliability of the equipment, and the time spent in preparation and testing. The largest uncertainty relates to the immobilized forms with radiation barriers, especially the ceramic forms, since there is no experience in recovering plutonium from these forms, and assumptions about the process must be made based on the general chemical literature.

4.1.1.6 Effect of plutonium Dilution on Utility

The plutonium dilution among the proposed disposition end-forms ranges from a low of 0.5 wt% plutonium in the Immobilized Borehole to a high of 12% in the Ceramic Greenfield and Ceramic Can-in-Canister alternatives. By comparison, normal spent fuel (from using LEU for BWRs and PWRs or natural uranium for CANDUs) may range from 0.4 to 1 wt% plutonium and spent MOX fuel may range from 0.8 to 5.1 wt% plutonium, depending upon the type of reactor (Table 5.3-1). Recovery of plutonium from disposition end-forms or spent fuel would not be seriously complicated by the lower concentrations (0.4 wt%) of plutonium. Although there would be some penalties in resources and time required for recovery of plutonium from the more dilute forms, recovery would still be feasible if adequate preparations were made.

4.1.1.7 Evaluation of Difficulty of Plutonium Recovery from plutonium Forms

Figure 4-2 lists the various feed, intermediate, and end forms in the proposed disposition program, and a number of metrics used to evaluate and rank the difficulty of plutonium recovery. The team made judgments about the subjective metrics, such as the complexity and difficulty of process steps, the numbers of personnel, and the times required. The plutonium forms are listed in roughly descending order of the difficulty of plutonium recovery, with the ceramic end form of the Ceramic Greenfield alternative listed at the top, more difficult than spent LWR fuel, because of the uncertainties in the dissolving behavior discussed previously. At the bottom of the list, representing forms easiest to recover, are oxides with no radiation barrier, and plutonium metal, which requires no purification.

The largest discriminators in determining the ranking of plutonium recovery difficulty were the presence of a radiation barrier, and the complexity of the mechanical and chemical processing steps, especially in the front end of the recovery process.

4.1.2 Utility of Reactor Grade Plutonium in Nuclear Explosive Devices

The single summary statement about the utility of plutonium from the disposition program and its potential for use in nuclear explosive devices is:

> “All plutonium is good plutonium; some is better than other”

There are no high Pu-238 content materials, heat source grade plutonium, in the weapons materials disposition program. The weapons grade materials, and materials with isotopic compositions not much different from weapons grade, are clearly directly weapons-usable once processed into the right chemical and physical forms.

The remaining question involves “reactor grade” plutonium. The isotopic compositions of these materials can range from 8 to 10% Pu-240 up to >40% Pu-240, 241, etc.

The Department of Energy has issued a press release[3] acknowledging that the United States has successfully tested a nuclear device using reactor grade plutonium, and that the device produced

	Pu Concentration	Number of Steps	Complexity of Steps	Process Efficiency	Shielding/Remote OPS	Published Technology	No. & Skills of Personnel	Lead Time to Prepare	Time for 1 SQ
Pu in ceramic with ^{137}Cs	12[a]	10[b]	H[c]	50-75	Y	80[d]	6[e]	6 mo	8 wk
Spent LWR fuel	**0.6**	**11**	**H**	**80**	**Y**	**100**	**6**	**6**	**8**
Spent MOX fuel	2	11	H	80	Y	100	6	6	8
Pu in glass with HLW	5	9	H	80	Y	90	6	6	8
Pu in glaswith ^{137}Cs	5	9	H	80	Y	90	6	6	8
Pu ceramic, Gd	12	10	M	50-75	N	80	4	3	6
Pu ceramic, Gd	0.5-1	10	M	50-75	N	80	4	3	6
Pu glass, Gd	10	9	M	80	N	90	4	3	6
Pu alloy	≈50	9	M	80	N	90	4	3	6
Pu alloy reactor or fuel	~30	9	M	80	N	90	4	3	6
Pu oxide reactor or fuel	13-27	9	M	80	N	90	4	3	6
PuO_2/UO_2/Zr rods	3	9	M	80	N	90	4	3	6
Halide salts/oxides		10	M	80	N	90	4	3	6
SS & C	<5	9	M	50-80	N	90	4	3	6
U/Pu Oxide		9	L	90	N	90	4	3	6
PuO_2/UO_2 powder	3	9	L	90	N	90	4	3	6
PuO_2/UO_2 pellets	3	9	L	90	N	90	4	3	6
PuO_2 (Impure)	50-85	7	L	90	N	90	4	3	4
PuO_2 (Pure)	88	2	L	90	N	100	2	1	<1
Pu Metal	100	0	na	100	N	100	1	0	0

KEY:

a. Weight % of Pu in form.
b. Assumes fusion step required. One cycle of anion.
c. Complexity is ranked H,M,L relative to spent LWR fuel.
d. Approx. % published technology.
e. Including one BSCh or ChE, one ME, one EE, or equiv.

Figure 4-2. Evaluation of Difficulty of Plutonium Metal Recovery from Plutonium Forms a yield of less than 20 kilotons. At the time of the test, the definition of reactor grade plutonium was "greater than 7% plutonium 240." To quote from the press release:

- "This test was conducted to obtain nuclear design information concerning the feasibility of using reactor grade plutonium as the nuclear explosive material."
- "The test confirmed that reactor grade plutonium could be used to make a nuclear explosive. This fact was declassified in July 1977."

In response to a question of why WPu is better than RPu, the release states: "Reactor-grade plutonium is significantly more radioactive, which complicates its use in nuclear weapons."

The two principal complications arising from plutonium isotopes other than Pu-239 are the spontaneous fission background (Pu-240), and the decay heat from the more radioactive isotopes (Pu-238, Pu-240 and Pu-241).[4]

These two weapon design issues affect utility depending on the scenario under consideration: host nation reuse (breakout), or non-nuclear-weapon state or sub-national use in a nuclear explosive. In this context, the host nation is already a nuclear weapon state (U.S. or Russia), and reuse and breakout means reconstitution of a strategic *weapons* stockpile, not fabrication of a few devices for regional power politics or threatening adversaries. For non-nuclear-weapons states, proliferation could reasonably be taken to be initial fabrication of a few devices, the first step toward development of a few to a few tens of militarily useful weapons. For a sub-national group, a reasonable goal might be possession of a few to a dozen devices that can be *transported* clandestinely to the target.

Therefore, the physics design issues could have greatly different impacts, depending on the "proliferant" and their desired goals. We assume that the weapon states already understand the impacts and difficulties of using reactor grade plutonium in nuclear devices. The U.S. has chosen not to use reactor grade plutonium for its stockpile so as to make designs more predictable, reduce intrinsic radiation, etc. That is, weapons grade plutonium would be the preferable alternative for stockpile development, even in a breakout scenario. But if necessary, breakout could begin with reactor grade plutonium.

For a non-nuclear-weapon state, a likely starting point might be a relatively simple, unsophisticated fission device. Since it would seem natural for a state to conduct a development program, the first device is not the end point of the program, but would give the state a nuclear capability, even if crude by U.S. or military standards. A significant point is that a simple fission design would not require testing to *prove* that it would work. The only debate would be about the yield. As the development program advances, there would be increased sophistication of the device, transition to a militarily useful weapon, and higher assurances of achieving design yield, even with reactor grade plutonium.

For a sub-national group, the political goals to be achieved through the possession of a nuclear explosive device include terrorism and intimidation, and not a traditional military capability. In a way, the starting point for a non-nuclear-weapon state could be considered to be the end point for a sub-national group, a simple, unsophisticated nuclear explosive device based in large part on information publicly available and on the expertise of a few competent scientists and engineers.

In summary, all plutonium that could be stolen or recovered from any of the various segments of the disposition program are readily weapons usable and could be used under any of the scenarios discussed for nuclear weapons or nuclear explosive device fabrication. Again, all plutonium is good plutonium, with some better (and posing fewer technical difficulties) than other plutonium.

4.1.3 Utility Conclusions

Plutonium in weapons-useful quantities can be recovered from any of the forms in the disposition program.
Most of the technology required for the recovery process is available in the unclassified, technical literature. An exception is the lack of technology for the dissolution of plutonium immobilized in ceramic forms, such as SYNROC. Although methods have not been published for these steps, it was judged by the team that either aqueous or non-aqueous recovery techniques could be developed for plutonium ceramic forms with relatively modest effort. Weapons grade plutonium is preferable for the development and fabrication of both nuclear weapons and nuclear explosive devices for terrorist/subnational groups, non-nuclear weapons states, and host nation rearmament. However, reactor grade material can also be used in any of these scenarios. Thus, weapons-usable plutonium can be recovered from any of the forms in the disposition program.

The resources required for the recovery of a significant quantity of plutonium would be relatively modest.
The two major discriminators in ranking the relative difficulty of recovering plutonium metal from the various intermediate and end-forms are the presence of a radiation barrier and the complexity of the mechanical and chemical processing steps, especially in the front end of the recovery process. The radiation barrier complicates the recovery by requiring shielding and remote operations. Chemical processing requires knowledge of plutonium processing technology, the accumulation and testing of a considerable amount of processing equipment, and the successful operation of that equipment for a number of weeks during plutonium processing.

For the forms with a radiation barrier, six skilled people could complete the operation. For the forms without a radiation barrier, only about four people would be required. The preparation lead-time varied from six months for a facility requiring shielding and remote operations to about three months for a facility requiring only containment. The time to produce 1 SQ varied from 8 weeks for materials with a radiation barrier to four weeks for plutonium oxide that required purification, and less than one week for pure plutonium oxide that could be directly reduced to plutonium metal. Thus, although chemical processing and a radiation field are discriminators, they are not sufficient barriers to prevent recovery should sufficient material be removed from within a disposition process.

Plutonium dilution is not a significant utility barrier.
Dilution complicates the recovery by requiring larger batches or more batches of material to recover a bomb's worth of plutonium, but with adequate planning and equipment, recovery would still be feasible.

4.2 INTRINSIC ACCESSIBILITY AND OBSERVABILITY

The Spent Fuel Standard is generally assumed to imply a significant contribution to proliferation resistance from intrinsic properties. All of the plutonium disposition options produce material in states that reduce reliance upon institutional measures and increase resistance to proliferation and diversion through intrinsic properties. The Intrinsic Accessibility & Observability components are provided by intrinsic properties of the material form and/or environment, which make access and removal of plutonium-bearing material difficult, and increase the difficulty of escaping with the material undetected. These are the most important intrinsic components of proliferation resistance since, as discussed in the previous section, if enough plutonium-bearing material is successfully acquired from within any disposition process, weapons-usable plutonium can be recovered with relatively modest resources.

This section examines the Intrinsic Accessibility and Observability components of proliferation resistance implied by the SFS. The intrinsic proliferation resistance of commercial spent fuel is provided primarily by properties of its material form, as well as by its storage environment. This section examines the implications of these properties in order to roughly compare the proliferation resistance from intrinsic features of the disposition end states - material form and environment - to the SFS for both unauthorized parties and host diversion. Comparisons to the SFS of disposition stages prior to end states in which significant intrinsic barriers exist are trivial - the PVRT generally assumed that the Accessibility and Observability barriers of proliferation resistance in these stages will be dominated by institutional measures. It's important to remind the reader that these discussions do not represent detailed vulnerability assessments of the full security systems provided for spent fuel or the other end-forms. Their purpose is to provide a rough characterization of the contributions to proliferation resistance provided by these intrinsic features in order to identify areas of potential shortfalls from the standards, i.e., proliferation vulnerabilities.

The idea behind the Spent Fuel Standard is to put the excess weapons plutonium in a form that is roughly as resistant to proliferation and diversion as the large and growing stock of plutonium in civilian spent nuclear fuel. Civilian reactors have been in operation for several decades. As a result, there is spent fuel that has been cooling for several decades and therefore has a much lower radiation field associated with more recently irradiated fuel. The PVRT chose to use LEU spent fuel that has been loaded into dry storage casks and stored at the originating reactor site, which was assumed to occur ten years after irradiation, to characterize the proliferation resistance of commercial spent fuel. This is consistent with the objectives behind the SFS, and allows the FMDP material to "hide behind" the majority of the stock of spent civilian fuel rather than just a fraction of it. This is a time in the life of spent fuel where the institutional barriers appear to be considerably lower and the intrinsic barriers provide the largest fraction of the proliferation resistance. It's very important to note that at no time are institutional barriers completely removed from spent fuel, although they are relaxed as the intrinsic barriers increase.

In the sections that follow, three intrinsic material form characteristics that provide proliferation or diversion resistance of spent nuclear are discussed. They are the radiation field, the plutonium concentration, and the physical size and mass of the fuel assemblies. Following that, the environmental contributions to proliferation resistance provided by spent fuel dry storage cask and by an underground repository are discussed. This allows judgments to be made of whether the intrinsic proliferation resistance provided by the various end states resulting from the disposition options falls short of or exceeds the levels roughly implied by the SFS.

4.2.1 Material Form

The proliferation resistance of spent fuel is commonly attributed to its radiation field, plutonium concentration, and physical size and mass of spent fuel assemblies. Each of these factors is considered below.

4.2.1.1 Radiation Field

The magnitude of the radiation field near a spent commercial fuel assembly depends on a number of factors, including design of the assembly, the burnup of the fuel in the assembly, and the decay time since irradiation. Three assembly designs will be considered: PWR, BWR, and CANDU. For our purposes, the decay time will be fixed at 10 years post irradiation. At later times up to about 100 years, the strength of the radiation field follows the decay of ^{137}Cs on a half-life of 30.17 years. Radiation dose rates from the three different types of fuel assemblies were calculated. The results are comparable to those obtained elsewhere and show that the radiation barrier for commercial spent fuel in the U.S. (BWR or PWR fuel) provides a dose rate of many hundreds to ~1000 rem/hr at 1 m from the surface. The effects of human exposure to these dose rate examined next.

4.2.1.1.1 Radiation Effects

The effects of acute doses of radiation on human beings are described in *Sources, Effects and Risks of Ionizing Radiation*[5] and *The Effects of Nuclear Weapons.*[6] The effects of an acute radiation exposure can be divided into three phases. During the initial phase, the symptoms of radiation sickness appear, including nausea, vomiting, and a general malaise. A latent phase follows in which the symptoms largely disappear and it is possible for the exposed individual to perform useful tasks. The final phase follows in which the symptoms of radiation sickness recur and may include skin hemorrhages, diarrhea, and hair loss. The final phase persists through the recovery or death of the individual.

The time to onset and duration of the phases and the severity of the symptoms depends on the dose received and vary from individual to individual. It is important to note that there is a delay between the delivery of an acute dose of radiation and the first appearance of the symptoms of radiation sickness. The delay depends on the total dose received and the two references cited above are not in total agreement on the delay at a given dose. For example, for a dose of 300 rem (a dose that is rarely fatal), the delay may be several hours between the delivery of the dose and the onset of symptoms. For a dose of 1000 rem (a dose that is usually fatal), the delay is on the order of 30 minutes and could be longer.

Table 4.2-1, extracted from reference *Sources, Effects and Risks of Ionizing Radiation,* gives a summary of the effects of acute radiation doses on human beings. The doses listed in the table are whole-body doses. The dose to the extremities (e.g., hands) can be considerably higher than the whole-body dose without causing equivalent harm.

The prognosis for an individual receiving an acute dose of radiation depends on the individual, the level of dose, and the level of care given after the dose is received. The following discussion pertains to otherwise healthy individuals that receive a radiation injury. Preexisting conditions or injuries received concurrently with the radiation injury can exacerbate the radiation-induced damage. For doses in the range of 25 to 100 rem, significant changes in the blood can occur but few, if any, outward signs of radiation injury are apparent. For doses in the range of 100 to

Table 4.2-1. Effects of Acute Ionizing Radiation Doses

		Dose Range (rem)				
		100-200	200-500	500-1000	1000-5000	> 5000
Initial	Incidence	0 - 50%	50 - 90%	100%	100%	100%
Symptoms	Latency	> 3 hr	1 - 2 hr	0.5 - 1 hr	0.5 hr	minutes
Critical period		2 - 6 wk	2 - 6 wk	2 - 6 wk	3 - 14 d	1 - 48 hr
Incidence of death		0 - 10%	0 - 90%	0 - 90%	90 -100%	100%
Death occurs in		months	weeks	weeks	2 weeks	1 - 48 hr
Leading system		Blood-forming			Gastro-intestinal	Nervous

200 rem, the symptoms of radiation sickness are mild and do not occur until several hours after the exposure. Doses of this magnitude rarely result in death. For doses in the range of 200 to 600 rem, the symptoms of radiation sickness are pronounced but occur after a significant, dose-dependent delay. If the victim can be hospitalized, there is reasonable confidence that treatment can be effective in preventing death. For doses in the range of 600 to 1000 rem, even with hospitalization, there is considerable variability in the response and thus uncertainty in the outcome. For doses above 1000 rem, survival is unlikely. Treatment for doses of this magnitude is given largely to reduce the symptoms as they progress.

4.2.1.1.2 Accessibility Barrier Provided by Radiation Field

A radiation field does not impede the ability of a host nation to retrieve material, since they have continuous, long-term access to the material and readily available equipment designed for that purpose. The PVRT considered a radiation field to be a significant accessibility barrier to unauthorized parties if the field is high enough to force a thief to shield the object during a theft. The shielding material, being heavy and cumbersome, and/or remote handling would force the thief to use lifting equipment during the theft and to haul away a significantly larger mass than just the stolen object. For this to be the case, the radiation dose absorbed by a thief during the theft must be sufficient to either a) incapacitate the thief during the theft for those for whom long-term survival is not important or, b) guarantee the eventual demise of the thief if the thief is one for whom survival is important. In the latter case, the total dose required would be above 600 rem, probably nearer to 1000 rem. In the first case, the dose required depends on the dose rate. Incapacitation can occur either from the onset of the symptoms of radiation sickness or from the immediate disruption of the nervous system that results with acute doses of about 5000 rem or greater. Which of these occurs first depends on the dose rate. For very high dose rates where a 5000 rem dose can be delivered in minutes (many tens of thousands of rem per hour and above), the disruption of the central nervous system will occur. For lower dose rates, on the order of 1000 rem/hr and protracted exposure times, the symptoms of radiation sickness will occur long before a 5000 rem dose is delivered.

The dose taken by a thief is the time integral of the dose rate at the midline of the thief. For a 1,000 rem/hr field (roughly the field 1 m from a commercial spent fuel assembly), the thief receives 100 rem every 6 minutes. A successful overt theft is estimated to take only ten or twenty minutes so even if the thief is exposed to the full field during a twenty minute theft, the dose accumulated will be about 300 rem. Such a dose, while it will eventually cause the symptoms of radiation sickness to appear, is unlikely to produce any symptoms during the course of the theft and is unlikely to result in death. Activities during a theft that may require the presence of the thief in the field are attachment of lifting lines, placement of cutting charges, and so on. At times, the thief may be required to place his hands on the assembly (where dose rates can be much higher than at 1 m) but the extremities are much less dose sensitive than the midline of the body. However, none of these activities will require the thief to be in the field for the full course of the theft so the midline dose taken could be considerably lower than 300 rem. During an overt theft, when reaction forces are presumably engaged, the radiation barrier may not be the largest hazard to the thief. Because a theft can be accomplished without shielding, a radiation barrier of 1000 rem/hr was considered not to be a significant accessibility barrier to an adversary with sufficient dedication.

It is useful to note the dose rates at which the radiation field was considered to be significant accessibility barrier to even the most dedicated thieves, as well as those that would not be considered an accessibility barrier for far less dedicated individuals (e.g., those unwilling to accept doses of several hundred rem) than those dealt with above. In order to force even the most dedicated thieves to shield the object during the theft, unshielded dose rates must be such that a dose of at least 1000 rem is delivered in the time frame of the theft. A dose rate of 10,000 rem/hr will produce a dose of 1000 rem in six minutes. Such a dose rate would quickly produce incapacitating effects, thereby impeding access for even for the most highly motivated individuals. If the thief is willing to accept a dose of 100 rem, the level at which no outward signs of radiation sickness occur, the dose rate required during a 20 minute theft is 300 rem/hr.

The foregoing discussion has divided the spectrum of dose rates into three regions. The divisions between them are not distinct. Dose rates up to perhaps a few hundred rem per hour, will not pose an accessibility barrier for any thief willing to expose himself to some element of danger. Dose rates in the range of a few hundred to several thousand rem per hour may not pose an accessibility barrier to those willing to take a dose of several hundred rem to accomplish the theft. Dose rates of many thousands of rem per hour and above deliver lethal doses that will incapacitate during a theft and pose a significant accessibility barrier to all, thereby forcing shielding and remote handling during the theft and requiring the use of heavy, cumbersome equipment.

4.2.1.2 Plutonium Dilution

As commercial nuclear fuel burns, plutonium is produced by neutron capture in ^{238}U. The plutonium content of the fuel increases with burnup. Figure 4-3 shows the plutonium content, in percent of the heavy metal present in the fuel, as a function of burnup for PWR and BWR fuel. In the overlapping region, the plutonium content is nearly the same for the two different reactor types as a function of burnup. The plutonium content of the PWR fuel reaches 1 percent at a burnup of about 40 MWD/kg U. The plutonium content of spent CANDU fuel is lower than that of PWR and BWR fuel because of its lower burnup, about 0.5 percent of the heavy metal.

4.2.1.2.1 Accessibility Barrier Provided by Plutonium Dilution

The low concentration of plutonium in spent nuclear fuel simply makes the mass of fuel material that must be removed during a theft large. The minimum mass of material that must be stolen to obtain 8 kg of plutonium from PWR or BWR fuel is over 1,100 kg, assuming that the fuel is mostly uranium dioxide (88 percent heavy metal) with a plutonium content of 1 percent in the

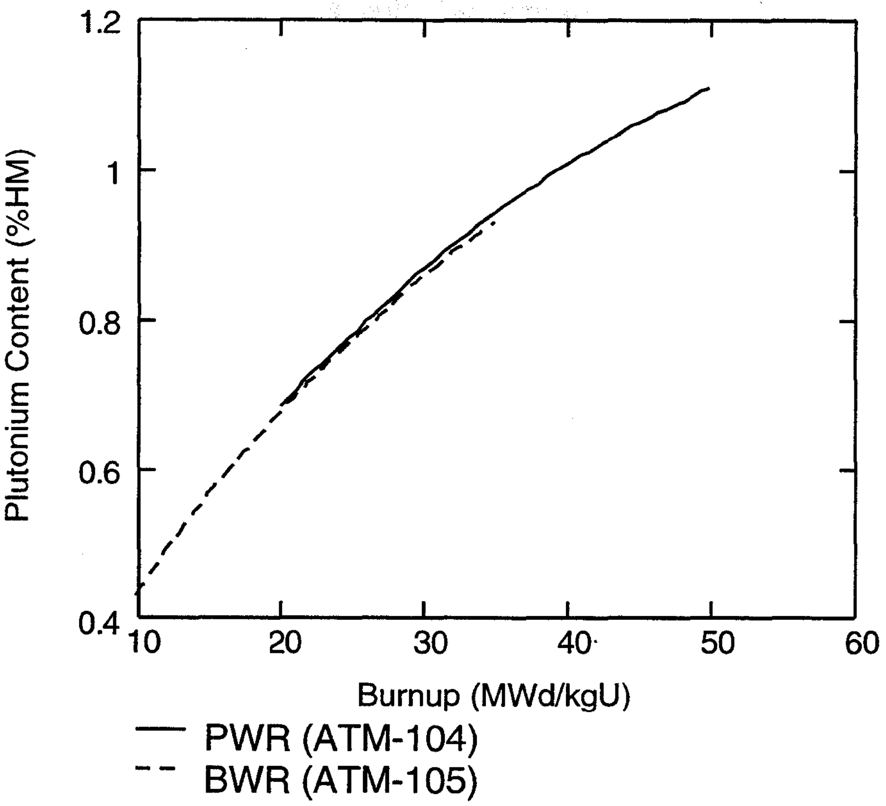

Figure 4-3. Plutonium Content of Commercial Nuclear Fuel as a Function of Burnup.[7]

heavy metal and a recovery efficiency of 80 percent. This does not include the mass of the structural elements (clad, grid spacers, nozzles, etc.) present in the fuel assemblies. For CANDU fuel, the minimum mass is 2200 kg. The use of lifting and hauling equipment will be required to move this mass during a theft. Thus, the low concentration of plutonium in commercial spent nuclear fuel is an accessibility barrier against theft by unauthorized parties. This applies to both overt and covert theft scenarios. The concentration of plutonium in the fuel has little effect on the resistance to diversion by the host.

4.2.1.3 Unit Size and Mass

Commercial PWR fuel assemblies are on the order of 4 m long with a square cross section about 20 cm on a side. A PWR fuel assembly has a mass of almost 700 kg. Commercial BWR assemblies are about the same length with a slightly smaller square cross section about 15 cm on a side. A BWR fuel assembly has a mass of about 300 kg. Commercial CANDU fuel assemblies are much smaller than PWR and BWR fuel assemblies, about 0.5 m long with a circular cross section about 10 cm in diameter.

The large masses of the PWR and BWR assemblies serve to force the use of lifting and hauling equipment during a theft in much the same way as the low plutonium concentration in spent fuel. However, if a given unit had more plutonium than was desired, it could potentially be quickly subdivided into smaller masses using explosives if doing so would facilitate the theft. If large units with high plutonium concentration can be quickly made into smaller units containing SQs of plutonium, the unit size and mass alone does not increase the proliferation resistance of an object to overt threats. The large size of commercial BWR and PWR assemblies makes their covert removal extremely difficult. This was considered to be a non-credible scenario by the PVRT.

4.2.2 Environment

Storage casks and geologic burial are two of the primary intrinsic features provided by the environments associated with the end states for commercial spent fuel and the disposition options. Dry storage casks are an intrinsic feature of the storage environment for spent fuel, both commercial LEU and MOX. Spent fuel and immobilized forms eventually are to be placed in a geologic repository. The intrinsic proliferation resistance provided by these features are examined below. It's important to remind the reader that these discussions do not represent detailed vulnerability assessments of the full security systems provided for spent fuel or that might be implemented for a disposition process. Their purpose is to provide a rough characterization of the contributions to proliferation resistance provided by these intrinsic features to identify areas of potential shortfalls from the standards, i.e., proliferation vulnerabilities.

4.2.2.1 Dry Storage Casks

The mass of a container is a barrier to theft. However, the wide availability of energetic materials forces one to look carefully at potential attacks that could rapidly open a container and allow the extraction of its contents. The tools available to the thief fall into the following classes.

Conical Shaped Charges	Penetration / Perforation
Linear shaped Charges	Cutting steel
High Explosives	Breaching Charges
Low Explosives	Lifting Charges or Bursting
Burn Bars	Thermite Cutting of metals and concrete

Proper design of an energetic attack requires knowledge of the design of the target and materials of construction. Uncertainties are usually treated by increasing the size of explosives. This works for simple targets and tasks such as perforation or fracture of homogenous materials. More complex materials such as reinforced concrete present more of a problem. Breaching charges of appropriate size to crush the concrete will not cut the reinforcing rods. If these must be cut, a second phase is necessary. The delay caused by the need to cut reinforcing rods can greatly exceed that necessary to carry out the initial breaching operation. Targets that consist of massive casks containing fragile components such as fuel elements present additional challenges. Excessive explosive charge size can rupture and deform the fragile component delaying their separation.

Given adequate time and information an explosive/thermal attack can be designed to efficiently penetrate very large, complex objects. To get a sense of the time that might be required, reference is made to some experiments conducted in the 1970's by Sandia National Laboratories. The experiments were directed at determining the delay various barriers would create. Though the goals of this set of experiments were different from those of a team trying to extract spent fuel from a dry storage cask, the times should be representative. In the absence of actual test data on dry storage casks, an estimate of 15 to 30 minutes is reasonable.

A dry storage cask represents a delay estimated to be a few tens of minutes for a small team with hand-carried equipment to expose the spent fuel contained inside. As such, it presents an accessibility barrier and increases the proliferation resistance of the spent fuel. However, because the cask can be defeated fairly quickly without the use of heavy equipment, the cask does not dominate the proliferation resistance of spent fuel.

4.2.2.2 Mined Geologic Repository

A mined geologic repository is the final stage for the reactor and immobilization disposition processes. However, it is not considered as the reference environment for the SFS because the commercial spent fuel stocks are not emplaced in a geologic repository, and there are large uncertainties in when such a repository might be available.

4.2.2.2.1 Accessibility Barrier for Mined Geologic Repository

Accessing the plutonium disposed in the mined geologic repository could be accomplished with a number of methods. Drilling of vertical shafts to a depth of 200 m is a common practice. It was done routinely for the underground nuclear testing program and is commonly done for industrial purposes, primarily mining. This type of drilling requires a large drilling rig with the associated pumps, compressors, fluid circulating equipment and other support items (pipe racks, mud pits, fork lifts, etc.). Vertical or horizontal, conventional mining and machine mining techniques, such as the tunnel boring machine (TBM) that is currently operating at Yucca Mountain, where DOE is currently characterizing the site the determine its suitability for locating a high level waste (HLW) repository, could also be utilized. Like drilling, mining also requires a sizable surface support area for ventilation, muck handling, and other large equipment. Peterson[8] estimated 6 months to access a HLW repository using a TBM to mine the 1 km minimum access route. That estimate is based on a high level of understanding of the operational requirements.

After reaching the repository level, conventional mining would be used to reach the storage containers. Mining done in the very warm and highly radioactive environment of the repository drifts would be extremely difficult. Without prior knowledge, the exact location of the excess weapons plutonium waste packages emplaced among the commercial spent fuel packages would somehow have to be determined. Even if the material were located, special handling equipment and procedures would be necessary to render the material into a manageable form that could then be retrieved.

4.2.2.2.2 Observability Barrier for Mined Geologic Repository

Surface activities for any of these operations would be readily observable from satellites and both the drilling and mining operations would create ground motion signals readily detectable with seismic sensors. Attempts to mask activities would be difficult and these sensors could even be left unattended.

4.2.2.2.3 Proliferation Resistance Provided by the Mined Geologic Repository

Access to a mined geologic repository would require readily observable, large excavation equipment, and surface support facilities in operation for an extended time period. Therefore, the resistance to both overt and covert theft is very high. Because these operations require the expenditure of extensive resources (potentially making other material sources more attractive) and because of the unavoidable high observability, the resistance to host diversion is also high.

4.2.3 Intrinsic Accessibility & Observability Conclusions

- For a radiation field to be a significant accessibility barrier against overt theft attempts, it must be high enough to force the attackers to employ shielding (thereby requiring them to employ larger forces and heavy, cumbersome equipment). None of the alternative final forms emit radiation fields large enough to require shielding for dedicated aggressors.
- The intrinsic barriers implied by the SFS make covert theft or diversion of material by unauthorized parties implausible. All end states for the disposition options are at least as resistant in this regard as the SFS.
- Plutonium dilution combined with a large unit size/mass is a significant accessibility barrier. Large unit size/mass alone is insufficient if the unit can be quickly subdivided to yield the required quantity of plutonium.
- A sealed geologic repository provides a very large intrinsic component to proliferation resistance, and enables institutional controls to be significantly reduced, although not eliminated.
- The intrinsic accessibility barriers implied by the SFS require a significant complementary element of institutional control to adequately protect against unauthorized access and removal by unauthorized parties.

4.3 INSTITUTIONAL OBSERVABILITY

This section summarizes some of the considerations affecting the Observability component of proliferation resistance provided by institutional measures. The SWS and SFS both imply very high standards for the capabilities to detect theft or diversion attempts and to measure and account for plutonium-bearing material. Rigorous domestic safeguards, particularly for stored weapons, are applied. Stored weapons and spent fuel are both distinct items, and inventories are regularly confirmed. The plutonium in stored weapons is well-characterized and measurable. Their vicinities are closely monitored, and any unauthorized movement of these items can be quickly detected by the host. Commercial spent fuel is subject to IAEA safeguards which, when in effect, enable undeclared removal to be unambiguously determined within relatively short timelines.

4.3.1 Overview

The stages of each disposition option were considered for potential features that would limit or challenge the ability to detect and recognize material theft or diversion to the levels implied by the SWS and SFS. Both domestic safeguards (for unauthorized threats) and international safeguards (for host diversion concerns) were considered. The primary institutional observability issue that was identified by the PVRT and considered here is the ability to accurately measure and account for plutonium within each of the disposition processes.

Each disposition alternative has material in both item accountable and bulk forms. For threats by unauthorized parties, no shortfalls from the standards for Observability were identified for disposition stages where item accounting applies, except that the U.S. will lose continuity of knowledge for options involving transfer of material to other nations. It is not clear that IAEA safeguards can be applied to the early disposition stages involving classified material. For the bulk handling stages, there are measurement uncertainties inherent in material accountancy capabilities that are large enough for the removal of multiple SQs of plutonium per year to go undetected by the material accountancy systems.

It should be emphasized that although material accountancy is a measure of fundamental importance in safeguards, it is not a stand alone measure. In domestic safeguards it is supported by physical protection and in international safeguards with containment and surveillance (C/S) as important complementary measures. Therefore, although measurement uncertainties for a bulk handling facility may be greater than a significant quantity of plutonium, the physical protection and C/S measures are designed and used to assure that material cannot be removed from the facility. However, the bulk handling stages where large measurement uncertainties exist provide windows of opportunity within these measurement uncertainties for undetected theft or diversion, and raise significant challenges for meeting the high levels in the Observability component of proliferation resistance that are implied by the SWS and SFS.

The assumptions underlying this analysis are presented below. These are derived from the legal requirements for domestic and international safeguards. This is followed by the discussion of the limitations in capabilities to monitor and account for plutonium in various forms and processes for the proposed plutonium disposition alternatives. This section concludes with a summary of some of the observations drawn from the analysis, and a discussion of potential mitigating options.

4.3.2 Assumptions

4.3.2.1 Domestic Safeguards

For resistance to theft or diversion by unauthorized parties, it is assumed that material in the U.S. will be subject to material control and accounting and physical protection to meet applicable U.S. government regulations. For the various plutonium disposal options, facilities may be owned by either the U.S. government, in which case safeguards are applied under Department of Energy regulations in DOE Order 5633.3B[9] or by private corporations, in which case safeguards are applied by the Nuclear Regulatory Commission (NRC) under the Code of Federal Regulations.[10] For civilian item control facilities such as reactors, safeguards are described in 10CFR70; for bulk handling facilities such as MOX fuel fabrication plants, safeguards are described in 10CFR74. Both the DOE and NRC regulations use graded safeguards, where the most severe requirements are applied to material of greatest attractiveness. Material in Canada will be under Canadian domestic safeguards applied by the Atomic Energy Control Board. Material in Europe will be under EURATOM safeguards per the EURATOM Treaty.[11]

Physical security is the responsibility of the individual State. Physical protection systems in the U.S. are designed for protection in depth where multiple layers of protection are used for those facilities having the most sensitive nuclear material. Portal monitors sensitive to both neutrons and gamma rays increase the ability to detect plutonium being stolen or diverted by unauthorized parties. Issues of security system performance that are related, although not specific, to Institutional Observability are addressed in the next section of this report on the Institutional Accessibility component of proliferation resistance.

4.3.2.2 International Safeguards

For all of the disposal options being studied, all of the States that may be involved (the U.S., Canada, the UK, and France) are NPT signatories, and we assume that plutonium to be disposed of will be subject to IAEA safeguards as described in INFCIRC 153 (Corrected).[12] One of the FMDP programmatic assumptions is that all operations involving surplus plutonium will be performed under IAEA safeguards, except those involved with classified parts, shapes, and information. Material in the U.S. will be under IAEA safeguards as specified in 10CFR75. Safeguards for the states involved are applied under state-specific agreements.[13,14,15,16]

The deterrence of diversion through international safeguards is accomplished by the risk of early detection, provided by materials accountancy, with containment and surveillance as complementary measures. In verifying the States material accountancy data, the IAEA must be able to derive a statement of material unaccounted for (MUF) and the statistical limit of error for MUF (LEMUF). Materials accountancy is discussed in the section immediately following.

Containment and surveillance (C/S) is a general phrase referring to a range of measures that provide "continuity of knowledge" about facility operations between IAEA inspections. Some technologies used for C/S purposes by the IAEA are leveraged from domestic technologies associated with material control and physical protection. However, the IAEA owns all C/S equipment, and normally provides their own equipment at a facility. In rare instances where the IAEA can use operator supplied equipment (i.e., dual-use equipment where data is used by both the operator for their purposes, and the IAEA for its purposes) an independent authentication by the IAEA of any data provided by the operator supplied equipment is required by the IAEA. The IAEA gives no credit for domestic safeguards. Some examples of C/S technologies include security seals, video surveillance cameras, personnel and vehicle portal monitors, and various kinds of security sensors.

Containment and surveillance are essential components of a comprehensive safeguards design. When used to provide accountability to international observers, C/S is a complementary measure that permits the effective use of material accountancy measures at key measurement points, as well as provide effective "continuity of knowledge" of facility operations between IAEA inspections. Although C/S cannot be quantified as material accountancy measures are, C/S allows observers to evaluate the safeguards significance of MUF figures and provides a measure of confidence that potential diversion paths are not being used to remove material from a process or facility.

In practice, a large facility could have an enormous amount of information generated by a multitude of sensors and surveillance equipment. The limited resources of inspection agencies restrict the amount of time available to assess this information. Safeguards systems being designed at this time are network-based systems that will permit data acquisition and reduction to be performed by computer. Another method of reducing the manpower required to monitor nuclear facilities is to employ remote monitoring technology to monitor the data via telephone or satellite communications. However, remote monitoring is not yet accepted by the IAEA for routine use. Plans to combine material accountancy and C/S instruments in an integrated safeguards system have been developed, but implementation must progress incrementally.

In order to implement effective material accountancy and C/S measures at a facility it is necessary to have a thorough understanding of the physical and operational details of the facility. For this reason the IAEA requires design information about the facility that must be provided as early as possible before nuclear material is introduced. The IAEA uses the design information to characterize the facility and determine the measures that will be required to achieve the safeguards objective. IAEA inspects the facilities to verify design information.

Facilities that are operating under international safeguards are inspected according to procedures developed for various types of facilities.[17] All the facility types within the plutonium disposition options that are subject to international safeguards are covered under these procedures. Facilities containing unirradiated direct use nuclear material are required to have monthly inspections; facilities with irradiated direct use nuclear material are inspected every three months.

4.3.2.3 Material Accountancy

MUF is defined by the IAEA as "the difference between book inventory and physical inventory" where the standard MUF equation is used:

MUF=PB+X-Y-PE, where

PB= beginning physical inventory

X= input

Y=output

PE= ending physical inventory.

The term "inventory difference" is sometimes used in place of MUF for U.S. domestic safeguards. MUF will be used throughout this report for material accountancy under both domestic and international safeguards. LEMUF is the statistically derived limit of error of MUF. The ability to detect loss of nuclear material is limited by the magnitude of MUF, and generally is accepted as either two or three times the value for MUF. Therefore, in each of the proposed disposal schemes material balance areas (MBAs) must be defined and measurement methods and measurement uncertainties for transfers of all nuclear material across material balance area boundaries and material in the process must be identified.

The IAEA is required to make full use of the State's system of accounting for and control of all nuclear material subject to international safeguards, and to avoid unnecessary duplication of the State's accounting and control activities. In order to be acceptable to the IAEA, the State's system needs to be based on a structure of material balance areas, and make provision for the establishment of such measures as:

(a) A measurement system for the determination of the quantities of nuclear material received, produced, shipped, lost or otherwise removed from inventory, and the quantities on inventory;

(b) The valuation of precision and accuracy of measurements and the estimation of measurement uncertainty;

(c) Procedures for identifying, reviewing and evaluating differences in shipper/receiver measurements;

(d) Procedures for taking a physical inventory;

(e) Procedures for the evaluation of accumulations of unmeasured inventory and unmeasured losses;

(f) A system of records and reports showing, for each material balance area, the inventory of nuclear material and the changes in that inventory including receipts into and transfers out of the material balance area;

(g) Provisions to ensure that the accounting procedures and arrangements are being operated correctly; and

(h) Procedures for the submission of reports to the IAEA.

Because the descriptions available for the plutonium disposition options are incomplete, detection of diversion by the host nation can't be fully evaluated for the different options.

4.3.2.4 Quality of Measurements

The system of measurements for material accounting are assumed to either conform to the latest international standards or be equivalent in quality to such standards, as required by the IAEA. The IAEA has adopted values originally developed by ESARDA, the research arm of EURATOM, which is the safeguards authority for the Commission of European Communities to represent such standards. The ESARDA target values are reviewed periodically, and the IAEA participates in this review process. The latest ESARDA Target Values were published in 1993, and accepted by the IAEA as "the latest international standards" for measurement of nuclear material.[18]

It is assumed in this review that the 1993 ESARDA Target Values will be used at facilities for domestic safeguards and by IAEA inspectors. ESARDA Target Values for some materials found in the proposed disposal options are summarized in Table 4.3-1.

Table 4.3-1. ESARDA Target Values for Materials in the Disposition Options

	RANDOM	SYSTEMATIC
Pu, PuO_2	0.15%	0.10%
MOX	0.55%	0.20%
SOLUTION	0.40%	0.25%
SCRAP (CHEM)	5.0%	0.50%
SCRAP (NDA)	7.0%	5.0%
ASSEMBLIES	1.5%	1.0%

The IAEA uses three levels of measurement quality in its inspection procedures: (1) **Gross defect measurements**, also referred to as *attributes measures*, are generally a gross test, for example to test if radiation from a sample is consistent with the declared content such as plutonium; (2) **Variables defect measurements** are a rough measure of the declared content of an item and are designed to measure to approximately 5-10% of the declared value; (2) **Bias defect measurements** generally are the most precise. These measurements usually are expected to meet ESARDA target values.

4.3.3 Limitations in Capabilities to Monitor and Account for Plutonium

The following summarizes information from the Alternative Technical Summary Reports on the various options, and draws some conclusions on the ability to measure and account for material to the levels implied by the proliferation resistance standards. This discussion applies to covert removal by unauthorized parties as well as host diversion.

4.3.3.1 Disassembly/Conversion Facility

This facility[19] is common to all disposal options. In the reactor options the facility receives 5 MT of plutonium per year, with approximately 3.5 MT (70%) as clean metal from pits and 1.5 MT (30%) as oxide, alloy and oxide reactor fuels, and various forms of scrap. The percentage of pure oxide relative to the other more difficult to measure materials is not specified. Input metal and clean oxide should be measured to meet ESARDA target values of 0.15% and 0.10%, respectively for random and systematic errors. Measurement uncertainty for other types of material will depend on purity, and may be as poor as 5% for some forms of scrap.

It is not clear if this facility will be open to IAEA inspections. For example, the following statement occurs in draft technical documents[20]: "Depending upon agreements that would be made between the U.S. and IAEA, part of the plutonium processing facility may or may not come under IAEA safeguards." It is assumed that plutonium metal or compounds will not be subject to international inspections until material has been blended and converted to oxide in the conversion facility where classified information will not be divulged from inspection operations. International inspections are assumed to start at the output of the conversion process. This material should be measured to meet ESARDA target values of 0.15% and 0.10%, respectively for random and systematic errors. Because we have no information on the beginning and ending inventory components to the MUF equation, their contributions to MUF were ignored. If we assume that all input material is clean metal or oxide and the product is clean oxide, the annual throughput contribution to MUF is estimated to be approximately 5 kg per year. Assuming that the detection limit is three times MUF, the best detection limit that can be expected for this process is approximately 15 kg/year. MUF and detection limits will be expected to be higher when beginning and ending inventory are included and when measurement uncertainty components for other forms of input material are considered. The value for MUF also is sensitive to input and output batch size and instrument calibration frequency as well as to the amount of material in the process.

4.3.3.2 Reactor Options

All of the reactor options will have the following three types of MBAs.[19] fuel fabrication, reactor, and spent fuel repository. Additionally, option R2.2 has lag storage facilities for storage of PuO_2 prior to shipment to Europe and receipt of MOX fuel assemblies from Europe. The ability to measure and account for plutonium within each of these MBAs is examined in the following sections.

4.3.3.2.1 Fuel Fabrication

Depending upon the particular reactor disposition option, this MBA receives between 3.2 and 4.1 MT of unirradiated direct use material as PuO_2 from the conversion process in batches of 525-535 kg, and ships unirradiated direct use material in the form of MOX fuel bundles to the reactor. Throughput is 3.2 MT/year of plutonium for the non-CANDU options, and 2.1 or 3.9 MT/year of plutonium for the CANDU options R6.0 and R6.1, respectively. Under international safeguards, the IAEA will perform verification inspection activities with a period no greater than 1 month plus 1 week between inspections, and a Physical Inventory Verification (PIV) will be performed annually to verify the Physical Inventory Taking (PIT) by the facility operator.

During inspections PuO_2 and MOX powder, pellets, and scrap are verified for gross, partial, and bias defects. Samples of pellets are taken at the rod loading station for bias defect verification at least four times per year. For automated fabrication lines measurement with a fuel rod scanner can replace pellet sampling if the plutonium content in the rods is determined with a precision not greater than 6%. Bias defect measurements are assumed to conform to the 1993 ESARDA Target Values.

The random and systematic errors for plutonium concentration in PuO_2 are 0.15% and 0.1% relative, respectively. PuO_2 stored at the facility may be verified as items if under successful dual C/S. Any PuO_2 not meeting purity specifications is dissolved and is purified through an aqueous process. The ESARDA target values for measuring plutonium in nitrate solution are 0.40% and 0.25%, respectively, for random and systematic errors using titrimetry. The purified nitrate solution is converted to PuO_2 and is blended with clean PuO_2 and UO_2.

ESARDA target values for measuring plutonium in MOX are 0.55% and 0.2%, respectively for random and systematic errors, which are the same as for measuring plutonium in MOX powder, assuming that plutonium is measured in pellets prior to loading into fuel elements.

Based on an annual throughput of 3.2 MT per year, the throughput contribution to MUF for the Fuel Fabrication Facility will be approximately 10 kg/year, and detection sensitivity will be approximately 30 kg/year. MUF and detection sensitivity will be higher when beginning and ending inventory are included in the calculations.

4.3.3.2.2 Lag Storage

For reactor disposition option R2.2, after plutonium processing to PuO_2 the product is shipped to a lag storage facility prior to shipment to Europe for MOX fuel fabrication. The ESARDA target values for gravimetric measurement of plutonium in PuO_2 are 0.15% and 0.10%, respectively for random and systematic errors. If the lag storage facility is treated as an item accountability area the facility should have zero MUF. The IAEA may wish to randomly sample cans of PuO_2 for analysis or perform NDA measurements on a randomly selected number of cans.

Shipment of PuO_2 to the European MOX facility and shipment of MOX fuel to the U.S. involve international transfers, and the IAEA must verify shipper/receiver differences. This also applies for the transfer of fresh fuel from the fabrication facility in the U.S. to the reactor in Canada in the CANDU disposition options.

The amount of PuO_2 shipped per year is 3.2 MT, and should be verifiable to meet the IAEA goal quantities that are 0.15% and 0.10% respectively for random and systematic errors for plutonium in PuO_2.

Finished MOX fuel assemblies are returned to the USA through the lag storage facility. Verification activities would be by item counting and seal identification and measurement for gross defects.

4.3.3.2.3 Reactor

Each reactor facility is a separate MBA. A facility has multiple collocated process sections: fresh MOX storage and handling, reactors, spent fuel cooling pond, and dry spent fuel storage.

All of the areas are treated as item control areas and should have zero MUF. This MBA receives unirradiated direct use material in the form of MOX fuel assemblies and produces irradiated direct use material in the form of spent fuel. The irradiated fuel assemblies may be stored on site for 10 years for the LWR options. IAEA performs Physical Inventory Verification (PIV) annually to verify the Physical Inventory Taking (PIT) by the facility operator.

Fresh MOX fuel received at the reactor under seals are verified either by detaching and verifying all of the seals or by verifying in place with a medium (50%) detection probability. Assemblies received not under seal are verified by item counting, serial number identification where applicable, and measurement for gross and partial defects with a 90% detection probability. Fresh MOX assemblies are stored in the fresh fuel pond prior to loading into the reactor, and verified monthly under international safeguards. Material control and accountability is by item counting and identification. IAEA verification also includes gross defect measurements with a medium (50%) detection probability.

Spent fuel will be stored at the reactor spent fuel storage pool for ten years. The material is irradiated direct use material, and subject to verification activities every 3 months under international safeguards, and under C/S. Material control and accountability is by item counting and identification, and gross defect measurements. The IAEA verifies seals with low (20%) detection probability.

Spent fuel shipments from the reactor are verified by item counting as shipping casks are filled, and by gross defect measurement with a medium (50%) detection probability. Loaded casks are placed under seal and the seal is verified and spent fuel items are counted at the receiving facility.

After ten years the spent fuel is transferred to dry storage containers on the reactor site, and is still considered as direct use irradiated material. Canada has designed dry storage containers and a safeguards approach that is intended to meet IAEA requirements.[21]

All material in the reactor facility can be treated as items. If it's under successful dual C/S and verification activities are performed monthly, there should be zero MUF.

4.3.3.2.4 Spent Fuel Repository

Casks received at the HLW repository are verified through seals placed at the reactor. Item accountancy applies, and there should be zero MUF. There is one PIV of the operators PIT during each calendar year. For spent fuel under dual C/S, seals are verified with a low (20%) detection probability. For spent fuel under single C/S the spent fuel is item counted or a spent fuel inventory check is performed. Spent fuel not under C/S is item counted and verified with a medium (50%) detection probability for gross defects.

Item counting or spent fuel inventory checks do not apply to spent fuel that is designated difficult to access.

4.3.3.3 Vitrification and Ceramic Options

4.3.3.3.1 Vitrification

The following description of the can-in-canister process is taken from UCRL-ID-122659 (April 8, 1996).[22] The can-in-canister vitrification process receives 5000 kg of plutonium annually as direct use unirradiated material, with 75% as PuO_2 and 25% as metal. The vitrification process is in the same facility as the conversion process.

Following conversion, oxide cans are transferred to lag storage. PuO_2 is transferred in batches to the first stage melter and mixed with borosilicate glass frit containing a neutron absorber to produce 25.6 kg of glass containing 10% plutonium. The molten glass product is collected in cans that are sealed and placed in interim storage. If the glass is homogeneous, the homogeneous glass product stream can be analyzed to meet ESARDA target values for MOX of 0.55% and 0.20%, respectively, for random and systematic errors. If the glass is not homogeneous measurement errors would be considerably greater. There is insufficient data on input and output batch sizes for the melter to estimate throughput contribution to MUF.

The cans containing 10% plutonium in the glass are placed in canisters with 20 cans/canister. Glass containing high-level waste from the SRP reprocessing waste tanks will be poured around the cans to fill the canisters. The canisters are stored in the Defense Waste Processing Facility at SRP.

In the alternative adjunct melter process the glass frit containing 10% of plutonium is transported to the adjunct melter facility. There it is mixed with additional glass frit and ^{137}Cs solution from the SRS HLW tanks. The plutonium content in the homogenized final glass is 5%. If it is assumed that plutonium in the product is distributed homogeneously, it can be measured in this material as for MOX, with the ESARDA target values for random and systematic errors of 0.55% and 0.20%, respectively. There is insufficient data on input and output batch sizes for the melter to estimate throughput contribution to MUF.

In the Greenfield variant, the plutonium glass frit can be blended with additional glass frit and a ^{137}Cs spike. The plutonium glass is analyzed and weighed prior to transfer to a blend tank where it is mixed with the borosilicate glass frit and the ^{137}Cs spike. The contents are blended to homogeneity, analyzed for accountability, and transferred to the second stage melter. The final glass canister contains 84 kg of plutonium in 1680 kg of glass or 5.0% of plutonium per product canister. The process produces 60 canisters per year and the storage area has a maximum capacity of 600 canisters or a 10 year production capacity.

4.3.3.3.2 Ceramic Form

The processes receive material as 25% metal in the form of ingots and 75% as oxide. The input material is considered direct use unirradiated material, and should be verified to meet ESARDA target values for both metal and oxide of 0.15% and 0.10%, respectively, for random and systematic errors.

The following information on flow rates is obtained from UCRL-ID-122665 (February 9, 1996).[23]

The oxide input to the ceramic immobilization facility proceeds to oxide dissolution. Metal proceeds at a rate of 6.1 kg/day to a size reduction and metal oxidation process, and the oxide is combined with the PuO_2. A total of 25 kg of plutonium are processed per day. The PuO_2 input to the process should be measured to meet ESARDA target values of 0.15% and 0.10%, respectively, for random and systematic errors. The oxide is dissolved with HNO_3 to produce 126 liters/day of solution containing 200 g plutonium per liter. The nitrate solution is transferred to storage tanks where samples are taken for accountability analysis. The number of storage tanks or the volume of the storage tanks is not specified. The nitrate solution is fed to a calciner to produce 206 kg/day of ceramic product containing 12% of plutonium. The titanium-based ceramic is known as SYNROC and also contains Gd neutron poison and ^{137}Cs. The inventory of PuO_2 should be verified monthly to meet ESARDA target values of 0.15% and 0.10%, respectively, for random and systematic errors. Alternatively, if cans are stored as items under successful dual C/S item counting could be applied. The powder is loaded in 33 kg batches each containing 4 kg of plutonium into bellows for hot-pressing to form the compact ceramic. The rate of production is 6.3 bellows per day. Twenty of the compacted bellows are loaded into a canister. The canister is assayed for plutonium content (see page 4-14 of UCRL-122665) but the measurement method is not specified. If the ceramic product is considered as items of direct use irradiated material it should be verified every three months. ESARDA target values for NDA of MOX scrap are 7% and 5%, respectively, for random and systematic errors using a high level neutron coincidence counter or the inventory sample coincidence counter, but it is not clear if these methods are applicable because of the added neutron poison. The canisters are stored on site until transported to a federal repository.

For national security reasons it is not clear if the metal feed will be subject to IAEA safeguards. If not, IAEA safeguards would start after oxide from the metal oxidation process is combined with input oxide or at the input to the ceramic production process.

Insufficient information on the inventory and the form of the inventory exists to estimate the throughput contribution to MUF and to evaluate the effectiveness of IAEA verification activities.

4.3.3.4 Borehole Options

4.3.3.4.1 Direct Emplacement

The following description of the facility is obtained from the cited reference.[24] The product from the disassembly/conversion facility are sealed 15 inch ID by 20 ft. canisters containing 40.5 kg of Pu/canister and if measured prior to placement in the canister should be measurable to meet ESARDA Target values for PuO_2, or a MUF of approximately 0.08 kg/canister. Maximum inventory is 1.67 MT of plutonium and should be measurable to meet ESARDA Target values for a MUF of approximately 3.5 kg. of plutonium and a detection sensitivity of approximately 10.5 kg of plutonium. Once sealed, the cans should item accountable with zero MUF.

4.3.3.4.2 Immobilized Emplacement

The following information was obtained from the cited reference.[25] Following disassembly and conversion, the PuO_2 is converted in the same facility to ceramic pellets. The PuO_2 is dissolved batchwise at a rate of 25 kg/day. Each batch contains 2 kg of plutonium. The dissolution product consists of a solution of 200 mg/ml of plutonium in 4 M HNO_3 and 0.1 M $AgNO_3$. The solution is stored in critically safe tanks. The plutonium in solution should be measurable to meet ESARDA target values of 0.40% and 0.25%, respectively, for random and systematic errors. The plutonyl nitrate solution is mixed with a slurry of ceramic precursors and gadolinium in tanks containing 12.5 kg of plutonium at a concentration of 3 g/L. The ceramic product contains 98.3% ceramic, 0.7% Gd, and 1.0% plutonium. Depending on homogeneity, plutonium in the ceramic may be measured to meet ESARDA target values for plutonium in MOX of 0.55% and 0.20%, respectively, for random and systematic errors, or ESARDA target values for plutonium in scrap of 5.1% and 0.5%, respectively, for random and systematic errors. Process rate is anticipated to be 25 kg of plutonium per day for 200 days of operation annually.

Maximum inventory of the conversion/immobilization facility is 2 metric tonnes. There was insufficient information available on the process to estimate MUF.

The ceramic pellets are placed in 55 gallon drums with 510 kg of pellets containing 5.1 kg of plutonium per drum. The drums can be considered as items for accountability purposes. The drums are shipped to the borehole site with 5 drums (25.5 kg of plutonium) per shipment.

At the borehole site the drums containing the 1% plutonium pellets are opened and mixed with an equal weight of pellets without plutonium for a final product containing 0.5% plutonium. The pellet mixture is mixed with an approximately 40% by volume of grout and poured down the borehole. For safeguards accountability the shippers value of drums may be accepted as the receipt value. It is not clear how the IAEA would verify the plutonium content of the pellet/grout mixture transferred to the borehole.

4.3.4 Summary of Material Accountancy Observations

Following are some observations/deficiencies concerning materials accounting in the various plutonium disposition alternatives.

1) Domestic safeguards, including the responsibility for physical protection, are applied by the host nation under applicable domestic regulations. In carrying out its international safeguards verification activities, makes full use of the host's system of accounting and control for all nuclear materials subject to international safeguards.
2) The disassembly/conversion facility is common to all of the disposition options studied. Because it handles weapons parts it is not clear that it can be subject to IAEA inspection prior to output cans of PuO_2. The throughput contribution to MUF is estimated to be approximately 5 kg/year, and the best detection sensitivity is approximately 15 kg/year. Because all of the input materials are not pure and because inventory also contributes to MUF, it is expected that MUF will be significantly higher.
3) The fuel fabrication facility is a bulk handling facility common to all of the reactor options. The contribution to MUF from throughput is estimated to be approximately 10 kg for a 3.2 MT/year facility; the inventory component cannot be estimated without more detailed knowledge of the process. The best detection sensitivity that could be expected is approximately 30 kg/year. Near-real-time accounting (NRTA) could be applied to improve the detection sensitivity for diversion or loss of plutonium.
4) Some reactor options involve fuel fabrication in Europe or shipment of fuel assemblies to Canada. The U.S. loses continuity of knowledge during this time.
5) All of the reactors can be considered as item control facilities, and for accounting purposes should have zero MUF.
6) For the immobilization disposition options, insufficient information on the inventory and the form of the inventory exists to estimate MUF and to evaluate the effectiveness of IAEA verification activities. Measurement errors for plutonium in glass can be comparable to those for MOX if adequate homogeneity is maintained.
7) For the borehole direct emplacement option, the throughput contribution to MUF may be as low as 3.5 kg/year. The inventory contribution to MUF cannot be estimated. For material received and disposed of as metal it is not clear if IAEA safeguards can be

applied without disclosing classified information. For the borehole immobilized emplacement option, MUF values may be large, depending on the form of the final product material. It is not clear how the IAEA could verify the plutonium content of the pellet/grout mixture transferred to the borehole.

4.3.5 Mitigating Options

For bulk handling facilities a technique referred to as near-real-time accounting (NRTA) has been developed. The technique relies on frequent physical inventories to supplement flow measurements, generally through the use of in-process instruments that do not interfere with process operations. The objective of NRTA is to improve the sensitivity and timeliness of detection through the use of statistical tests specifically tailored to the sequential nature of the data. The primary advantage of NRTA is to enable the facility to meet the monthly material balance closure required by international safeguards for bulk handling facilities containing direct use unirradiated nuclear material. Specific tests have been designed to detect protracted as well as abrupt diversion or loss of nuclear material. It can be applied to the conversion process of all of the alternative disposal methods, to the fuel fabrication process of the reactor options, and to the bulk process areas of the glass and ceramic options.

Processes can be designed to incorporate better measurement techniques and process operation and process control features that reduce MUF. Diversion of nuclear material from facilities can be minimized by automating to the degree possible the handling of the nuclear material. Through automation human access to the material is minimized, reducing possibilities for theft or diversion.

4.3.6 Institutional Observability Conclusions

- Bulk processing stages for every plutonium disposition option provide windows of opportunity for the undetected removal of multiple SQs of plutonium per year. Limitations inherent in material accountancy capabilities for these processes result in conservative estimates for MUF and detection sensitivity large enough for the removal of multiple SQs of plutonium per year to go undetected by the material accountancy systems. It should be emphasized that material accountancy is not a stand alone measure. In domestic safeguards it is supported by physical protection and in international safeguards with containment and surveillance (C/S) as important complementary measures. These measures are designed and used to assure that material is not removed from the facility. However, the bulk handling stages with large MUF values and detection sensitivities provide windows of opportunity for undetected theft or diversion within the measurement uncertainties, and represent challenges to meeting the high levels of the Observability component of proliferation resistance that are implied by the SWS and SFS.
- Some stages of every disposition option may not be available for international safeguards by the IAEA. Facilities and processes involving material containing classified parts, shapes, or information are not subject to IAEA safeguards in order to protect national security information. Many process activities upstream of the disassembly and conversion facility, which is common to all disposition options, are currently assumed to be unavailable for international safeguards.

4.4 INSTITUTIONAL ACCESSIBILITY

Institutional Accessibility refers to the set of measures imposed by the host to provide Protection-In-Depth against unauthorized access and removal of plutonium-bearing material. Since these measures are applied and controlled by the host, and since there is no protective role of international safeguards, there are no institutional accessibility barriers against host diversion. These measures augment the inherent resistance to theft or diversion during processing or storage beyond that provided by material form or physical environment.

The concept of Protection-In-Depth requires an adversary to bypass or defeat a number of protective measures in sequence to attain his goal. These systems can be viewed as successive layers of protection against unacceptable acts. They generally fall into three categories:

- **Physical Security Systems -** These systems are composed of detection, assessment, delay, and response components designed to detect any attempt to enter or leave designated security areas or to violate restrictions imposed to maintain control of an asset, and to ensure that response can be made in time to prevent successful theft or diversion. Electronically monitored perimeter systems with instrumented gates and portals are examples of detection and delay components.
- **Administrative Controls -** These are rules of operation and behavior that are imposed on personnel and vehicles authorized to be present in a facility or with access to protected materials. These include enforced levels of access authorization, approved procedures, and multiple-person rules to ensure that only approved and appropriate actions can occur, and that unauthorized actions are detected and reported.
- **Accountability -** These are measures that track and document the location, continued presence, and amounts of protected materials within a facility or system. These systems can include various types of monitoring devices that track and quantify the material, and record its progress through the system while maintaining records of custody at all times.

The latter of these was addressed in the previous section of this report. These components can be configured to form the protective layers of a Protection-In-Depth system. If, for example, the form of a material makes it very difficult to measure and inventory within acceptable limits of accuracy, then administrative controls can be put in place to ensure that attempts to divert material from the process stream will be detected or observed. To protect against collusion or coercion, physical barriers and detectors can be placed on the perimeter to ensure that material remains confined to the material access area.

The levels and requirements for these institutional measures depend upon and supplement the intrinsic proliferation resistance provided by material form and/or environment. They require a continuing and effective institutional presence in order to maintain an adequate level of proliferation resistance. These measures can, therefore, only be relied upon for the foreseeable future and imply a continuing capability and resolve on the part of the custodial agency to assure material custody and control. It is important to remember that they may not be effective beyond the level of threat assumed at the time of their design.

It is important to note that established government regulations, such as DOE Order 5633.3B and the Code of Federal Regulations, define requirements that must be met by domestic safeguards for nuclear material, and that the security systems for these plutonium disposition processes are not yet designed. In analyzing the Institutional Accessibility component of proliferation resistance, the PVRT considered features associated with the plutonium disposition options that could reduce the confidence in the security posture, increase exposure to theft or diversion opportunities, or elevate security system challenges compared to the SWS. Features falling in two categories were identified and are presented here. Presented first are some general features and issues associated with the changing security environment that are not specific to the disposition alternatives, yet that are important to recognize when analyzing and developing the security systems for the FMDP. In the second category are both common and discriminating features that are specific to the disposition alternatives. When considered within the context of the other proliferation resistance issues presented in the preceding sections of this report as well as the general security environment issues, the features in this second category were assessed by the PVRT as shortfalls from the level of proliferation resistance implied by the SWS that could potentially be exploited if not adequately considered and addressed during the development, optimization, and implementation of the disposition options.

4.4.1 Evolving Security Environment

4.4.1.1 Threat

For the time frame in which the plutonium disposition program will operate, it must be recognized the threat is different both in level and character than it was during the Cold War, when most of the existing physical security systems were deployed.

We are now faced with a developing global SNM market, and many of the non-weapons states have already declared their desire to acquire nuclear power status. Global political, ethnic, and religious-based realignments have changed the balance of power and increased the resolve of some states to acquire nuclear weapons and the required nuclear materials. Economic disruptions that have occurred within the some of the major nuclear powers have made the plutonium market more attractive to some with current access to the material.

Other forces have given rise to sub-national groups with access to billion dollar resources that could be used to fund the acquisition of weapons of mass destruction, including nuclear weapons. Simultaneously, disarmament is downsizing the nuclear weapons design, development and manufacture community, and those experienced resources are potentially available to adversary groups. The ever-increasing proliferation of detailed information needed to acquire materials and fabricate weapons has significantly increased the technical sophistication in all types of terrorist activity.

Large car and truck bombs and chemical/biological agents have become credible tools for terrorists, if for no other reason than their use has become commonplace. Increased motivation has also been amply demonstrated by suicidal attacks carried out regularly in the Middle East. Terrorist actions in the U.S. carried out by both domestic and foreign elements have increased. Since the materials involved in this disposition program could very likely be targets of this new generation of adversary, we must design to larger and more sophisticated threats from outsider attacks.

The "insider" threat considers personnel with authorized access as part of the adversarial potential. The value of the material, and the length of time available for adversarial action, and some characteristics of the evolving threat increase the potential for the insider threat.

Since the potential level and nature of the threat is evolving, it is essential that a "resilient" rather than "brittle" response to this changing threat environment be employed. Most of the security systems in use today are very effective against the threat to which they were designed. A resilient response to address an evolving threat will insure that the systems needed for the plutonium disposition program will contain the necessary elements to continue to provide robust proliferation resistance.

4.4.1.2 Safeguards and Security Readiness

Some existing facilities are suggested for use in the plutonium disposition options. Most of the existing safeguards and security systems are ten years old, and are based on twenty year old technology. As the components age, maintenance costs are increasing rapidly and unforeseen modes of equipment failure are beginning to emerge. It is becoming more difficult to budget for continued effectiveness. The requirements for maintaining effective Protection-in-Depth that is flexible in the face of an evolving threat must be carefully examined and adequately supported over the life of the disposition program in order to ensure adequate levels of proliferation resistance.

Control of information and material an increasingly difficult task. It is also a basic assumption of the material disposition program that unclassified and non-DOE facilities, and perhaps some privately owned and operated facilities, will be used after declassification of the materials. Such factors and trends in an environment of evolving threat increase the challenge of providing protection against multiple insiders.

4.4.1.3 Security System Analysis and Design

Design for Protection-In-Depth is based on formal Vulnerability Analyses. The results of these analyses are very sensitive to the scenarios analyzed and the assumptions made about the nature of adversary actions and the countermeasures applied. These assumptions are also highly dependent on the threat guidance in place at the time the analysis is performed. As we have noted, the threat applicable to the disposition program is continually evolving. Vulnerability analyses that model only the scenarios chosen may not reflect threats that become credible since the work was done. The security systems for all facilities involved in plutonium disposition should be examined and developed in consideration of the evolving threat and anticipated future needs.

Because of shrinking budgets and the escalating costs of maintaining security levels of the past, there is an understandable tendency toward the application of cost-benefit analysis to security operations along with other aspects of doing business. Cost-benefit analysis is not an appropriate tool for evaluating security systems against rare event threats. Rare events can lead to far-reaching and serious consequences, which is certainly true where the potential for loss of weapons grade plutonium is a concern. Cost-benefit may not be able to provide a realistic picture of consequences on either side of the equation.

A reasonable approach to this problem is risk-based planning. It is very difficult to plan for protection against rare events, and to justify the costs associated with countermeasures. The risk-based approach involves scoping the anticipated threat and analysis of potential consequences. This allows establishment of an acceptable level of risk and provides a means of making comparative estimates of effectiveness among proposed countermeasure systems.

4.4.2 Proliferation Resistance Shortfalls in Institutional Accessibility

Several issues were identified during the course of the study that warrant consideration during the development, optimization and implementation of disposition options for surplus weapons plutonium. The focus of our effort was to identify potential shortfalls in Institutional Accessibility compared to the SWS within disposition alternatives that, if exploited by a resourceful adversary, could be used to obtain multiple significant quantities of weapons usable plutonium. The following areas have features and issues that, when considered within the context of the other proliferation resistance components and general security issues previously discussed, have the potential for significant impact on the ability to establish, maintain, and assure proliferation resistance to the levels implied by the SWS over the life of the disposition options:

- Bulk processing
- Transport of SNM
- NRC Facilities with Different Deadly Force Policy

4.4.2.1 Bulk Processing Facilities

Facilities and processes that handle bulk forms of plutonium, especially in concentrated form, are more susceptible to covert theft and diversion than those that handle only sealed items using item accounting. All of the disposition options have bulk processing facilities for which detection sensitivities (based upon MUF estimates) for material accountancy measures will be multiple SQs of plutonium per year. This provides a window of opportunity for diversion or theft within the measurement uncertainties by a careful and resourceful adversary. Protection against such diversion and theft scenarios involves placing greater reliance on portal detection of attempted SNM removal, on the integrity of coworkers who would normally serve as the principal detection mechanism for unauthorized actions, on effective administrative controls, and on the integrity of critical computer systems.

4.4.2.1.1 Computer Security

Many of the elements of modern physical protection and safeguards systems today rely on computers, for data or control, or both. The two most important systems are the computer controlling physical access to a facility, and the computer controlling the material control & accounting system for SNM. Each supports elements of a total Defense-In-Depth approach to prevent the theft or diversion of SNM. Compromise of these two computer systems could impact physical protection. Without complete assurance of software integrity there are opportunities for subversion of security or accountability systems.

4.4.2.2 Transportation

If we compare the security posture and effectiveness during transportation stages in the plutonium disposition options with the "high standards of security and accounting applied to stored intact nuclear weapons" - the Stored Weapons Standard, we find some significant differences. First, the physical Protection-In-Depth that is provided at fixed sites is not available. What is missing is the stand-off distance and early warning given by the perimeter detection and assessment systems, the physical barriers of the facility, and the protection against eyes-on target identification.

To make up for this, compensatory measures are applied. Mobile and very well armed couriers with deadly force authorization and training are provided. They act as both detection system and response force since they keep the trucks in visual contact at all times. They recognize patterns that pose threats, and are constantly ready to deploy and engage. We also use Safe Secure Trailers (SSTs) pulled by Armored Tractors that are quite literally rolling vaults equipped with multiple delay and access denial systems.

There is no doubt that the SST fleet operated by the Transportation Safeguards Division of DOE is one of the most secure rolling transportation systems in the world. There are years and millions of miles of operational experience that prove it to be both safe and secure. Such a high level of effectiveness however, does not detract from the need to be prudent and to limit the exposure from long and frequent transportation segments.

4.4.2.2.1 Foreign Transport

A discriminating concern is the potential for foreign transport for the reactor alternatives. The reactor variants, as currently configured, all require the shipment of pure weapons grade plutonium dioxide from the plutonium Conversion Facility to the MOX fabrication plant. This second transportation segment moving very rich plutonium cargo raises concern when carried out in-country by the SST fleet. However, the Eurofab reactor variants require that this undiluted plutonium oxide be transported by ship to Europe, and then by land mode to the MOX facilities. This segment is not well-defined in the alternative reports, and until it is, the security implications of sea-going shipment and foreign agency custody of U.S. weapons-grade plutonium remain unresolved. This question also arises, but to a lesser degree, in the CANDU reactor variant under which the MOX fuel must be transported on Canadian soil to the Bruce facility on the shores of Lake Ontario.

4.4.2.2.2 Commercial Transport

Another concern surfaces in the potential intersite transport of plutonium immobilized in ceramic pellets to the wellhead facility in the immobilized borehole alternative. The concentration of plutonium is low enough (~1%) and the quantity is small enough (<16 kg per load) that, according to current regulations, SST transport may not be required for intersite transport (DOE order 5633.3B, Category III-D material). That is, transportation by commercial carrier may be an allowed option. However, a single truckload of pellets could contain more than a significant quantities of weapons grade plutonium, for which only a cold (no gamma shielding) chemical separation is required to recover pure weapons grade plutonium.

4.4.2.3 NRC Facilities with Different Security Policies

4.4.2.3.1 DOE Facilities

Section 161K of the Atomic Energy Act establishes the security ground rules for the protection of Special Nuclear Material (SNM). One of the elements of that protection is the use of force, including deadly force, to prevent the removal of SNM from DOE owned and operated facilities. The law, rules, and training are clear that deadly force is authorized to prevent the theft of SNM, or unauthorized removal from the premises. It is not necessary that the Protective Force Officer know that the thief actually has SNM in his possession, but rather that deadly force is authorized, under 10 CFR 1047, to "prevent theft, sabotage or unauthorized control from fixed site or area where Category II or greater amounts are known to be stored." As with other federal deadly force policies, "Its use may be justified only under conditions of *Extreme Necessity*, when all lesser means have failed or cannot reasonably be employed." Further, the Atomic Energy Act extends and authorizes this deadly force policy to contract guard forces at DOE facilities.

4.4.2.3.2 NRC Licensees

In contrast, the rules for facilities licensed by the Nuclear Regulatory Commission (NRC) do not allow the unconditional use of deadly force to prevent the theft of SNM. The use of force, up to and including deadly force, in the prevention of the theft of special nuclear material from a facility licensed by the NRC under 10CFR70 is mentioned in section 73.50, Requirements for the physical protection of licensed activities, subpart g, Response requirement, paragraph 4, which is quoted as follows:

> "The licensee shall instruct every guard to prevent or impede attempted acts of theft or radiological sabotage by using force sufficient to counter the force directed at him including deadly force when the guard has a reasonable belief it is necessary in self-defense or in the defense of others."

This policy places a severe restriction on the potential use of deadly force by requiring that an element of self defense or defense of others be present, and appears to leave open the question of after-the-fact justification for the use of deadly force.

As a further clarification, Section 161.k of the Atomic Energy Act (42 USC 2201.k) authorized deadly force for DOE, NRC and their contractors and subcontractors, ***but not the licensees of NRC***. NRC has requested the same deadly force authorization for their licensees as currently authorized for DOE, but Congress has not yet acted on that request.

Without the same federal authorization for the use of deadly force as DOE and its contractors, NRC licensees might then face the applicability of numerous and varying state laws on permissible and justifiable use of force in the protection of property (SNM). This arises in part from the fact that the standards under the law for the protection of property are fundamentally different from those for self defense and defense of others.

The differences in policy and application of deadly force to prevent removal of SNM from a facility extend to other contract arrangements that could be part of the disposition program. Reduced levels of protection provided by the guard force because of the self-defense policy raise questions about the overall effectiveness of security at these facilities when processing, handling and storing surplus weapons grade plutonium. In the face of an escalating design basis threat, it is not obvious that increasing other layers of the total defensive system can compensate for the reduced ability of the guard force to stop the theft or removal of SNM.

Since the use of NRC licensed facilities is one of the assumptions of the material disposition program, the potential exists for variation in consequences to the adversary depending on the ownership of the facility. This could make certain facilities considerably more attractive than others as targets for adversary actions. The same level of protection should be afforded all SNM at all facilities.

4.4.2.4 Security by Others

Another potentially discriminating feature among disposition alternatives concerns the abdication of control over SNM to foreign agencies. Two of the disposition options involve transferring the SNM to a foreign party. One is the Eurofab option, in which plutonium powder is fabricated into MOX reactor fuel in Europe and returned to the U.S. for use in U.S. reactors. The other option involves burning MOX fuel in CANDU reactors at the Bruce Station in Ontario. Clearly, security at the transition point is within the scope of the program. While security outside of U.S. borders is the responsibility of "others," loss of material would, at a minimum, reflect negatively on the entire program, and could even halt such a disposition option.

4.4.3 Institutional Accessibility Summary and Conclusions

- Features of the evolving threat represent significant changes from the threat spectrums that have previously been considered in the design of security systems.
- Current trends in security practice and policy can lower the security posture for facilities involved in the plutonium disposition options. These include
    - aging systems with increasing maintenance costs,
    - security system analysis and design that are threat-specific and cost-benefit driven, and
    - cost-justified relaxation of security standards and practice and the downsizing of security forces.
- As security and administrative systems become more dependent on computer technology, it becomes increasingly important to ensure the integrity of the computers and their software.
- Facilities that handle bulk forms of material, especially in concentrated form, are areas of lower proliferation resistance than implied by the SWS. Limitations in materials accountancy provide a window of opportunity for covert theft or diversion by careful and resourceful adversaries.
- The frequent and long-term transport of very attractive materials for this program increases its exposure and represents an area of lower proliferation relative to the SWS. Our success at this endeavor during the Cold War era is clear, but we now face a much different threat spectrum.
- The proposed use of non-DOE facilities in the disposition process raises the question of the allowable level of deadly force in the protection against theft. NRC-licensed facilities would not be authorized this deterrent measure under current law.

All of these factors, coupled with our natural tendency to respond to rather than to anticipate changes in the threat climate, tend to lower confidence in our ability and resolve to ensure adequate safeguards and security over the life of the plutonium disposition program.

4.4.4 Recommendations

Based on our examination of Institutional Accessibility issues, we make the following recommendations to enhance resistance to proliferation for the plutonium disposition options:

- Assure resilient security design response to evolving and growing threats in order to help maintain effective protection-in-depth over the disposition campaign. The materials involved in the disposition program are attractive targets in a rapidly changing global environment. Policy must be proactive to assure adequate proliferation resistance.
  - consider larger and more sophisticated threats in the design and evaluation of security systems for the facilities involved, adequate support for continuing assessments and upgrades of the safeguards and security systems and procedures.
  - risk-based planning that considers the consequences of loss in establishing acceptable levels of risk and assessing relative effectiveness of proposed countermeasure systems.
  - rigorous control over information and computer systems employed in physical security system control and MC&A. The integrity of the computer system and its resident software must be assured from the very beginning of development. This will add cost and complexity to software design and acquisition.
- Minimize transport of attractive materials, such as by co-locating processing facilities.
- Carefully evaluate commercial transport of significant quantities of plutonium, even in dilutissuese form.
- Apply the same protection policies to all the plutonium, regardless of custodial agency.

4.5 SUMMARY OF GENERAL PROLIFERATION VULNERABILITIES

The preceeding sections of this chapter examined many of the issues of proliferation resistance and proliferation vulnerabilities that emerged during the course of the PVRT assessment. In order to facilitate their consideration, these issues were partitioned into four "regions" of the proliferation resistance framework developed as part of this activity: Utility, Intrinsic Accessibility & Observability, Institutional Observability, and Institutional Accessibility. In this section, the general shortfalls in proliferation resistance from the standards, i.e., proliferation vulnerabilities are summarized. The following chapter covers additional issues, or variants of these general ones, that are specific to particular disposition alternatives.

Once sufficient material is successfully removed from a disposition process, the barriers to recovery of weapons-usable plutonium are relatively modest. Much of the material in the early stages of disposition is directly usable form, or can be made so with minimal processing. Changing the material into a form that requires chemical processing for recovery and purification introduces a non-trivial barrier to recovery. Integrally combining a sufficiently intense radiation barrier to force shielding and remote operations during recovery processing adds another tangible increment in resources, complexity, and time. However, the requirements for recovery appear to be relatively modest, particularly in light of the information, funding, and personnel resources that are readily available to many potential threats. Isotopically denatured plutonium recovered from the reactor alternatives, although somewhat less desireable than weapons-grade, is still weapons-usable. Assuming that the Utility barrier provided by material form provides significant proliferation resistance and adequate deterrence against credible future threats seems dangerous. The PVRT concluded that the Utility barrier, at its best, should be considered a relatively small component of proliferation resistance for the disposition alternatives. The Accessibility barrier must be large enough to deter and prevent the successful access and removal of sufficient plutonium-bearing material.

Bulk processing stages, especially those involving material with high plutonium concentrations, represent the most significant source of proliferation vulnerabilities against threats of covert theft or diversion by unauthorized parties. Every disposition alternative has such stages. Neither the Observability nor the Accessibility barriers can be assumed to be equivalent to those implied by the SWS. For many of the bulk processes involved with plutonium disposition, measurement limitations provide a window of opportunity for the covert removal of multiple SQs of plutonium within the detection limits of the materials accountancy systems. Physical security measures and administrative controls are intended to provide sufficient Protection-in-Depth to ensure against unauthorized material removal. The potential for collusion by multiple insiders, the continuation of trends that serve to weaken administrative controls, and issues of computer security collectively raise challenges to the ability to ensure that the layers of protection around this window of opportunity will maintain protection to the levels implied by the SWS over the duration of disposition campaign. These issues are exacerbated for potential Russian implementations. Other that bulk processing involving high-concentration material and one alternative-specific issue discussed in the next chapter, no other stages of the disposition alternatives have features that would reduce the proliferation resistance against covert theft/diversion by unauthorized parties relative the SWS and SFS.

All of the disposition alternatives require sustained, long-distance transportation campaigns involving frequent shipments with very high plutonium content. Most of the domestic intersite transport is assumed to be by SSTs operated by the Transportation Safeguards Division of DOE, which is one of the most secure rolling system in the world with millions of miles and many years of demonstrated success. Nevertheless, transport of attractive material on public roadways to the extent required for the disposition options does increase the exposure to potential adversaries with features that will continue to evolve. These issues are magnified in the foreign transportation segments, especially those involving shipment to Europe, for which TSD will likely not be providing security. Some of the bulk processing stages involve active handling of small, easily portable items with high plutonium concentrations. In light of the evolving threat characteristics and trends in security environments, these should also be recognized as stages that challenge the ability to ensure continuing high levels of security against overt (forcible) theft. The FMDP has assumed that all operations that are conducted in the U.S. in new facilities or are performed in the private sector will be licensed by the NRC. The PVRT has identified the current differences in security policies between facilities run by private NRC licensees and DOE Category 1 facilities, particularly regarding the authorization to use deadly force, as a shortfall from the SWS, and recommended that the same security policies be applied to all SNM regardless of custodial agency.

All of the disposition alternatives significantly increase the intrinsic components of proliferation resistance by altering the form and/or location of the plutonium, thereby reducing the reliance upon institutional measures. However, it is not until the material is sealed in an underground repository (which includes deep borehole), that proliferation resistance is dominated by intrinsic barriers, and even then some institutional presence is required for periodic monitoring and to provide response capability. The intrinsic protection provided by material form and storage containers must be accompanied by sufficient institutional protective measures to rapidly detect, respond, and sufficiently delay attempted thefts by determined, well-prepared adversaries. The storage containers that were examined can be breached by explosives to expose their contents by operations estimated to take no more than 15-20 minutes. The radiation fields for the end states examined are not high enough to force a sufficiently determined adversary to use shielding and remote handling during the theft. Low plutonium concentrations uniformly diluted within a large size and mass unit can force the use of lifting and hauling equipment, however. Should the combination of institutional and intrinsic measures not prevent the successful access and removal of sufficient material, the intrinsic properties of the end state materials can impose delays of a month or two in recovering plutonium sufficient for a nuclear explosive device by a modestly equipped, well-prepared adversary. Once the end state material is emplaced underground, the threat of unauthorized theft is effectively removed.

In going from current storage conditions that are consistent with the SWS to a more intrinsically proliferation resistant end state, every disposition process was judged by the PVRT to have stages with features that lower the proliferation resistance against theft or diversion by unauthorized parties to levels that are below that standard. Some of these features can likely be effectively mitigated, while concerns for others cannot be eliminated. Thus, plutonium disposition is a path that should be well-prepared against the evolving spectrum of threats and carefully traversed.

In considering the potential for diversion by a nuclear nation host, it is important to note that no provisions are currently provided for international monitoring or verification of plutonium in the early stages of disposition or in processes prior to disposition such as dismantlement, storage, or transportation of weapons parts. The same applies for strategic reserves of plutonium that might be available to a nuclear state. For those stages of disposition under effective international safeguards, removal of plutonium in item accountable form should be readily observable by the IAEA within timelines determined by their inspection schedules. Covert diversion within the measurement uncertainties by the host nation of multiple SQs from the bulk processing stages over the course of the disposition campaign may not be detected with confidence by the IAEA. However, given the opportunity of a nuclear state to hide multiple SQs of plutonium in areas that are not subject to monitoring and verification, and simply not declaring it as surplus for disposition, the covert host diversion scenarios did not seem plausible to the PVRT. Removal of large quantities of plutonium sufficient for significant rearmament by a nuclear state should be readily observable through international safeguards. Thus, although breakout for rearmament cannot be prevented (unless the plutonium is transferred to another host), undetected breakout for rearmament is unlikely.

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[1] See for example:
M. Benedict, T. Pigford, H. Levi, Nuclear Chemical Engineering, 2nd Ed. (McGraw-Hill Book Co., New York, 1981).

C. E. Stevenson, E. A. Mason, A. T. Gresky, Progress in Nuclear Energy, Series III Process Chemistry, (Pergamon Press, London, 1970).

O. J. Wick, The Plutonium Handbook, (Gordon and Breach, New York, 1967).

[2] T. Kan and L. Gray, "Proposed Measure of Proliferation Resistance for Plutonium Disposition and Criteria for Application of the Spent Fuel Standard," LLNL Draft. April 16, 1996.

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[3] DOE Facts, "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-Grade Plutonium, U.S. Department of Energy, Office of the Press Secretary, Washington, DC 20585, no date.

[5] Hakkila, E. A., Richter, J. L. and Mullen, M. F., "Reassessment of Safeguards Parameters," Los Alamos National Laboratory, Los Alamos, NM, no date.

[6] United Nations Scientific Committee on the Effects of Atomic Radiation, Sources, Effects and Risks of Ionizing Radiation, United Nations, New York, NY, 1988.

[7] S. Glasstone and P. J. Dolan, The Effects of Nuclear Weapons, United States Department of Defense and the Energy Research and Development Administration, Washington, DC, 1977

[7] The curve for the PWR is from reference [R. J. Guenther, et al., Characterization of Spent Fuel Approved Testing Material—ATM-104, PNL-5109-104, Pacific Northwest Laboratory, Richland, WA, 1991] and the curve for the BWR is from reference [R. J. Guenther, et al., Characterization of Spent Fuel Approved Testing Material - ATM-105, PNL-5109-105, Pacific Northwest Laboratory, Richland, WA, 1991].

[8] Peterson, Per F., Long-Term Retrievability and Safeguards for Immobilized Weapons Plutonium in Geologic Storage, U.S. DOE Plutonium Stabilization and Immobilization Workshop, Washington, D.C., Dec. 12-14,1995.

[9] U.S. Department of Energy, DOE Order 5633.B (Sept. 7, 1994).

[10] U.S. Code of Federal Regulations, Volume 10.

[11] EURATOM Treaty, Treaty Establishing the European Atomic Energy Community (EURATOM), Rome (1957).

[12] The Structure and Content of Agreements Between the Agency and the States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/153 (Corrected), International Atomic Energy Agency Vienna, (November 18, 1977).

[13] Agreement Between the United States of America and the International Atomic Energy Agency for the Application of Safeguards in the United States (and Protocol Thereto), INFCIRC/288, Vienna, Austria (November 18, 1977).

[14] Agreement Between Canada and the International Atomic Energy Agency for the Application of Safeguards in Canada, INFCIRC/164.

[15] France Agreement, INFCIRC/290 Vienna (1978).

[16] United Kingdom Agreement, INFCIRC/263 (1976).

[17] Safeguards Criteria 1991-1995, International Atomic Energy Agency, Department of Safeguards, Vienna (November (1990).

[18] S. Deron et. al., "1993 International Target Values for Uncertainty Components in Fissile Isotope and Element Accountancy for the Effective Safeguards of Nuclear Material," International Atomic Energy Agency, Vienna, STR-294, Rev. 1 (February, 1994).

[19] Reactor Alternative Team, Fissile Materials Disposition Program, "Reactor Alternative Summary Report Rev. 3," ORNL/MD/LTR-43, Volume 2 (January 12, 1996).

[20] "Fissile Material Disposition Program, Alternative Team Technical Document, Ceramic Greenfield Alternative," Report L-20218-1 (October 2, 1995), p. 48.

[21] C. R. Frost et. al., "Proposed Safeguards Provisions for Pickering NGS Dry Storage Facility," in Proceedings 15th Annual Symposium on Safeguards and Nuclear Material Management, ESARDA, Rome, Italy, 11-13 May 1993, pp. 215-221.

[22] "Fissile Material Disposition Program, Alternative Team Technical Data Document: Vitrification Can-in-Canister Alternative," Report UCRL-ID-122659 (April 8, 1996).

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[23] "Fissile Material Disposition Program, PEIS Data Call Input Report: Ceramic Immobilization Facility with Radionuclides," report UCRL-ID-122665 (February 9, 1996).

[24] Ananda M. Wijesinghe et al., "Fissile Material Disposition Program: Alternative Technical Summary Report for Direct Disposition in Deep Boreholes: Direct Disposal of Plutonium Metal/Plutonium Dioxide in Compound Canisters," Report UCRL-LR-121737, Version 3.0 (April 15, 1996).

[25] Ananda M. Wijesinghe et al., "Fissile Material Disposition Program: Alternative Technical Summary Report for Immobilized Disposition in Deep Boreholes: Immobilized Disposal of Plutonium in Coated Ceramic Pellets in Grout without Canisters," Report UCRL-LR-121736, Version 3.0 (April 15, 1996).

5. ALTERNATIVE-SPECIFIC ASSESSMENTS

In the previous section a general assessment was made of the proliferation vulnerability factors—Utility, Intrinsic Accessibility and Observability, Institutional Observability, and Institutional Accessibility—as they applied across the alternatives. In section 5 we present alternative-specific issues that draw on the material presented in the previous section. Intrinsic Accessibility was treated in section 4 from the standpoint of the SFS, specifically focusing on the attributes of spent fuel related to material form. The borehole alternative is discussed in detail in section 5 because it, unlike reactors and immobilization, relies on its unique environment more than 2 km beneath the surface rather than material form to limit accessibility. Storage is also discussed briefly; while it is not a *disposition* alternative, it is an alternative to disposition.

5.1 IMMOBILIZATION ALTERNATIVES

All the immobilization alternatives and variants start with pure PuO_2 from the conversion process described in section 3.1.2 and end up as 5% to 12 % plutonium in a canister weighing ≈2200 kg or less. The total amount of plutonium varies from 51.2 kg to 84 kg. In three of the five variants, plutonium at a concentration from 10% to 12% is contained in smaller cans or bellows contained in the canister. The processing produces attractive intermediate forms with plutonium concentration ≥ 10%. These are in the form of packages with weights from 25 to 35 kg. The theft of just three or four would equal a SQ.

The Proliferation Resistance elements Utility and Accessibility will now be discussed.

5.1.1 Utility

All forms are effectively high grade plutonium ores. The glass and ceramic forms are essentially equivalent for these considerations, except the ceramic would be harder to grind and dissolve. plutonium-loaded DHLW Glass is roughly equivalent to the Utility component of the SFS. The ^{137}Cs loaded Ceramic is a little more resistant than SFS in terms of Utility, as discussed in Section 4.1. The weapons-grade plutonium in the immobilized forms would be preferable to commercial spent fuel for a weapon-state host nation stockpile. For terrorists, either isotopic mix can be made into weapons. Cans or bellows, if separated from the radiation barrier in the surrounding matrix, have a lower Utility component of proliferation resistance than for the SFS since they would no longer require shielded, remote operations for the first steps of the chemical recovery process. However, as noted above, the Utility component is not very large for any of the disposition options. If the material is successfully accessed and removed, the requirements for recovering weapons-usable plutonium are relatively modest.

5.1.2 Accessibility

The immobilization alternatives descriptions in February, 1996 assumed a radiation barrier of 1000R/h at 1 m from the surface at 30 years. This level had been reduced by a factor of 10 in April versions. 100 R/h is certainly less than spent fuel, but in neither case is the radiation level intense enough to force the use of shielding and remote handling during theft.

Table 5.1-1 summarizes the forms of material included in the immobilization alternatives, and some of their features relevant to accessibility. The higher concentration of plutonium in the Immobilization Alternative end forms means five to ten times less total material must be stolen to get 1 SQ than would be the case for most spent fuel. In all cases it is estimated that intrinsic resistance to theft could be overcome in 15 to 30 minutes by one heavy lift helicopter and a few people on the ground. This estimate should apply to all alternatives. This is NOT a vulnerability assessment. It is given to emphasize the importance of institutional safeguards until this material is emplaced and sealed in an underground repository.

Table 5.1-1. Possible Targets

FORM	Material Wt.	Pu Weight	Total Unit Wt.	Wt. per SQ	SQs per Unit
PuO_2	**4.5 kg**	**4 kg**	4 kg	**≈ 9 kg**	1/2
10% Pu Glass in "can"	**25.6 kg**	**2.56 kg**	≈28 kg	**84 kg**	1/3
10% Pu Glass frit in process container	**25.6 kg**	**2.56 kg**	≈28 kg	**84 kg**	1/3
Mt Canister with 20 cans	**980 kg**	**51.2 kg**	**≈ 1400 kg**		**6**
12 % Pu + 50 g ^{137}Cs Ceramic HP in Bellows	**33kg**	**4 kg**	≈ 35 kg	**70 kg**	1/2
Canister with 20 cans in DHLW glass Also for Ceramic Can in Canister	**1680 kg**	**51.2 kg**	**2200 kg**		**6**
Canister with 20 bellows (hot) in TiO_2	**660 kg**	**80 kg**	**2200 kg**		**10**
Canister with 5% Pu in DHLW glass	**1680 kg**	**84 kg**	**2200 kg**		**10**
DHLW Shipping Cask	**5 Canisters in Cask**	**420 kg**	**87,000 kg**		**50**

Based upon the information available for this assessment, the PVRT determined that the cans/bellows are mechanically separable from the canisters in relatively short times with modest resources. Attacks could be tailored for the specific canister design (type of steel, thickness, diameter). Alternative can-in-canister designs could make it more difficult for an adversary to rapidly separate the Pu-bearing cans from the radioactive DHLW matrix. The immobilization alternative design teams are developing specific container materials and attachment schemes to hinder such separation. Success could be claimed when it is more trouble to separate the "cans" than to carry off the canister.

5.1.3 Immobilization Conclusions

In terms of the Utility component of proliferation resistance, the most significant differences between the immobilized end forms and the SFS are: weapons-grade plutonium is more desirable than reactor-grade plutonium (especially for a nuclear nation host's enduring military stockpile); the chemistry for plutonium recovery from the ceramic end forms is more challenging than for spent fuel. Reactor-grade plutonium should not be considered a significant obstacle, however, to the ability of a nuclear host to rearm nor for a terrorist or other unauthorized party to develop a credible nuclear device. Neither the higher plutonium concentrations nor the lower radiation fields of the immobilized forms were considered to be significant in terms of the Utility component of proliferation resistance. Although techniques for recovery from ceramics are not well known presently, this is not considered to be a significant barrier for the long term.

The Intrinsic Accessibility component of proliferation resistance for the immobilized forms is less than that for the SFS against overt theft attempts. This is due to the relatively high concentration of plutonium in these forms, as well as the separability of cans from the surrounding matrix (for can-in-canister). In general, the radiation levels of immobilized forms are lower than spent fuel of the same age, but neither spent fuel nor any of the immobilization end-forms have sufficiently high radiation fields to incapacitate unshielded aggressors during the theft and should not be relied upon to be large Intrinsic Accessibility barriers. Large unit size/mass is not sufficient. Due to the relatively high concentration of plutonium in the immobilized forms, explosives can be used to quickly separate SQ's of plutonium from a canister. In the description of the can-in- canister alternatives available for this examination, it is possible to quickly separate the HLW glass from the radiation-free cans containing 10% plutonium. In any case, unauthorized parties could gain relatively quick access to relatively small amounts of material containing SQs of weapons-grade plutonium, perhaps absent a radiation field, thereby facilitating their ability to escape. However, other designs may be able to mitigate the separability shortfall for can-in-canister.

As is the case with spent fuel, the intrinsic features for immobilized forms should not be relied upon to provide significant levels of proliferation resistance prior to emplacement in an underground repository. Until that time, sufficient institutional measures must be provided to prevent unauthorized parties from accessing and removing sufficient material. The shortfalls in intrinsic barriers relative to the SFS should be recognized in configuring adequate institutional protective measures.

5.2 BOREHOLE ALTERNATIVES

In addition to the general proliferation vulnerabilities discussed in the previous chapter, the Deep Borehole disposition alternatives have a few specific issues associated with them. The potentially significant proliferation vulnerabilities identified for the alternatives are: the bulk processing steps to convert plutonium oxide into ceramic pellets; the option to transport these pellets by commercial carrier; and a more challenging security environment at the wellhead site. The PVRT also examined options for retrieving material from a deep borehole. These topics are summarized below.

5.2.1 Processing for the Immobilized Variant

The immobilized variant envisions incorporating the excess weapons plutonium feed materials into ceramic pellets containing 1% plutonium oxide. The pellet form is considered by the Borehole Alternative team to provide greater assurance against potential nuclear criticality after emplacement in the borehole. It is also considered to be somewhat more resistant to re-use (due to the necessity to extract the plutonium from the ceramic pellet matrix).

In the Direct-Disposal variant for the Borehole Alternative, the plutonium oxide is packed directly into product cans and then into Primary Containment Vessels (PCVs) under DOE Category I-A security and accountability controls. The additional processing of the plutonium oxide into pellets for the Immobilized involves bulk-processing operations. The increased criticality safety after disposal should be weighed against the reduced proliferation resistance during processing for this variant.

5.2.2 Commercial Transport Option

An option described in the Borehole Alternative report for the transport of pellets from the DC&I facility to the Deep Borehole Disposal facility is to use commercial carriers instead of SSTs. This option is possible if the total plutonium content of each shipment is less than 16 kg. The DOE Nuclear Material Attractiveness and Safeguards Categories for plutonium specify that the 1% plutonium-loaded pellets are "Low-Grade Material," and that quantities less than 16 kg make the shipments Category III-D. Such shipments could be transported by commercial carrier under DOE Order 5633.3B. The PVRT considered this option to be a significant reduction in proliferation resistance because of several concerns. Although there may be less than 16 kg in a single shipment, the frequency, regularity, and number of shipments increase the exposure and opportunity for theft or diversion by unauthorized parties. It was felt that the physical security provided by a commercial-transport driver while the material was in transit would be nowhere near the level provided by TSD shipment in SSTs. Since the processing requirements to recover weapons-usable plutonium dilutely immobilized in ceramic pellets are only modest, the consequences of a successful hijack should outweigh the potential cost savings from commercial transport.

5.2.3 Wellhead Security Posture

The Deep Borehole Disposal facility will be protected according to DOE Nuclear Material Attractiveness and Safeguards Categories as a Category-I facility. This implies a robust protective posture and materials accountancy measures. The disposal facility has two very different areas to be protected – the Surface Processing facility (materials storage and processing buildings), and the wellheads for the disposal boreholes. Whereas protection of the Surface Processing facility buildings is based on considerable past experience and practices, the wellheads present different security challenges. The wellheads may be out in the open, (unless it is decided that they must be enclosed by buildings) with fewer access barriers. Open-air sites are more vulnerable to overt attack by adversaries using helicopters.

Furthermore, the vehicles specified in the Borehole Alternative team's proposal for transporting the plutonium from the Surface Processing facility to the wellhead are designed to protect the public only against hazardous-material threats – not against security threats. Overt attacks during transportation from the Surface Processing facility to the wellhead may pose a significant risk.

In the immobilized variant, the 1% plutonium-loaded ceramic pellets are mixed with equal volumes of inert pellets at the wellhead before being emplaced down the borehole. The mixing activity is by nature a bulk process with potentially very large MUF, as identified in Section 4.3. The challenging security environment at the wellhead during this bulk handling process may make effective defense-in-depth more difficult to ensure.

5.2.4 Accessibility of Emplaced Materials

Several methods could be employed to attempt to retrieve the plutonium disposed in the deep boreholes but not without the utilization of special heavy equipment and significant manpower and other resources for at least several months, if not years. The most likely options are:

- Tunnel Boring Machine (TBM) and conventional mining
- Re-entry drilling and *in-situ* leaching
- Directional drilling and *in-situ* leaching
- Shaft drilling and conventional mining

5.2.4.1 Tunnel Boring Machine and Conventional Mining

A tunnel boring machine and mining operation would provide the most efficient access and retrieval. According to Peterson,[1] at a difficult but feasible downward slope of 1:2 (27°) the operation would require access to a surface portal location approximately 4 km from the repository site. Peterson[1] also stated that an advance rate of 100 m/day is possible for a TBM with an average of about 30 m/day in granite. At the Svartisen hydropower project in Norway, TBMs tunneled a total of 57 km in "hard" rock with the best one month average advance rate of 39 m/day.[2] Experience with operating at a significant tunnel slope (20%) indicates a substantial (20%) reduction in efficiency due to cutter wear.[3] However, the formidable but believed achievable TBM advance rate of 100 m/day would require a little over six weeks (4.4 km of tunnel) to reach the top of the emplacement zone of the first hole. This time estimate does not include mobilization and setup that could require at least another three weeks. There will also be the inevitable operational problems and delays that are inherent in major field operations. Once the emplacement zone is reached conventional mining at average of approximately 5 m/day[14] would be used to attain and retrieve the plutonium bearing material or canisters from the emplacement zone at nearly 100% recovery. The second repository hole could be reached in less than a week of TBM operation. The main tunnel could be used to access the two other holes with a side drift or with continued TBM operation.

5.2.4.2 Re-entry Drilling and In-Situ Leaching

If the drilling barriers that are being considered are not utilized or prove ineffective (highly unlikely), re-entry drilling (redrilling through the sealed emplacement hole) may be the most direct and rapid means of accessing the emplacement zone. However, this approach is fraught with great uncertainties about material recovery. Direct circulation of the material to the surface requires ideal particle characteristics and maintaining precise fluid properties and flow conditions. Solution-type mining at this depth would be extremely difficult especially with the nature of the materials and poorly known physical and chemical properties. In situ leaching (ISL) successfully produced uranium from a depth of 610m during the Mobil Crownpoint research and development project[5] but was abandoned as not economical. Historically ISL techniques in the U.S. have only been applied in permeable sandstones at depths less than 300 m.[5] The use of downhole explosives to obtain the desired results of liberating the plutonium and creating material suitable for recovery by circulation or leaching would involve a high level of risk, which is probably why this practice is not employed for ISL in the U.S. Peters,[6] describes why *in situ* leaching is not applicable to most ore bodies, even at shallow depths. Core recovery is feasible for the Immobilized disposal material but again requires material that is "competent" (not friable or fractured) and almost any engineered protection would be difficult to overcome. Borehole "fishing" operations may be considered for the Direct Disposal Alternative but these operations are difficult under normal circumstances and would be extremely difficult and lengthy because the "fish" would be well encapsulated and grouted in the hole.

5.2.4.3 Directional Drilling and In-Situ Leaching

Directional drilling would avoid the drilling barriers that may be installed in the emplacement hole but would still have the recovery challenges. Precision, deep directional drilling in the oil industry has been successfully accomplished for decades but is a time consuming process.[7] Directionally drilling of a hole in granite for the Hot Dry Rock geothermal project in New Mexico to a depth similar to the planned emplacement depth took over 400 days of operation.[8] It may also be difficult to maintain orientation to stay within the emplacement hole while drilling or coring. To recover the entire 50 metric tons of plutonium would require four re-entry, or four directionally drilled holes (could originate from one main hole).

5.2.4.4 Shaft Drilling and Conventional Mining

Conventional mining from the surface could also be employed. It would be less expensive than using a TBM but considerably slower (5 m/day[1]). The top of the emplacement zone could be reached with shaft drilling. Once there, conventional mining would be employed to access and recover the plutonium bearing material. Construction of the 2.3 m-diameter, 1.9 km-deep shaft required over 320 days of drilling and a total operational time of almost two years.[9] All four emplacement holes could be accessed using these techniques with one main shaft and side drifts. Almost complete recovery would be assured. Greater emplacement hole separation would increase the operational time requirements.

5.2.4.5 Other Retrieval Considerations

Other scenarios related to the borehole disposal scheme could be considered. Diversion during the blending and emplacement of the pellet and grout mixture for the Immobilized Disposal Alternative is possible through creative wellhead plumbing hardware. This is a Materials Control and Accountability issue. The proposed emplacement technique is a common industrial practice and it would be extremely difficult to conceal with proper facility design review and inspection procedures. New and advancing technologies such as borehole hydraulic mining, that has shown some promise for certain soft, friable rocks but has yet to become an established technique, and other rapid excavation techniques (e.g., rock melting, sonic drilling), could reduce future proliferation resistance of a geologic repository.

5.2.4.6 Summary of Deep Borehole Accessibility

In summary, access to a deep borehole repository would require readily observable, large excavation equipment (mining or drilling), and surface support facilities in operation for an extensive time period. Therefore, the threat from unauthorized parties is virtually nonexistent. Also, because these operations require the expenditure of extensive resources (making other material sources potentially more attractive) and because of the unavoidable high observability, the threat of undetected recovery by the host is extremely small.

The final disposition of excess weapons plutonium in deep boreholes at the depth interval of 2 to 4 km would make the plutonium even more difficult to access than the commercial spent fuel to be disposed in the high-level waste repository, thus far exceeding the proliferation resistance implied by the SFS.

Thus, no scenario can be conceived of that the host nation or unauthorized parties could employ for retrieval of weapons-usable plutonium, disposed in a geologic repository (either a mined high-level waste repository in the western U.S. or four deep boreholes) that would not require a major operation involving large and special equipment fielded in a conspicuous manner for an extended period of time. Not only would the resources required make the material much less attractive even to the host nation, any attempt to obtain the material could not be accomplished covertly. Both of the proposed alternatives for geologic disposal of the 50 metric tons of excess weapons plutonium would far exceed the level of proliferation resistance implied by the Spent Fuel Standard.

5.2.5 Mitigation Options

The potentially significant proliferation weaknesses identified by the PVRT are as follows:

- Bulk processing steps to convert the weapons plutonium to ceramic pellets,
- Transportation of ceramic pellets by commercial carrier, and
- Reduced security posture during intra-site transportation and emplacement operations at the Deep Borehole site.

Mitigation of the first potential weakness clearly is to not convert the plutonium into ceramic pellets. The decision whether the enhanced post-disposal criticality safety warrants the reduction in proliferation resistance during the conversion process can be aided by ongoing work on disposal criticality being done for the Yucca Mountain Project. As part of the licensing process for the high-level waste repository, a detailed analysis of the risks of potential criticality events will be submitted to the NRC.

The second potential weakness can be remedied by always transporting the plutonium-loaded pellets in specially equipped vehicles under armed escort by federal officers. Should the pellets require intersite transportation, the increased usage of the SST fleet may be a cost concern, but the greater proliferation resistance from this form of transportation may justify such a decision.

The more challenging security posture during intra-site transportation and emplacement operations for the Deep Borehole alternatives may be the area that requires the greatest additional consideration. A successful attack at this stage of the Deep Borehole disposal process could yield terrorists many tens of kg of weapons-grade plutonium. Mitigation options for this potential threat include designing facilities and procedures that reflect the more challenging conditions for this alternative and are resilient to possible future threats. Security at the Nevada Test Site (NTS) clearly demonstrates our ability to do so.

5.2.6 Borehole Conclusions

The Deep Borehole alternatives have fewer transportation and bulk processing steps going from stored weapons to final disposition than the other alternatives. The direct-disposal variant permits item accountability to be maintained on the plutonium throughout most of the process, although the highly concentrated, direct use material requires that very effective institutional protection, at the level of the SWS, be maintained. This may be challenging at the emplacement facility.

Once the material is emplaced, it is effectively unrecoverable without very obvious indications to monitoring observers. After emplacement, the requirements for institutional control can be greatly relaxed, while still maintaining security of the plutonium. However, it must be emphasized that some levels of institutional controls would still be required, in the form of periodic monitoring for retrieval activities and, for domestic safeguards, a response capability to disrupt such activities. Without complementary institutional controls, albeit at a much lower level, the intrinsic barriers to proliferation resistance can still be overcome.

5.3 REACTOR ALTERNATIVES

The radiation barrier intrinsic to spent commercial fuel serves principally to complicate the recovery of plutonium from the fuel by forcing the inclusion of thick shielding and remote operations in the design of the recovery facility. This increases the cost of both the construction and operation of the facility, and complexity and timelines for recovery operations. However, it does not prevent recovery, and the additional technical burdens upon a terrorist operation seem to be relatively modest. Against host diversion, the radiation adds no proliferation resistance since the host already owns facilities capable of performing the recovery operations.
The radiation field is not intense enough to require a sufficiently dedicated adversary to use shielding and remote handling during a theft. The dose rates at 1 m from the fuel are not high enough to deliver a lethal or incapacitating dose during the tens of minutes that a theft might require, assuming close proximity operations to the fuel would be necessary.

Evaluation of the reactor alternatives involved consideration of the operational phases to accomplish the final disposition of WPu in spent fuel elements.

Three discriminating parameters of the reactor options important to proliferation resistance were derived from the review of the reactor alternatives and the above operational phases: reactor type, facility location, and facility ownership.

5.3.1 Reactor Type

The type of reactor used in a reactor option determines the characteristics of the fuel (both fresh and spent) that is available for theft or diversion. The characteristics of the end-state spent fuel that affect the proliferation resistance of a given option are listed in Table 5.3-1. The table also includes data on fuel assemblies from existing reactors operating with the normal fuel cycle (low enriched uranium for BWRs and PWRs or natural uranium for CANDUs). Since the fuel assemblies in the reactor options are outwardly identical to the assemblies in reactors operated on the normal fuel cycle, the size and mass of the assemblies are the same. The largest differences between the reactors used for plutonium disposition and their counterparts on the normal fuel cycle are in the plutonium content of the heavy metal (HM) and therefore the plutonium mass per assembly. The radiation dose rates, which are primarily determined by the burnup of the fuel, are equivalent between the MOX-burning reactors and the uranium-burning reactors.

As can be seen from the table, all of the reactor options yield end-state spent fuel that is richer in plutonium content than the corresponding reactors operated on the normal fuel cycle. The MOX fuel is from a factor of two to a factor of five higher in plutonium content. This represents a somewhat lower Accessibility barrier for the MOX fuel because of the smaller mass of material that must be stolen to obtain a given quantity of plutonium.

5.3.2 Location of Facilities

The location of the facilities used in the reactor options (Pu conversion, MOX fuel fabrication, reactor) affects the exposure of the plutonium due to transportation and in some cases requires that U.S. custody of the weapons-grade material be surrendered. In the options involving CANDU reactors, custody of the plutonium is permanently transferred to Canada during transport of the MOX fuel from the fabrication facility to the reactor.

Two options use a co-functional plutonium processing and MOX fabrication facility, thereby eliminating a transportation step involving high-grade plutonium dioxide. Elimination of the transport of 50MT of plutonium oxide is a very desirable attribute of these options.

Reactor alternative R2.2 includes transport of plutonium oxide to Europe for MOX fabrication and return of MOX fuel to the U.S. for reactor irradiation. These shipments would involve transport in the U.S. by SST, ocean leg by ship, and truck or rail transport in Europe. Category I material would leave custody of the U.S. at dockside until return to a U.S. port. Safeguard and security of this material outside of the U.S. would be the responsibility of IAEA and Euratom not the U.S. military or DOE. Thus, U.S. continuity of knowledge during this time would not be maintained. Since loss of sufficient plutonium would have the same consequences regardless of who the custodian is, the security during this phase would need to be ensured.

Reactor alternative R6.0 includes transport of MOX CANDU fuel to Ontario by DOE SSTs. It includes crossing the U.S.-Canadian border at which time the U.S. DOE would no longer have ownership of the material nor the full response capability available during domestic transport. Safeguard and security of this material would be the responsibility of the IAEA, AECL and the Canadian government. Although to a lesser degree, the issues of foreign transport mentioned above also apply here. CANDU spent fuel would remain in Canada ultimately to be placed in a Canadian geological repository. It should be noted that the CANDU options provide the greatest

Table 5.3-1. Characteristics Important to Proliferation Resistance of Spent Fuel Assemblies Produced by the Reactor Options

Variant	Reactor	Pu Content (% HM)	Pu Mass (kg)	Long Dim. (m)	Mass (kg)	Dose Rate[a] (rem/hr)
2.0/2.1/2.2	BWR	1.94	3.3	4.55	303	~600
2A.0	PWR	3.5	15	3.81	664	~1400
3.0/3.2	adv PWR	5.14	21	3.8	664	~1400
3.1	adv PWR	5.1	24	4.35	686	~1400
6.0	CANDU	0.81	0.15	0.5	24	~30
6.1	CANFLEX	1.4	0.25	0.5	24	~50
Reactors on "normal" fuel cycle						
BWR on LEU		~1	2	4.55	303	~600
PWR on LEU		~1	5	3.81	664	~1400
CANDU on Natural U		~0.4	0.07	0.5	24	~30

[a] *The dose rates given are approximate and are at 1 m from the surface of the fuel assembly at the midplane*

barrier to recovery by the U.S. of this plutonium, although comparable issues as before apply to the new host.

5.3.3 Ownership of Facilities

The ownership of the MOX fabrication facility and the reactors can be either private, federal, or foreign, depending on the option. The plutonium processing facility is always a federally-owned facility. The relative proliferation resistance of these three types of ownership is covered in Section 4.4. In particular, the issue of differing policies for use of deadly force to protect Category I or II material in private NRC-licensed facilities was identified as a feature of lower proliferation resistance, albeit one that can likely be mitigated through appropriate legislation.

It is noted in passing that the ten Phase II reactor alternatives did not include any partial MOX cores. The PVRT examined partial (1/3) MOX core loadings for possible relevance to this proliferation vulnerability study. It was concluded that partial MOX core loading had no significant effect on the proliferation resistance of the reactor base case (R2.0). The PVRT did not pursue the question of full MOX vs 1/3 MOX any further. However it was noted that the exclusion of partial MOX core loading will seriously restrict the availability of existing LWRs to implement this WPu disposition program. Obtaining license amendments necessary to load full

MOX cores into existing LWRs will prove to be very difficult. On the other hand, 1/3 MOX loading may be relatively straightforward for many of the existing LWRs.

5.3.4 Reactor Conclusions

- All of the reactor options yield end-state spent fuel that is richer in plutonium than the corresponding reactors operated on an LEU fuel cycle. The MOX fuel is from a factor of two to a factor of five higher in plutonium content. This affects the accessibility of the material because a thief must steal a smaller mass of material to obtain a given quantity of plutonium.
- Spent fuel is not self-protecting against sufficiently dedicated adversaries. The radiation barrier is insufficient to require shielding during theft. The large storage casks can be breached and the spent fuel assemblies can be subdivided, if necessary, at the theft site. It does forceshielding during reprocessing, increasing the recovery resource requirements and timelines. However, these are still relatively modest.
- Many of the facilities in some of the reactor options are assumed to be private, NRC-licensed facilities. These are currently subject to more restrictive deadly force policies than DOE Category 1 facilities, and are thus considered less proliferation resistant.
- Transfer of U.S. WPu to others is uniquely associated with some of the reactor options. When this occurs, the U.S. no longer has responsibility or control of domestic safeguards.
- The reactor alternatives are the only ones that change the isotopics of WPu. Although this is most important to a weapons state from the standpoint of rebuilding an enduring military stockpile, it does not preclude rapid rearmament.

5.4 LONG-TERM STORAGE ALTERNATIVES

Plutonium has been stored for many years and will continue to be stored for at least as long as the U.S. maintains a strategic reserve. The protection afforded stored nuclear weapons is considered to be the standard against which all stages of plutonium disposition for the various alternatives are to be compared. The spent fuel standard is applied to final forms and relies more on intrinsic properties and less on institutional barriers.

In considering the storage alternative, it was assumed that pits will be stored as pits and that all other plutonium will be in the form of metal or stabilized oxide in inerted, welded material containers. Surplus plutonium will be stored in the same way as strategic reserve plutonium except that provisions may be made for international inspections.

To evaluate the proliferation resistance of long-term storage, it is first necessary to consider the threats. Pits stored in a vault provide no resistance to the overt host-nation threat. Covert host-nation diversion could be addressed by international monitoring (in real-time, if necessary) of discrete items stored in a vault. However, acceptable verification and monitoring measures for pits in storage have not yet been resolved. Terrorist/subnational threats, especially in Russia, are of most immediate concern (the "clear and present danger"). Storage is potentially more resistant to this threat than any other alternative, simply because it minimizes bulk processing and transportation. This statement is qualified because storage relies so heavily on institutional barriers; if not done right, storage could be very vulnerable.

In discussing the disposition stages of the various alternatives, the NAS study recommended that plutonium be protected to the "stored weapons standard" until the form meets the "spent fuel standard." This is easier said than done, as discussed in this report. These considerations are even more important in Russia.

A key recommendation of the 1994 NAS study on Management and Disposition of Excess Weapons Plutonium[10] was:

> Disposition options beyond storage should be pursued only if they reduce overall security risks compared to leaving the material in storage, considering both the final form of the material and the risks of the various processes required to get to that state. In the current unsettled circumstances in Russia, this minimum criterion is a significant one.

After a disposition alternative is chosen, it will take about 10 years for actual disposition to begin and another 10 to 25 years before it is completed (assuming more plutonium is not declared surplus). During that time the surplus plutonium will have to be stored in addition to the plutonium in the strategic reserve, which will be stored indefinitely. The differences in the proliferation resistance between the storage alternatives are small relative to the differences between any of the storage alternatives and any of the other disposition alternatives; i.e. all of the disposition alternatives require more transportation and more processing than any of the storage alternatives. Since weapon disassembly occurs at Pantex, subsequent transportation could be minimized by storing the pits at Pantex and storing the rest of the surplus plutonium where it currently resides.

5.4.1 Storage Conclusions

Continued storage minimizes processing and transportation and, on that basis, is more proliferation resistant against threats from unauthorized parties than any of the disposition alternatives. But this does not mean that disposition should not be undertaken; only that due consideration must be given to the risks involved in transforming plutonium into forms meeting the spent fuel standard. Unless acceptable mechanisms are established for international verification and monitoring of plutonium storage, it provides essentially no resistance to host diversion for rearmament.

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[1] Peterson, Per F., Long-Term Retrievability and Safeguards for Immobilized Weapons Plutonium in Geologic Storage, US DOE Plutonium Stabilization and Immobilization Workshop, Washington, D.C., Dec. 12-14,1995.

[2] Drake, J. and Johansen, E. D., 1993, Hard Rock Boring at the Svartisen Hydroelectric Project, in Options for Tunnelling 1993, H. Burger editor, Developments in Geotechnical Engineering, 74; Elsevier Science Publishers.

[3] Whittaker, B. N. and Frith, R. C., 1990, Tunneling: Design Stability and Construction, Institute of Mining and Metallurgy, London England, Stephen Austin/Hertford Publisher.

[4] Tunnel Engineering Handbook, 1996, Chapman and Hall, 2nd Edition; Bickel, John O.; Kuessel, Thomas O.; and King, Elwyn H., Editors.

[5] Underhill, D. H., In-Situ Leach Uranium mining in the United States of America: Past, Present and Future, IAEA Report, October, 1992.

[6] Peters, William C., Exploration and Mining Geology, Wiley and Sons, p. 199-207, 1978.

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[7] Bruist, E. H., 1972, A New Approach in Relief Well Drilling, Journal of Petroleum Technology, June, 1972.

[8] Rowley, John C. and Schuh, Frank, J., Experience from Crystalline Rock Drilling and Technology Directions for Effective Ultra-Deep Coring and Drilling, Conference on Observations of the Continental Crust through Drilling, III, Chalmers University of Technology, Mora and Orsa, Sweden, September 7-10, 1987.

[9] Fenix and Scisson, Inc., Time and Cost Study UA-1, Informal report to the USAEC, Nevada Operations Office, May, 1970.

[10] "Management and Disposition of Excess Weapons Plutonium," National Academy of Sciences, 1994, p.226.

6. CONCLUSIONS

Keeping plutonium inaccessible is the key to proliferation resistance.

All plutonium from all stages of all alternatives can be made weapons usable, should sufficient material be successfully removed. For the host nation it is no problem at all. Although weapons-grade plutonium is preferable for the development and fabrication of nuclear weapons and nuclear explosive devices, reactor grade plutonium can be used. The technology for recovering plutonium from spent fuel is in the open literature and can be adapted for the material forms within the alternatives. The resources required for the recovery of a significant quantity of plutonium are estimated to be relatively modest. The presence of a radiation barrier sufficient to require shielding and the complexity of the mechanical and chemical processing steps during recovery provide the greatest discrimination among the material forms. However, a small, well-prepared group could recover sufficient plutonium for a device within perhaps two months. Thus, the Utility barrier is not sufficient. Keeping plutonium inaccessible is the key to proliferation resistance.

Certain interim stages of every disposition alternative are less proliferation resistant than the stored weapons standard.

Transportation and bulk-processing stages are less proliferation resistant than levels implied by the stored weapon standard. The frequent and long-term transport of very attractive materials for this program increases its exposure. The disposition options should be configured to minimize this exposure, such as through collocation of facilities, and utilizing SSTs for domestic intersite legs. Limitations in materials accountancy during bulk processing of material, especially in concentrated form, provide a window of opportunity for covert diversion by careful and resourceful adversaries, and trends in the security environment raise challenges to maintaining effective protection-in-depth over the duration of the disposition campaign. Since continued storage minimizes these stages, it is the most proliferation resistant of the options considered against unauthorized threats, although it provides essentially no resistance to host diversion. These concerns may be exacerbated for Russian implementations.

Intrinsic features of final forms relax but do not replace institutional requirements.

One of the primary goals of the disposition program is to put the plutonium in a form that is roughly as unattractive and inaccessible for retrieval and weapons use as the much larger and growing stock of plutonium in civilian spent fuel. However, the intrinsic features of spent fuel (radiation field, chemical composition, plutonium dilution, size, weight, etc.) are insufficient to protect it from sufficiently dedicated adversaries with relatively modest resources. The institutional protection provided by domestic safeguards is necessary to augment the intrinsic barriers. The intrinsic barriers for the immobilized end forms are currently somewhat less than those implied by the SFS due to lower dilution and the separability of cans from the surrounding radioactive matrix, although these can likely be mitigated and the security posture can be graded accordingly. Sealing any of the end forms in a geologic repository imposes very long and observable access requirements, and enables the institutional measures to be greatly relaxed.

Host diversion cannot be prevented, but undetected breakout for rearmament is unlikely.

Even with IAEA monitoring, covert diversion of several SQs a year during disposition is a possibility because of the large MUF resulting from high throughput bulk-processing operations, the long campaign times, and the host country control of the security and accountancy

MS 0342	Mark J. Davis, 1880 (4)
MS 0405	David E. Bennett, 12333 (4)
MS 0463	R. L. Hagengruber, 5000
MS 0567	Ken J. Ystesund, 5318 (4)
MS 0939	John A. Milloy, 7900 (4)
MS 1131	Lyle W. Kruse, 5849 (4)
MS 1146	Gary A. Harms, 9363 (4)
MS 1168	Douglas H. Garbin, 9322
MS 1326	Ralston W. Barnard, 6851 (4)
MS 9001	Thomas O. Hunter, 8000
MS 9004	M. E. John, 8100
MS 9005	J. B. Wright, 2200
MS 9005	Bill G. Wilson, 2204 (5)
MS 9015	Carolyn Pura, 2221 (5)
MS 9201	Patricia K. Falcone, 8114
MS 9201	John P. Hinton, 8114 (10)
MS 9201	William A. Swansiger, 8114 (4)
MS 9405	Robert W. Crocker, 8230 (4)

MS 9021	Technical Communications Department, 8815 for OSTI (10)
MS 9021	Technical Communications Department, 8815/Technical Library, MS 0899, 4414
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