SANDIA REPORT
SAND 2008-1403
Unlimited Release
Printed February 2008

NON-PROLIFERATION IMPACT ASSESSMENT FOR GNEP: ISSUES ASSOCIATED WITH TRANSPORTATION

Ross Radel and Gary Rochau

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online order:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2008-1403
Unlimited Release
Printed February 2008

Non-Proliferation Impact Assessment for GNEP: Issues Associated with Transportation

Ross Radel and Gary Rochau
Fuel Cycle Experiments and Analysis
Nuclear Energy and Global Securities Technology Center
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0748

Abstract

This report evaluates transportation issues for nuclear material in the proposed Global Nuclear Energy Partnership (GNEP) fuel cycle. Since many details of the GNEP program are yet to be determined, this document is intended only to identify general issues. The existing regulatory environment is determined to be largely prepared to incorporate the changes that the GNEP program will introduce. Nuclear material vulnerability and attractiveness are considered with respect to the various transport stages within the GNEP fuel cycle. Physical protection options are then outlined for the transportation of this nuclear material. It is determined that increased transportation security will be required for the GNEP fuel cycle, particularly for international transport. Finally, transportation considerations for several fuel cycle scenarios are discussed. These scenarios compare the current “once-through” fuel cycle with various aspects of the proposed GNEP fuel cycle.

CONTENTS

FIGURES

TABLES

ACRONYMS

ABR	Advanced Burner Reactor
CFR	Code of Federal Regulations
DOE	Department of Energy
DOT	Department of Transportation
GNEP	Global Nuclear Energy Partnership
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ISSM	Integrated Safeguards and Security Management
LLW	Low Level Waste
LWR	Light Water Reactor
MOX	Mixed Oxide
NRC	Nuclear Regulatory Commission
OST	Office of Secure Transport
SNF	Spent Nuclear Fuel
TAD	Transportation, Aging, and Disposal
TRU	Transuranic
UN	United Nations

1. INTRODUCTION

This paper overviews transportation issues for spent nuclear fuel and other nuclear materials generated in the proposed Global Nuclear Energy Partnership (GNEP) nuclear fuel cycle. The existing regulatory environment is summarized and evaluated for its preparedness to incorporate the changes that the GNEP program will introduce. Nuclear material vulnerability and attractiveness are considered with respect to the various transport stages within the GNEP fuel cycle. Finally, transportation considerations for several fuel cycle scenarios are discussed.

1.1. Global Nuclear Energy Partnership

The Global Nuclear Energy Partnership, as introduced in early 2006, is a plan to work with other nations to develop and deploy advanced nuclear recycling and reactor technologies (GNEP 2006). It combines a major technology development initiative with a major international policy initiative. The objective of the GNEP program is to spur the development of nuclear energy with less of the waste burden of older technologies. This is to be accomplished without making available separated pure plutonium that could be used by rogue states or terrorists for nuclear weapons production.

The GNEP program is an ambitious attempt to create a sustainable future for nuclear energy in the United States and across the world. The goals of the GNEP program include (GNEP 2006):

- expanding nuclear power in an environmentally sustainable manner,
- developing and deploying spent nuclear fuel (SNF) reprocessing technologies in a manner that does not separate pure plutonium,
- reducing inventories of civilian plutonium and civilian spent fuel,
- ensuring the need for a single geologic repository this century in the United States,
- developing and deploying advanced burner reactors that consume transuranic elements from recycled SNF,
- developing and deploying advanced, proliferation resistant reactors appropriate for power grids of developing countries,
- establishing nuclear fuel supply and SNF return arrangements among nations to encourage the use of nuclear energy without spreading enrichment and reprocessing technologies, and
- developing enhanced nuclear safeguards, in cooperation with the International Atomic Energy Agency (IAEA), to monitor nuclear materials and facilities to ensure peaceful use of nuclear technology.

It is envisioned that the culmination of these goals will result in a fuel cycle such as that pictured in Figure 1. The U.S. Light Water Reactor (LWR) fleet produces SNF at a rate of approximately 2000 metric tonnes per year. These LWRs will likely be replaced by Generation III+ and/or Generation IV reactors. It is envisioned that the LWR spent fuel will be used as feedstock for the GNEP fuel cycle.

The proposed LWR SNF separation facility separates the constituents of LWR SNF into a series of product and waste streams. Fission products and structural material will be disposed as either Low Level Waste (LLW) or High Level Waste (HLW). Unused uranium will be separated and placed in storage or recycled back into the fuel supply (this is yet to be determined). The major actinides, including plutonium, will be recycled into fuel for advanced burner reactors (ABR). Irradiation in the ABR results in a partial destruction of the transuranic (TRU) material, with a fraction of the original TRU remaining in the spent fuel, along with newly created fission products. A second separations process, labeled 'Transmutation Fuel Separation' in Figure 1, will extract the remaining TRU and uranium from the ABR fuel. The remaining material will be sent to either LLW or HLW disposal sites. A variation of this process introduces an intermediate step where uranium and TRU are used to create mixed-oxide (MOX) fuel, which is burned in light water reactors and then recycled.

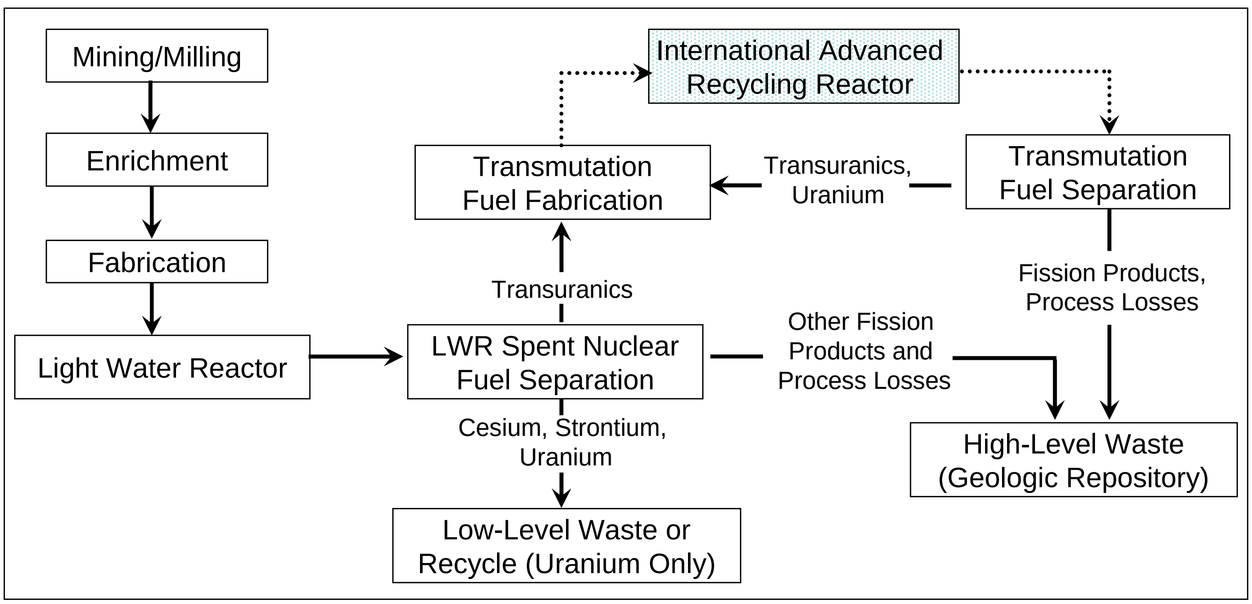

Figure 1. Proposed GNEP fuel cycle (adapted from GNEP 2006).

While the primary mission of the GNEP program is the peaceful sharing of advanced nuclear technology for peaceful use, it is recognized that barriers must simultaneously be developed to mitigate the chance of non-peaceful diversion of this technology and associated nuclear materials. The risk of non-peaceful use of the civilian nuclear fuel cycle comes from two principal sources. The first is a nation desiring the capability to build nuclear weapons on a shortened timetable. This risk is addressed by keeping enrichment and reprocessing facilities in "fuel service" countries and transporting fuel and SNF to and from the user countries. The second threat is a terrorist group wanting to steal nuclear materials to fabricate an improvised nuclear device or a dirty bomb. This risk is reduced by eliminating, over time, excess stockpiles of civilian plutonium and by providing adequate physical protection at nuclear facilities and during transportation.

1.2. Nuclear Material Transportation

Transporting nuclear materials is not a new endeavor. In the past six decades, significant experience has been gained in transporting nuclear material, both in the civilian and military sectors. Millions of miles have been safely logged without incident. While the fuel cycle shown in Figure 1 represents a significant departure from current practices, the domestic transportation requirements within the current GNEP fuel cycle are not dramatically different from existing practices. Moreover, the existing Nuclear Regulatory Commission (NRC) and Department of Transportation (DOT) regulations will likely cover most of the actions proposed in the GNEP program, as discussed in Chapter 2. However, there are two fundamental shifts in the proposed GNEP program that will require new thinking and perhaps new regulation. One is the increased use of plutonium in Category I quantities. The transport of large quantities of plutonium is not often required in the civilian sector, even in a non-separated form. This material also has an increased desirability to terrorist organizations, as discussed in Chapter 3. The second shift is the international nature of the GNEP fuel cycle. The introduction of international civilian nuclear material transport in significantly larger quantities will require new considerations, and will require close cooperation with the IAEA.

2. REGULATORY ENVIRONMENT

The United States agencies responsible for regulating the transport of radioactive materials are the U.S. Department of Transportation (DOT) and the U.S. Nuclear Regulatory Commission (NRC). In addition, the International Atomic Energy Agency (IAEA), along with the United Nations (UN) establishes safety standards for the international transport of nuclear materials. Member states are then responsible for regulation. Since many GNEP components will originally be operating at Department of Energy (DOE) facilities, these regulations are relevant as well. These regulating bodies typically provide generalized policies, allowing user entities the freedom to follow the guidelines as best they see fit. Due in part to this broad nature, the policies currently in use will generally be applicable to GNEP fuel and SNM transport. However, as the GNEP program moves forward, attention will need to be paid to the regulations to ensure that the regulatory environment can be adapted to meet the changing needs.

The primary regulations, standards, and requirements of interest for transportation of GNEP material are 10CFR71 (Code of Federal Regulations), 10CFR73, 10CFR74, 49CFR172-180, DOE-P-470, IAEA-TS-R-1, and IAEA-INFCIRC/225. Each of these regulations, and its relationship with the envisioned GNEP program, is described below. A more detailed discussion of the U.S. regulatory environment as it applies to GNEP is found in *Transportation and Storage Regulations Applicable to the GNEP* (Yoshimura 2007).

2.1. U.S. Nuclear Regulatory Commission

10CFR71: Packaging and transportation of radioactive material. This regulation sets the requirements for packaging, preparation for shipment, and transportation of Type A(F) and Type B quantities of radioactive material. Although the physical form of GNEP high-level waste is undecided, the heat loads and radiation fields on packaging should be enveloped by current 10CFR71 regulations.

10CFR73: Physical protection of plants and materials. This code regulates the physical protection of radioactive materials at fixed sites and in transit. This regulation also defines Categories I, II, and III quantities of SNM for transit (see Table 1). The transmutation fuels envisioned for GNEP will need to be evaluated based on their SNM isotopic masses to determine physical protection requirements. Likewise, the separated actinides will need to be evaluated to determine physical protection requirements. Unirradiated transmutation fuel will likely contain Category I quantities of SNM, although details of the fuel forms are yet to be determined.

10CFR74: Material control and accounting of special nuclear material. Categories of SNM are defined in 10CFR74 (see Table 1). This code also regulates the material control and accounting (MC&A) of SNM at fixed sites and for documenting the transfer of SNM. As the specifics of the GNEP fuel cycle are defined, the MC&A requirements will need to be evaluated, and the applicability of 10CFR74 be assessed. As many portions of the GNEP fuel cycle contain plutonium, significant MC&A requirements will likely be imposed.

Table 1. Definitions of Category I, II, and III SNM (adapted from 10 CFR 73).

Nuclear Material	Form	Quantity		
		Category I	Category II	Category III
Plutonium-239	Unirradiated	2 kg or more	Less than 2 kg, but more than 500 g	500 g or less, but more than 15 g
Uranium-235	Unirradiated: Uranium enriched to 20% U-235 or more	5 kg or more	Less than 5 kg, but more than 1 kg	1 kg or less, but more than 15 g
Uranium-235	Unirradiated: Uranium enriched to 10%- 20% U-235	N/A	10 kg or more	Less than 10 kg, but more than 1 kg
Uranium-235	Unirradiated: Uranium enriched up to 10% U-235	N/A	N/A	10 kg or more
Uranium-233	Unirradiated	2 kg or more	Less than 2 kg, but more than 500 g	500 g or less, but more than 15 g
Fuel consisting of depleted or natural uranium, thorium, or low-enriched fuel (<10% fissile content)	Irradiated	N/A	More than 500 g of plutonium	500 g or less, but more than 15 g of plutonium

2.2. U.S. Department of Transportation

49CFR172: Hazardous materials table … and training requirements. Sections 310, 403, 436, 438, 440, and 556 of 49CFR172 pertain to marking and labeling of radioactive material. Section 800 describes the requirements for the development and implementation of plans to address security risks related to the transportation of hazardous materials in commerce. A hazardous material applicable to GNEP will be highway route-controlled quantities of a Class 7 (radioactive) material, as defined in 47CFR173.403, in a motor vehicle, rail car, or freight container.

49CFR173: Shippers--general requirements for shipments and packaging. Sections 401-476 provide general requirements for the transport of radioactive materials. The scope, as stated in Section 401, states, "This subpart sets forth requirements for the packaging and transportation of Class 7 (radioactive) materials by offerors and carriers subject to this subchapter. The requirements prescribed in this subpart are in addition to, not in place of, other requirements set forth in this subchapter for Class 7 (radioactive) materials and those of the Nuclear Regulatory Commission in 10CFR71."

49CFR174: Carriage by Rail. Sections 700-750 provide requirements for Class 7 (radioactive) materials during rail transport. These include special handling requirements (700), regulations for radiation levels of transport cars after use (715), and requirements for leakage incidents (750). It is noteworthy that rail cars that only transport radioactive material are held to lower standards (10 mRem/hr at the interior surface) for cleanliness if labeled "for radioactive materials use only."

49CFR175: Carriage by Aircraft. Sections 700-705 provide requirements for Class 7 (radioactive) materials during air transport. These include limitations and requirements (700) and special requirements for plutonium shipments (704). However, it is unlikely that significant quantities of GNEP material will be transported by air.

49CFR176: Carriage by Vessel. Part 176 provides requirements for vessel transport. Section 69 provides stowage requirements for hazardous materials.

49CFR177: Carriage by Public Highway. Section 842 regulates the transport of Class 7 (radioactive) materials during transport on public highway. Section 843 regulates contamination levels of transport vehicles.

49CFR178: Specifications for Packagings. Part 178 regulates the manufacturing and testing specifications for packaging and containers used for the transportation of hazardous materials in commerce. Subpart K provides specifications for transport of radioactive materials.

49CFR179: Specifications for Tank Cars. Part 179 regulates the manufacturing and testing specifications for tank cars used for the transportation of hazardous materials in commerce.

49CFR180: Continuing Qualification and Maintenance of Packagings. Part 180 prescribes requirements pertaining to the maintenance, reconditioning, repair, inspection and testing of packaging.

2.3. U.S. Department of Energy

DOE-P-470: Integrated Safeguards and Security Management (ISSM) Policy. Since many GNEP components will originally be operating at DOE facilities, these regulations will be important for GNEP. Section 4.1 establishes requirements for safeguards and security planning, evaluation, and management within the DOE complex. Section 4.2 integrates physical protection into DOE operations. Section 4.6 prescribes DOE requirements for MC&A at DOE facilities.

2.4. International Agencies

IAEA-TS-R-1: Regulations for the Safe Transport of Radioactive Material. Guidelines are specified for radiation protection and emergency response. Requirements are set for nuclear material packaging and shipment

IAEA-INFCIRC/225: The Physical Protection of Nuclear Material and Nuclear Facilities. Section 8 details the requirements for physical protection of nuclear material during transport. Separate requirements for Category I, II, and III special nuclear material are specified.

Convention on the Physical Protection of Nuclear Material. This international convention was signed in 1980 and amended in 2005 (although the amended convention is not yet in force). The convention makes it legally binding for countries to protect nuclear facilities and material in peaceful domestic use, storage as well as transport. It also provides for expanded cooperation between and among states regarding rapid measures to locate and recover stolen or smuggled nuclear material, mitigate any radiological consequences of sabotage, and prevent and combat related offences.

Recommendations on the Transport of Dangerous Goods. The so-called "Orange Book" is produced by the United Nations (UN) Economic and Social Council. In the special case of nuclear material, work is coordinated with the IAEA. These recommendations address the following areas:

- List of dangerous goods most commonly carried and their identification/classification
- Consignment procedures: labeling, marking, and transport documents
- Standards for packaging, test procedures, and certification
- Standards for multimodal tank-containers, test procedures and certification

2.5. Chapter Summary

The United States agencies responsible for regulating the transport of radioactive materials are the U.S. DOT and the U.S. NRC. In addition, the UN and IAEA establish safety standards for the international transport of nuclear materials. The primary regulations and standards of interest for transportation of GNEP material are 10CFR71, 10CFR73, 10CFR74, 49CFR172-180, DOE-P-470, IAEA-TS-R-1, and IAEA-INFCIRC/225. U.S. Nuclear Regulatory Commission regulations set requirements for packaging, transportation, physical protection, and accounting of high activity nuclear material during transportation. U.S. Department of Transportation regulations set requirements for LLW packaging, labeling, handling, and maintenance for nuclear material packaging during shipment via rail, air, ship, or truck. The U.S. Department of Energy ISSM policy establishes requirements for safeguards and security planning, evaluation, and management within the DOE complex. The International Atomic Energy Agency sets safety standards for international transport of nuclear material.

3. GNEP TRANSPORTATION CONSIDERATIONS

When evaluating the needs of a physical protection system, it is first necessary to determine the scope of the threat. The threat addressed in this paper is primarily that of a non-state entity (i.e. terrorist group) wanting to steal or disperse nuclear materials. In order to determine the level of this threat at each stage of the proposed GNEP fuel cycle, two measures must first be established - the vulnerability and attractiveness of the nuclear material.

3.1. Nuclear Material Vulnerability

Material vulnerability is often categorized by the physical protection system in which the material is placed (Bari 2006). In the case of transportation, however, this system is located in a public area by default. Physical vulnerability is discussed in detail in *Vulnerability Analysis Considerations for the Transportation of Special Nuclear Material* (Purvis 1999) and physical protection considerations for transportation are discussed in *The Design and Evaluation of Physical Protection Systems* (Garcia 2001). However, there are other factors that impact special nuclear material vulnerability. In this section, vulnerability is characterized by the physical and chemical form the material takes, the inherent isotopic content, and radiological hazard of handling it. For these factors, the vulnerability of a material is directly related to its attractiveness, as described below. For example, pure plutonium metal is highly vulnerable for use in a nuclear explosive. It is therefore also highly attractive as a target for theft.

3.2. Nuclear Material Attractiveness

Attractiveness is based on the nuclear material's effectiveness for use in a nuclear weapon. The Department of Energy established attractiveness and *category* levels in Table 2 of DOE M 470.4-6, *Nuclear Material Control and Accountability* (DOE 2001). This information is reproduced in Table 2 below. In the DOE graded physical protection system, there are five levels of material attractiveness (A to E, based on physical form, isotopic content, chemical composition, and radiation level), and four physical protection categories (I to IV, based on quantity of material present). Separate categories are used for Pu/U-233 and U-235/Np-237. The information is used by the U.S. DOE in specifying the physical protection requirements for materials that could be potential theft targets for use in nuclear explosives.

Table 2. Summary of SNM attractiveness levels and categories (adapted from DOE 2001).

	Attractiveness Level	Pu/ U-233 Category (kg)				U-235/ Np-237/ Am-241/ Am-243 Category (kg)			
		I	II	III	IV	I	II	III	IV
WEAPONS: Assembled weapons and test devices	A	All	N/A	N/A	N/A	All	N/A	N/A	N/A
PURE PRODUCTS: Pits, major components, button ingots, recastable metal, directly convertible materials	B	>2	>0.4< 2	>0.2<0.4	<0.2	>5	>1<5	>0.4<1	<0.4
HIGH-GRADE MATERIALS: Carbides, oxides, nitrates, solutions (>25 g/L) etc.; fuel elements and assemblies; alloys and mixtures; UF_4 or UF_6 (> 50% enriched)	C	>6	>2<6	>0.4<2	<0.4	>20	>6<20	>2<6	<2
LOW-GRADE MATERIALS: Solutions (1 to 25 g/L), process residues requiring extensive reprocessing; moderately irradiated material; Pu-238 (except waste); UF_4 or UF_6 (> 20% < 50% enriched)	D	N/A	>16	>3<16	<3	N/A	>50	>8<50	<8
ALL OTHER MATERIALS: Highly irradiated forms, solutions (<1 g/L), uranium containing <20% U-235 or <10% U-233[1] (any form, any quantity)	E	Any reportable quantity[2] is Category IV							

[1] The total quantity of U-233 = [Contained U-233 + Contained U-235].
[2] A reportable quantity is 1 gram or more of Pu-239 to Pu-242 and enriched uranium, and 0.1 g of Pu-238.

Materials that fall within attractiveness levels A to D in quantities within category levels I to III have restrictive physical protection requirements. In contrast, materials that are highly irradiated, as well as all forms of uranium with enrichment below 20%, are assigned the lowest attractiveness level: Level E. All Level E materials fall under the least protective safeguards requirements of Category IV. In general, these materials are both intrinsically difficult to handle and remove from a facility, (i.e., they are bulky and/or radioactive), and they are difficult to process into weapons-usable forms after removal. Current LWR fuel falls into Level E. However, the advance fuel cycle proposed in GNEP will generate materials that fall into higher levels. For example, an unirradiated ABR fuel assembly would have a rating of CAT I-C in the plutonium category. However, these ratings are set by the DOE; the NRC has not established attractiveness levels. Such a shipment will be jointly regulated by the NRC and DOE, which may add additional complication.

3.3. Evaluation of the GNEP Fuel Cycle

Having defined levels of nuclear material desirability and vulnerability, these parameters will be used to evaluate the inherent risk of theft or dispersion during the various stages of the proposed GNEP fuel cycle, as pictured in Figure 1.

Ore Transport to Fabrication/Fuel Transport to LWR

The beginning of the GNEP fuel cycle involves only natural, depleted, or low-enriched uranium. In addition to requiring more advanced technology to generate a nuclear weapon, the large volumes of material required make theft during transport more difficult. Thus, this material falls into CAT IV-E and is not considered a proliferation risk, as seen in Table 2.

Cesium, Strontium, and Uranium from LWR Spent Fuel Separation to Storage

Cesium and strontium cannot be used to construct nuclear weapons, and therefore pose no proliferation risk. However, their transport (if transported from the separations site) will require security due to their attractiveness for a dispersion event or theft for use in a dirty bomb. The U-235 enrichment in the spent uranium will be lower than typical LWR fuel, but higher than in natural uranium. This material falls into Attractiveness Level E in Table 2, and is not a proliferation risk.

Fission By-Products from LWR Spent Fuel Separation to High Level Waste Storage

Due to its use in nuclear weapons, tritium is a material of strategic importance; therefore, a graded safeguards program is in place for its transportation. As it is not a fissile material, it is not found in any attractiveness category shown in Table 2. If tritium is placed into modules for storage (this is yet to be determined), it must be protected and monitored during transport like fissile material.

Transuranic Material Transportation

Once the transuranics have been extracted at the separation facility, the attractiveness level of the nuclear material remains heightened. Transport of TRU material to the transmutation fuel fabrication facility, the burner reactor, and the transmutation fuel separation facility will all fall within similar physical protection guidelines. If burner reactors are exported to other countries, the transport of TRU fuel to and from the reactor will occur outside of the U.S. As some of these countries don't have the same level of infrastructure as the U.S. (i.e. local first responders), international transport will likely require additional security measures for TRU fuel transport.

The high radiation levels of this material make it somewhat 'self-protecting' (Hassberger 2001). However, this will not stop a determined adversary. Additionally, the higher radiation levels increase the attractiveness of the material for a dispersion event. The presence of large amounts of plutonium in TRU fuel is the chief proliferation concern. Since certain isotopes of plutonium (Pu-240 and Pu-242) act as "poisons" for nuclear weapons, nuclear fuel can be engineered to be less attractive for weapons use. A breakdown of the plutonium isotopes in selected materials is shown in Table 3. (Peterson 1996). The separated neptunium-237 and americium (Am-241 and Am-243) must be protected, controlled, and accounted for as if they were SNM as well (DOE 2001).

Table 3. Isotopic composition of various Pu grades (adapted from Peterson 1996).

Grade	Isotope				
	Pu-238	Pu-239	Pu-240	Pu-241[a]	Pu-242
Super-grade	-	0.98	0.02	-	-
Weapons-grade	0.00012	0.938	0.058	0.0035	0.00022
Reactor-grade[b]	0.013	0.603	0.243	0.091	0.05
MOX-grade[c]	0.019	0.404	0.321	0.178	0.078
FBR Blanket[d]	-	0.96	0.04	-	-

[a] Pu-241 plus Am-241

[b] Plutonium from low-enriched uranium PWR spent fuel with 33 megawatt-days/kg burn up, stored 10 years before reprocessing.

[c] Plutonium from 3.64 percent fissile plutonium mixed-oxide (MOX) spent fuel produced from reactor grade plutonium, with 33 megawatt-days/kg burn up and 10 years storage before reprocessing.

[d] Fast breeder reactor.

3.4. Chapter Summary

Safeguards concerns during transportation in the GNEP program are governed by the details of the material being transported at each portion of the fuel cycle. Material vulnerability and attractiveness are metrics used to judge the probability of an attack during transport. Since this paper is concerned primarily with physical protection during transportation, the vulnerability of a material is directly related to its attractiveness. Attractiveness is based on the nuclear material's effectiveness for use in a nuclear weapon. In the DOE graded physical protection system, there are five levels of material attractiveness. Current LWR fuel falls into the lowest attractiveness level. However, the advance fuel cycle proposed in GNEP will generate materials that fall into higher levels.

The initial stages of the GNEP fuel cycle utilize relatively unattractive materials for use in nuclear weapons development. Mining, milling, and fabrication stages involve only natural, depleted, or low-enriched uranium. Spent LWR fuel does contain materials that could be used as nuclear weapon feedstock, but in less attractive forms. However, transporting these materials will require high security levels due to their attractiveness for a dispersion event or theft for use in a dirty bomb. Once the transuranics have been extracted at a separation facility, the attractiveness level of the nuclear material remains heightened. The presence of large amounts of plutonium in this fuel is the chief safeguards concern. However, other transuranics pose a concern as well.

4. TRANSPORTATION RISK SCENARIOS

This chapter reviews the transportation requirements and risks associated with four potential scenarios. The first scenario is used as a baseline. It is a "business as usual" case where the United States continues to use a once-through fuel cycle. The second scenario incorporates the GNEP mission of exporting nuclear energy to other countries, but continues to utilize a once-through fuel cycle. The third scenario represents the full realization of the current GNEP mission. In this case, LWR fuel undergoes reprocessing for use in advanced burner reactors. Some of these reactors are constructed in foreign countries, and plutonium-bearing fuel must be exported to them and later imported back as SNF. The final scenario evaluates the safeguards impact of the transportation of waste streams from a reprocessing plant.

4.1. Current LWR Fuel Transport

The existing United States nuclear fleet utilizes a once-through fuel cycle (pictured in Figure 2). In this fuel cycle, uranium ore is extracted from the ground, often through open-pit or in-situ leach mining. The uranium ore is then milled to yield a dry powder-form material (often called yellowcake) consisting of natural uranium with the chemical composition U_3O_8. The yellowcake is then sent to an enrichment facility. It is chemically converted to a gaseous form (UF_6) and the U-235 isotope concentration is increased from the natural 0.71 percent to 3-5 percent (depending on the reactor type) through either a gaseous diffusion or centrifuge process. The enriched UF_6 is then chemically converted to UO_2 powder that is sintered into ceramic pellets. These pellets are loaded into fuel assemblies and are shipped to a reactor. A further discussion of the once-through fuel cycle can be found in *Understanding Radioactive Waste* (Murray 2003).

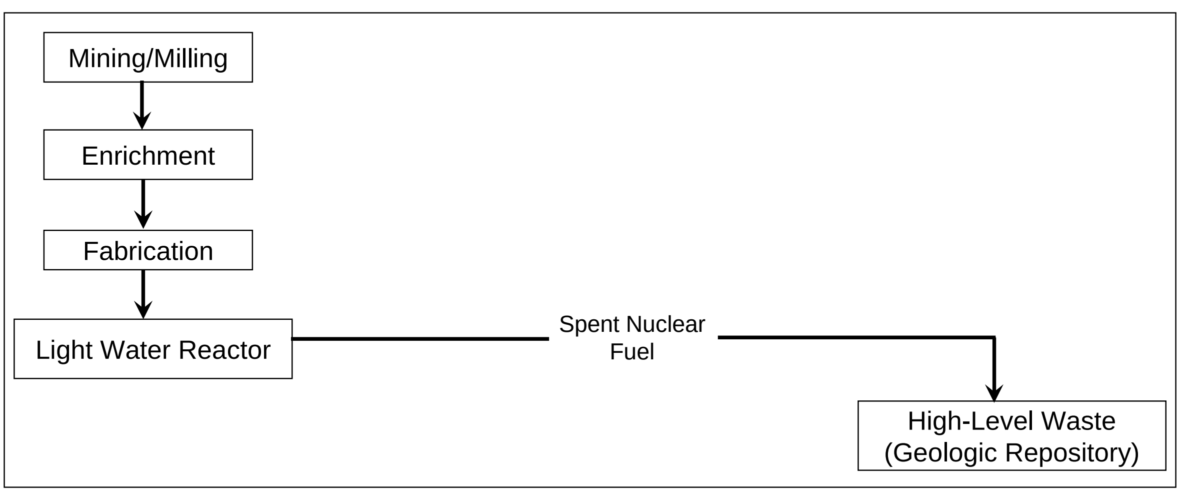

Figure 2. Once through fuel cycle.

Transportation methods vary throughout the fuel cycle and internationally. Prior to enrichment, the uranium-bearing material is in a natural form and is not considered a target (see

Chapter 3). Once the uranium has been enriched to 3 to 5 percent U-235, it still has a low enough enrichment that extraordinary precautions are not needed to protect it. After being burned in a reactor, however, SNF is well protected from accidental release and theft. This is not due to the fissile content of the material, but primarily because of the high amounts of radiation given off by the SNF. In an accident or sabotage event, significant quantities of toxicity and radiation could be dispersed. This material is therefore well protected to reduce risk of dispersion to acceptable levels (US DOE 2002).

The Transportation, Aging, and Disposal (TAD) canister will most likely be used for transporting fuel assemblies throughout the nuclear fuel cycle in the coming years. The TAD canister is a robust waste containment package that has gone through rigorous analysis, and will be subjected to equally rigorous testing in the coming years. As its name suggests, the TAD canister is designed for interim storage at nuclear plants, transportation to a repository or reprocessing facility, and for permanent waste disposal. During transport, it is coupled with a transportation overpack. This overpack is certified under title 10CFR71 to enclose TAD canisters for transportation (Zebransky 2006). It is designed to protect the TAD canister during normal conditions of transport and design basis accidents, dissipate decay heat from the contained SNF, and protect workers and the public from radiation.

The two primary modes of transportation for canisters containing SNF are truck and rail transport. Representative routes for rail transport of SNF within the United States to the proposed geologic repository at Yucca Mountain are shown in Figure 3. Rail transport via dedicated trains is generally preferred over truck transport. This is due in part to the larger capacity of a single rail transport. Rail transport also places the SNM further from the public. While trucks on highways are inherently near other vehicles and homes, rail lines are generally far from public places. However, rail lines often run through large cities. Bypass lines may need to be constructed to route nuclear shipments away from city centers. The lack of nearby traffic also makes a rail shipment somewhat easier to protect from attack. Conversely, the use of rail transport provides a more predictable route for potential attackers.

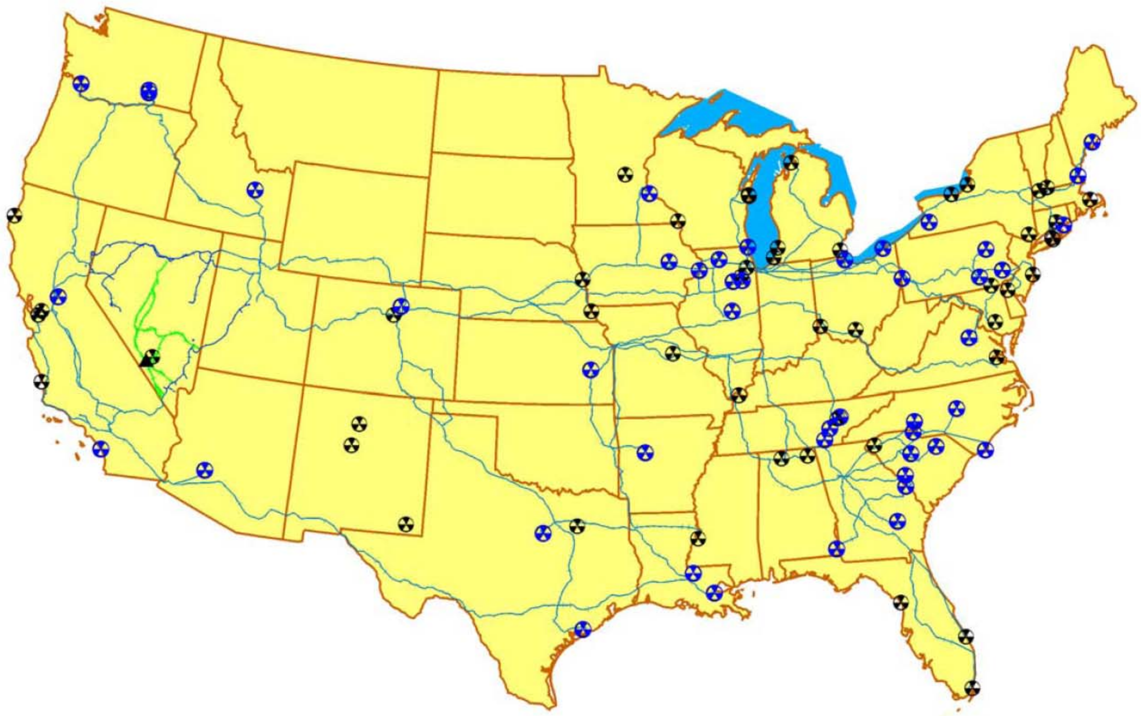

Figure 3. DOE "representative" rail routes to Yucca Mountain (with permission from Halstead 2005).

The vulnerability level found in the back end of the current LWR fuel cycle is dominated by the characteristics of spent fuel. The Pu-239 found in LWR spent fuel makes it somewhat desirable for weapon production, although Pu-240 content makes separation difficult. The material is highly radioactive, providing some level of “self protection” from direct attempts at theft (Hassberger 2001). This material will still require high levels of security to prevent sabotage resulting in dispersion. Since it is low grade, it is therefore also bulky and therefore more difficult to steal. The high levels of radiation also increase its detectability should it fall into adversary hands.

4.2. International LWR Fuel/SNF Transport

This scenario is very similar to the one described in Section 4.1 above. As pictured in Figure 4, the front end of the fuel cycle is identical to the current practices in the US. In this case, however, some of the fabricated LWR fuel is destined for use in international reactors. After the fuel has been burned in these reactors, it may be returned to the United States for permanent disposal in a geologic repository. Procedures will therefore need to be developed for transporting both fresh and spent nuclear fuel abroad.

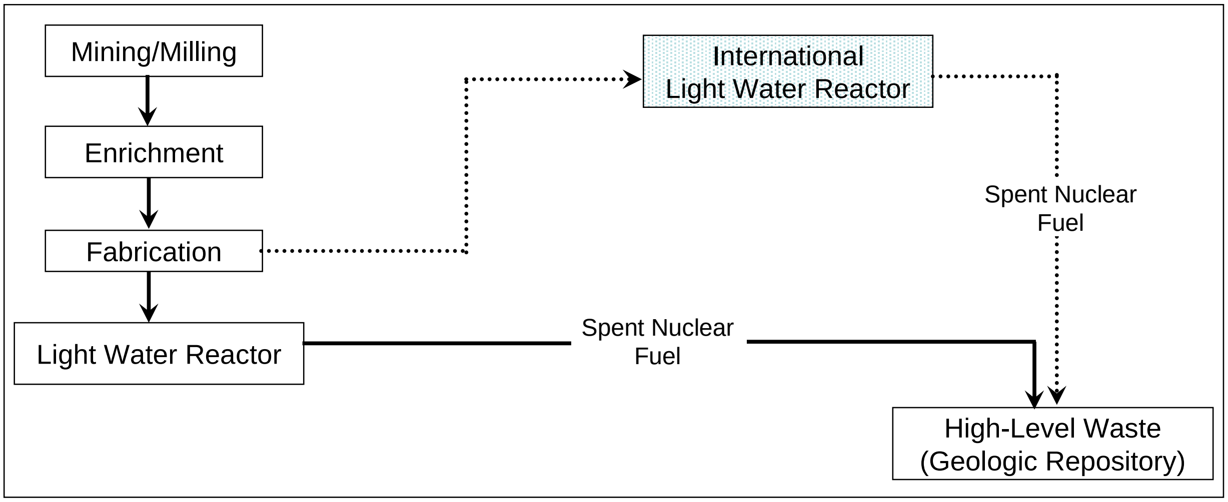

Figure 4. Once-through fuel cycle with fuel export/spent fuel import.

This scenario introduces the prospect of international transport of both fresh and spent nuclear fuel. While fuel has been transported in many countries outside of the United States for decades, it will nonetheless require additional logistical considerations. This is particularly true in developing countries that may not be as secure internally as current "nuclear states". Additional security personnel may be required, depending on the ability of local law enforcement to respond to a call for backup during an attack. In addition to truck and rail shipment, fuel will also be transported via ship. Accidents or sabotage at sea could result in dispersion of nuclear material over land (Sprung 1998). The longer duration of such a shipment may require new strategies for protection forces. It may also require additional security at shipping ports during loading and unloading.

4.3. International Burner Reactor Fuel/SNF Transport

This scenario is a significant departure from current practices in the United States, and is the fuel cycle currently envisioned by the GNEP program. The front end of the fuel cycle is identical to the two previous scenarios. However, instead of sending SNF directly to a geologic repository, it is reprocessed at a LWR SNF separation facility. Fission products and structural material will be disposed as either Low Level Waste (LLW) or High Level Waste (HLW). Unused uranium will be separated and placed in storage or recycled back into the fuel supply. The TRU will be recycled into fuel for burner reactors, some of which will be located outside the United States. These reactors partially burn up the TRU material, leaving a fraction of the original TRU in the spent fuel, along with newly created fission products. A second separations process (Transmutation Fuel Separation) will extract the remaining TRU and uranium and recycle it for further use in burner reactors. The remaining material will be sent to either LLW or HLW disposal sites. A proposed alternative is to introduce an intermediate step where uranium and TRU are used to create mixed-oxide (MOX) fuel, which is burned in light water reactors and then recycled. In this scenario, all aspects of the fuel cycle are located in fuel exporter countries, such as the United States, with the exception of some burner reactors.

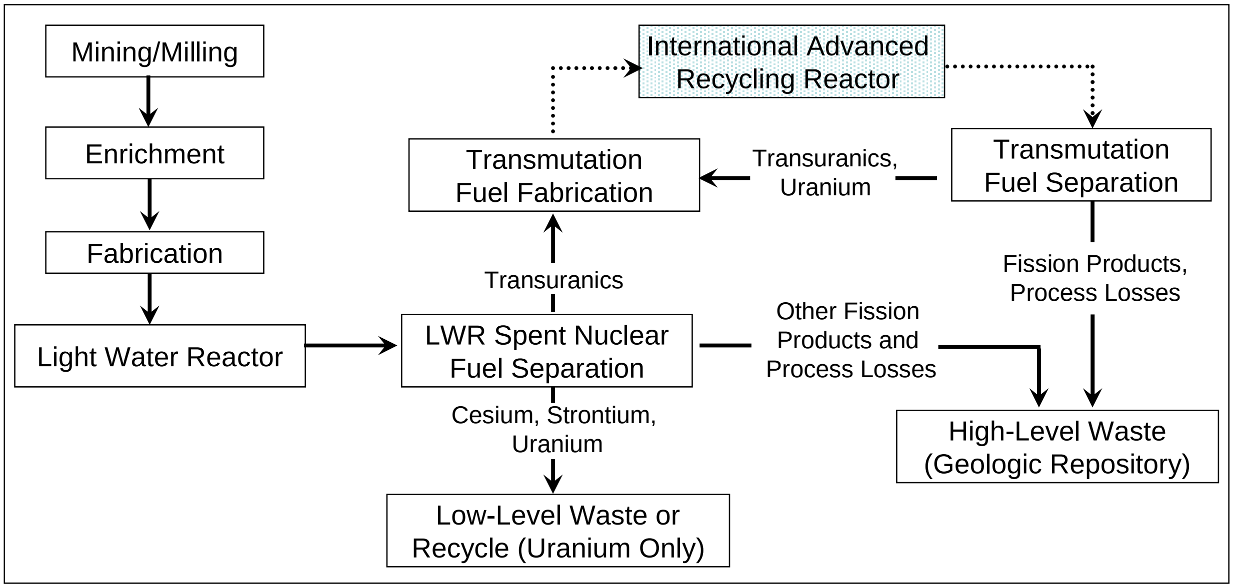

Figure 5. Proposed GNEP closed fuel cycle. (adapted from GNEP 2006).

While the fuel cycle described above does not significantly increase the risk of a sabotage event, it does present a dramatically heightened safeguards concern. The increased levels of plutonium present in both the “fresh” and spent TRU fuel is the critical difference between this and two previous scenarios. As discussed in Chapter 3, plutonium-bearing fuel is highly attractive for the production of a nuclear weapon. This attractiveness can be countered by using high-burnup fuel, but not eliminated. This would, however, increase the fuel’s attractiveness for sabotage. Other transuranics, notably Np-237, Am-241, and Am-243, are also attractive for nuclear weapons production.

This heightened risk of theft for nuclear weapons development will therefore require the use of increased security during transportation. Security personnel and other delay mechanisms will need to be increased, particularly during transportation outside of countries, such as the U.S., that have reliable local first responders. These personnel will require escort platforms such as those described in *Security Feature Requirements for the ONT Escort Coach Railcar* (Roesch 2004). Such platforms will act as housing during normal operation (particularly important for long international transport), a mobile command and communications post, and a hardened fighting position during attack.

4.4. Transportation of Other Separated Materials

In addition to the transportation issues described in Section 4.3, the implementation of the GNEP fuel cycle will introduce many new materials that may require transport. These materials will result from a spent fuel separation process similar to the GNEP Reference (UREX+1a Process) shown in Figure 6. They include radioactive gasses (such as tritium and krypton), radioactive liquids (such as iodine), repackaged fission products, including cesium and strontium, and target materials from fast breeder reactors. While most of these materials are not high proliferation hazards, they are potential targets for dispersion or theft for use in "dirty bombs." The risk they represent will greatly depend on the packaging of the materials prior to transport.

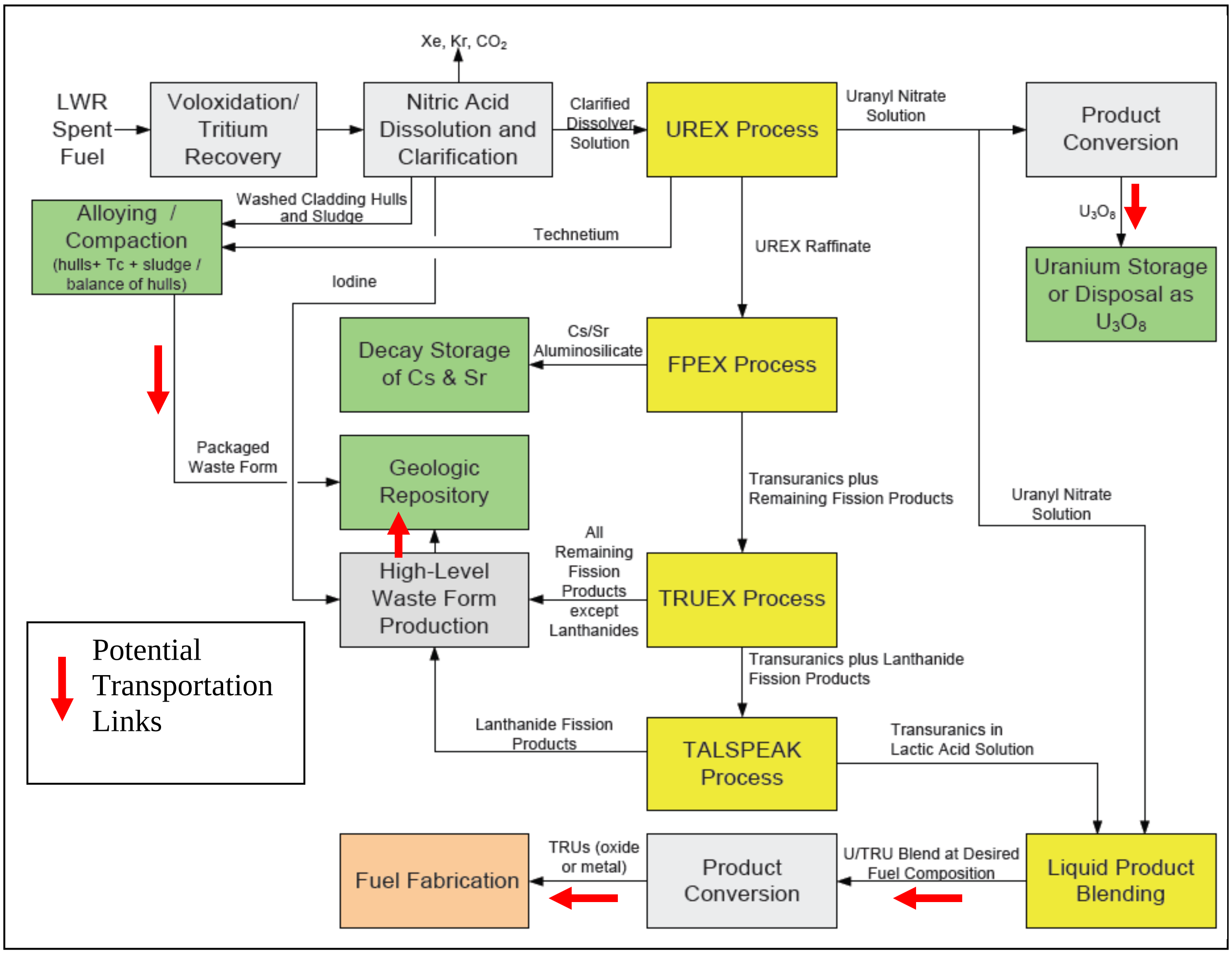

Figure 6. Flow diagram of the UREX+1a SNF separation process (with permission from Laidler 2007).

In some versions of the current PUREX spent fuel separation process, gaseous and liquid radioactive by-products are released to the ocean or atmosphere. However, one of the goals of the GNEP program is to generate "limited emissions." Therefore, the GNEP Reference incorporates recovery of these products into the separation process. In the current plan, tritium will be collected as tritiated water, incorporated into grout, and encapsulated (Laidler 2007). Since tritium is a material used in nuclear weapons, it will require additional protection and/or monitoring during transport to a storage facility. Other radioactive gasses will be collected as well. Xenon and krypton could be immobilized in zeolite or clathrates and carbon-14 could be converted to carbonates (Laidler 2007). Both would be disposed of as HLW in a geologic repository. Likewise, iodine can be trapped in silver-coated zeolite, converted to potassium iodate, and transported as HLW (Laidler 2007).

Solid fission products may also be transported to a storage facility. In the current plan, cesium and strontium will be immobilized in an aluminosilicate mineral matrix (Laidler 2007). They will then be stored until the radionuclides have decayed to levels acceptable for disposal as LLW. It is unclear at this time if this storage will occur at the reprocessing facility. Technetium can be recovered in metallic form, combined with undissolved solids and a fraction of the cladding hulls, and disposed as a metallic HLW form. The remaining fission products can also be incorporated into glass or metal waste forms and transported as HLW to a geologic repository. While not a nuclear weapons risk, this material must nonetheless be protected against theft and sabotage.

While it can be safely assumed that these conversions will occur at the separation site, they must be pointed out as potential transportation risks that should not be overlooked.

Some material may be separated from spent LWR and burner reactor fuel as dedicated targets for transmutation in various reactors to more efficiently dispose of the material. The primary candidate materials for this treatment are americium and curium (Grouiller 2003). Transmutation of these products may be advantageous to their ultimate disposal while reclaiming any energy benefit. However, the fissile nature of this material will require protection during transport as both a fresh and spent product.

4.5. Summary

Four scenarios have been evaluated with respect to their impact on nuclear material safeguards during transportation. These scenarios are summarized below.

Scenario 1: "Business as Usual"

- The US continues to utilize a "once-through" fuel cycle
- Risk of SNM theft is low due to generally low attractiveness of material
- Back-end material has somewhat higher attractiveness
- Much of this material remains a risk for sabotage

Scenario 2: International LWR Export

- A "once-through" fuel cycle is coupled with LWR export
- Material attractiveness issues are identical to the previous scenario
- International shipments of SNF may require heightened security

Scenario 3: Proposed GNEP Fuel Cycle

- The US leads an effort to reprocess proliferation-resistant fuel and export advanced LWRs and/or FBRs
- Recycling of plutonium and other TRU increases SNM attractiveness
- Increased physical protection is required, particularly internationally
    - Robust shipping containers with hardened escort vehicles
    - Additional security personnel, delay mechanisms, tracking, and communication

Scenario 4: Transportation of other Material in GNEP Fuel Cycle

- Additional nuclear material process steams will be generated in the GNEP fuel cycle
    - Tritium will require added security during transport
    - Transmutation targets (Cm and Am) will required heightened safeguards

5. CONCLUSIONS

5.1. Global Nuclear Energy Partnership

- The Global Nuclear Energy Partnership is in a state of development. At this time, the details of the fuel cycle and material forms have yet to be determined.
- Decisions that have yet to be made, such as whether to co-locate various sections of the separation and fuel fabrication facilities, will have a large impact on the transportation protection requirements.

5.2. Regulatory Environment

- The NRC, DOT, DOE, and IAEA regulations and guidelines that are currently in place will go a long way toward framing the requirements for GNEP nuclear material transport.
- Shipment of CAT I quantities of ABR fuel and the unique nature of other nuclear material generated by the GNEP fuel cycle will likely require the modification of current regulations or the creation of new ones.

5.3. Transportation Risk in GNEP

- Introducing a closed fuel cycle will increase the attractiveness of some nuclear material.
    - However, the proposed GNEP fuel cycle minimizes this risk.
- Attractiveness levels of nuclear material in the GNEP fuel cycle will vary greatly depending on decisions made in the upcoming years.

5.4. Transportation of GNEP Nuclear Materials

- For the "once-through" fuel cycle, the risk of theft for use in nuclear weapons is low due to the nature of the nuclear material in transit. However, if LWR fuel is exported, increased security levels may be required.
- The proposed GNEP fuel cycle increases the use of plutonium and other transuranics.
    - This will require increases in physical protection systems; including additional personnel, delay mechanisms, tracking, and communications.
    - Tritium, curium, and americium will require added security during transport. Fission products, while not proliferation hazards, will require transportation security to prevent dispersion or theft for use in a dirty bomb.

6. REFERENCES

Chapter 1 References

Global Nuclear Energy Partnership Technology Demonstration Program Preliminary Plan – Pre-Decisional, GNEP-TDP-002-06, Global Nuclear Energy Partnership Technology Demonstration Program Office, September 5, 2006

Chapter 2 References

10 CFR 71: Packaging and transportation of radioactive material.

10 CFR 73: Physical protection of plants and materials.

10 CFR 74: Material control and accounting of special nuclear material.

49 CFR 172: Hazardous materials table, special provisions, hazardous materials communication, emergency response information, and training requirements.

49 CRF 173: Shippers--general requirements for shipments and packagings.

49CFR174: Carriage by Rail.

49CFR175: Carriage by Aircraft.

49CFR176: Carriage by Vessel.

49CFR177: Carriage by Public Highway.

49CFR178: Specifications for Packagings.

49CFR179: Specifications for Tank Cars.

49CFR180: Continuing Qualification and Maintenance of Packagings.

International Atomic Energy Agency, 1980, *The Convention on the Physical Protection of Nuclear Material*, INFCIRC/274/Rev.1. IAEA Publications, Vienna, Austria.

International Atomic Energy Agency, 1998, *The Physical Protection of Nuclear Material and Nuclear Facilities*, IAEA- INFCIRC/225. IAEA Publications, Vienna, Austria.

International Atomic Energy Agency, 2005, *Regulations for the Safe Transport of Radioactive Material*, IAEA-TS-R-1. IAEA Publications, Vienna, Austria.

United Nations Economic Commission for Europe, 2005, *Recommendations on the Transport of Dangerous Goods*, ST/SG/AC.10/1/Rev.10. UN Publications, Geneva, Switzerland.

US Department of Energy, 2001, *Integrated Safeguards and Security Management Policy*, DOE P 470. Approved May 8, 2001.

Yoshimura, R.H. et al, 2007, *Transportation and Storage Regulations Applicable to the GNEP*, Sandia National Laboratories, Albuquerque, NM.

Chapter 3 References

Bari, R. and the Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Gen IV International Forum, 2006, *Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems*, GIF/PRPPWG/2006/005. Printed by the OECD Nuclear Energy Agency for the Generation IV International Forum.

Garcia, M.L., 2001, *The Design and Evaluation of Physical Protection Systems*. Elsevier, Burlington, MA.

Hassberger, J.A., 2001, *Application of Proliferation Resistance Barriers to Various Existing and Proposed Nuclear Fuel Cycles*, UCRL-ID-147001. Lawrence Livermore National Laboratory, Livermore, CA.

Peterson, P.F., 1996, Long-Term Safeguards for Plutonium in Geologic Repositories, *Science and Global Security*, Vol. 6, No. 1, pp 1-29.

Purvis, J.W. and L.G. Nicholson, 1999, *Vulnerability Analysis Considerations for the Transportation of Special Nuclear Material*, SAND99-1851C. Sandia National Laboratories, Albuquerque, NM.

US Department of Energy, 2001, *Integrated Safeguards and Security Management Policy*, DOE P 470. Approved May 8, 2001.

Chapter 4 References

Grouiller, J.P., et al, 2003, Minor actinides transmutation scenario studies with PWRs, FRs and moderated targets, *in Journal of Nuclear Materials*, vol. 320, pp. 163–169.

Halstead, B. and F. Dilger, 2005, Nuclear Waste Transport From California to Nevada. Presented at the LEA/CIWMB Partnership Conference, Anaheim, CA, May 12, 2005.

Hassberger, J.A., 2001, *Application of Proliferation Resistance Barriers to Various Existing and Proposed Nuclear Fuel Cycles*, UCRL-ID-147001. Lawrence Livermore National Laboratory, Livermore, CA.

Laidler, J.J., 2007, GNEP Spent Fuel Processing; Waste Streams and Disposition Options. Nuclear Waste Technical Review Board Meeting, Washington, DC, May 15, 2007.

Murray, R.L., 2003, *Understanding Radioactive Waste, 5th Ed*. Battelle Press, Columbus, OH.

Peterson, P.F., 1996, Long-Term Safeguards for Plutonium in Geologic Repositories, *Science and Global Security*, Vol. 6, No. 1, pp 1-29.

Roesch, J.J. et al, 2004, *Security Feature Requirements for the ONT Escort Coach Railcar*. Sandia National Laboratories, Albuquerque, NM.

Sprung, J.L. et al, 1998, *Data and Methods for the Assessment of the Risks Associated with the Maritime Transport of Radioactive Materials Results for the SeaRAM Program Studies*, SAND98-1171/1, Sandia National Laboratories, Albuquerque, NM.

U.S. Department of Energy, 2002, *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada*, DOE/EIS-0250.

Zebransky, D.K., 2006, *Preliminary Transportation, Aging and Disposal Canister System Performance Specification, Revision B,* WMO-TADCS-0000001. US DOE Office of Civilian Radioactive Waste Management, Washington, DC.

DISTRIBUTION:

(Electronic copies only)

MS0899 Technical Library, 9536

Ross Radel, 6763

Gary Rochau, 6763

John Matter, 6754

Ken Sorenson, 6774

Veena Tikare, 6761

William Rhodes, 6418

Dunbar Lockwood
Route Symbol: NA-243
Location: WASHINGTON DC
Routing: NA-243
Organization: Office of International Regimes and Agreements
Title: FOREIGN AFFAIRS SPECIALIST
Internet Address: Dunbar.Lockwood@nnsa.doe.gov

Mary Anne Yates, Ph.D
Deputy Director, National and Homeland Security Programs
Argonne National Laboratory
9700 S. Cass Avenue, Bldg. 208
Argonne, IL 60439-4842
Internet Address: mayates@anl.gov

Sandia National Laboratories