

SANDIA REPORT

SAND2017X-XXXX

Unlimited Release

Printed September 2017

Hypothetical Case and Scenario Description for International Transportation of Spent Nuclear Fuel

Adam D. Williams, Doug M. Osborn, Katherine A. Jones, Elena A. Kalinina, Brian Cohn,
Maikael Thomas, M. Jordan Parks, Ethan Parks & Amir H. Mohagheghi

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

Sandia National Laboratories is a multimission laboratory managed and operated
by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned
subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's
National Nuclear Security Administration under contract DE-NA0003525.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

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@osti.gov
Online ordering: <http://www.osti.gov/scitech>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: <http://www.ntis.gov/search>



Hypothetical Case and Scenario Description for International Transportation of Spent Nuclear Fuel

Adam D. Williams
Amir H. Mohagheghi
6833 Global Security Research & Analysis
Brian Cohn & Doug M. Osborn
8852 Severe Accident Analysis
Katherine A. Jones
8831 Operations Research & Computational Analysis
Elena A. Kalinina
8845 Storage and Transportation Technologies
Maikael Thomas
6832 International Safeguards and Engagements
Ethan Parks & M. Jordan Parks
6835 International Nuclear Security Engineering

Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185-MS1371

ABSTRACT

To support more rigorous analysis on global security issues at Sandia National Laboratories (SNL), there is a need to develop realistic data sets without using “real” data or identifying “real” vulnerabilities, hazards or geopolitically embarrassing shortcomings. In response, an interdisciplinary team led by subject matter experts in SNL’s Center for Global Security and Cooperation (CGSC) developed a hypothetical case description. This hypothetical case description assigns various attributes related to international SNF transportation that are representative, illustrative and indicative of “real” characteristics of “real” countries. There is no intent to identify any particular country and any similarity with specific real-world events is purely coincidental. To support the goal of this report to provide a case description (and set of scenarios of concern) for international SNF transportation inclusive of as much “real-world” complexity as possible—without crossing over into politically sensitive or classified information—this SAND report provides a subject matter expert-validated (and detailed) description of both technical and political influences on the international transportation of spent nuclear fuel.

[PAGE INTENTIONALLY LEFT BLANK]

TABLE OF CONTENTS

ABSTRACT.....	3
1. Introduction.....	8
2. Hypothetical Case Description	10
2.1. Background and Regional Description	10
2.1.1. Kaznirra.....	12
2.1.2. Famunda.....	13
2.1.3. Zamau.....	14
2.3. Route Description	15
3. Technical Description	17
3.1. Spent Nuclear Fuel.....	17
3.2. Cask.....	21
3.3. Transportation Vehicles	22
4. Scenarios	23
4.1. Scenario 1: Train Derailment + Attack.....	23
4.2. Scenario 2: Transfer of Cask from Famunda to Kaznirra at the Border	23
4.3. Scenario 3: Port of Famunda Refuses to Receive SNF on Barge from Zamau	23
References	24
Appendix A: Case Description & Route Assumptions.....	26
Appendix B: Technical SNF & Cask Assumptions	30
Appendix C: Calculated Inventories for PWR & BWR Assemblies	32

FIGURES

Figure 1. A Notional Region and Route for the Transport Scenario	11
Figure 2. A Notional Region and Route for the Transport Scenario	16
Figure 3. Generic Transportation Cask Inventory, from [5]......	20
Figure 4. Normalized Inventory of PWR & BWR Assemblies, from [5].	20
Figure 5. A Generic Spent Fuel Cask from Fig. 2-1 in [6, p. 17]......	21

TABLES

Table 1. National Security Index for the Country of Kaznirra.	12
Table 2. National Security Index for the Country of Famunda.	13
Table 3. National Security Index for the Country of Zamau.	14
Table 4. Example of Calculated Inventories for 60 GWD/MTU PWR & BWR Assemblies, from [5]......	19
Table 5. Summary of case description and route assumptions.	27
Table 6. Summary of nuclear material and SNF cask technical assumptions.	31
Table 7. Example of Calculated Inventories for 50 GWD/MTU PWR & BWR Assemblies.	32
Table 8. Example of Calculated Inventories for 40 GWD/MTU PWR & BWR Assemblies.	33

[PAGE INTENTIONALLY LEFT BLANK]

NOMENCLATURE

Abbreviation	Definition
AAR	Association of American Railroads
BWR	Boiling Water Reactor
CPPNM	Convention on the Physical Protection of Nuclear Material
DOE	U.S. Department of Energy
DPRA	Dynamic Probabilistic Risk Assessment
GWD/MTU	Gigawatt Days per Metric Tonne of enriched Uranium
IAEA	International Atomic Energy Agency
NNSA	U.S. National Nuclear Security Administration
NFC	Nuclear Fuel Cycle
NPT	The Treaty on the Non-Proliferation of nuclear weapons
NSG	Nuclear Suppliers Group
PWR	Pressurized Water Reactor
RAM	Radioactive Material
SNM	Special Nuclear Material
SNF	Spent Nuclear Fuel
SQ	Significant Quantity
STPA	System-Theoretic Process Analysis
UNSCR	United Nations Security Council Resolution
WINS	World Institute for Nuclear Security
WNTI	World Nuclear Transport Institute

[PAGE INTENTIONALLY LEFT BLANK]

1. INTRODUCTION

To support more rigorous analysis on global security issues at Sandia National Laboratories (SNL), there is a need to develop realistic data sets without using “real” data or identifying “real” vulnerabilities, hazards or geopolitically embarrassing shortcomings. In response, an interdisciplinary team led by subject matter experts in SNL’s Center for Global Security and Cooperation (CGSC) developed a hypothetical case description, that includes as realistic a description as possible of:

- a set of hypothetical countries;
- their respective nuclear infrastructures;
- their respective national nuclear decision-making structure;
- their respective maturity in implementing international best practices in safety, security and safeguards;
- regional political tensions and interrelationships; and,
- relevant International Atomic Energy Agency documents, conventions, agreements and treaties.

Further, and in direct support of the LDRD 191154 “System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle” project evaluating international spent nuclear fuel (SNF) transportation [1], this team further developed realistic descriptions of:

- SNF material characteristics;
- SNF transportation cask characteristics;
- route descriptions (including potential threats, vulnerable sections and hazards);
- transportation vehicle characteristics;
- security, safety and safeguards implementation; and,
- multimodal transfer processes.

In developing this hypothetical case description, other efforts describing the “real-world” complexity of international nuclear material transportation were used as reference material (e.g., the World Institute for Nuclear Security [WINS]/World Nuclear Transportation Institute [WNTI] joint best practices document [2]). Consider, for example, this anecdote from the transportation security session at the IAEA’s 2016 International Conference on Nuclear Security:

when nuclear material put on ship in international waters, who is responsible? Country of origin, closest country, or country in which the vessel is flagged? How do we reconcile regulations of a ship’s flag of origin with operational needs for transporting SNM?

Addressing such “real-world” complexities, especially when combined with the likely increase in international SNF transportation over the next few decades, requires rigorous analysis of the related technical, procedural, social, political and culture challenges to reducing global nuclear dangers. This hypothetical case description was designed to aid in this endeavor.

Tenets of ground theory [3] were implemented to capture as much real-world complexity as possible. More specifically, a wide range of open source documents—including (but not limited

to) academic articles, press releases, IAEA documents, professional reports and governmental action briefs—related to international SNF transportation¹ were reviewed, analyzed and categorized. Pertinent details, dynamics and descriptions from these documents were included in the realistic hypothetical case according to the tenets of grounded theory. All key assumptions for (and most of the details included in) the hypothetical case study are traceable back to these documents, including those for the case and route descriptions in Appendix A, as well as those for the SNF and cask in Appendix B.

In addition, a select group of real countries were selected as proxies in order to determine better depictions of aggregate national and regional political data and relationships for the hypothetical case description. For example, the decision on whether or not to use dedicated transportation vehicles for SNF transport is a national government responsibility subject to multiple, non-nuclear, influences. These countries were selected in an attempt to match real geographic areas where trends and predictions suggest future international SNF transportation is more likely to occur. In order to avoid the use of country specific data, the assumptions and details in the hypothetical case description used averaged values or descriptions to represent challenges to SNF transportation. For example, fictitious measures for the Nuclear Threat Initiative’s Nuclear Security Index² were developed by averaging across real countries that best fit the notional examples in the hypothetical case.

Again, this hypothetical case description assigns various attributes related to international SNF transportation that are representative, illustrative and indicative of “real” characteristics of “real” countries. There is no intent to identify any particular country and any similarity with specific real-world events is purely coincidental. To support the goal of this report to provide a case description (and set of scenarios of concern) for international SNF transportation inclusive of as much “real-world” complexity as possible—without crossing over into politically sensitive or classified information—this document is organized as follows:

- Regional, geopolitical & national descriptions;
- SNF transportation route & justification;
- SNF characteristics, cask technical details & transportation vehicle description;
- Descriptions of international SNF transportation scenarios of concern; and,
- Explanations of key assumptions & details for this hypothetical case description.

¹ Based on the initial small sample of documents available, the search was broadened to include international transportation of special nuclear material (SNM) as well.

² For more on the Nuclear Security Index, please: <http://www.ntiindex.org/>

2. HYPOTHETICAL CASE DESCRIPTION

2.1. Background and Regional Description

The country of Zamau has been using nuclear power for 48 years, and has exceeded the storage capacity available onsite for their fuel. In 2 years, they plan to begin shipments to the nation of Kaznirra, which has an economic incentive to receive spent nuclear fuel (SNF) from surrounding countries.

While Zamau has executed some in-country transportation of SNF in the past, it has not historically participated in regional shipments. Kaznirra has received SNF from one other nation as part of its efforts to establish itself as a central reprocessing and storage location for the area, but those shipments only involved a single border crossing and one mode of transportation (truck).

The geopolitical situation in the region is similar to that of east Africa, with instability and some strong insurgent groups in the area, as well as state level corruption in several cases. The greatest instability along the transportation route is in the country of Famunda, which is between Zamau and Kaznirra. The region and route are shown in Figure 1. The route is described in detail in section 2.

The notional countries described are loosely based on real countries for the purpose of borrowing realistic descriptions of infrastructure condition, climate, and political/security considerations.³ They are not intended to represent a real-world route under consideration, and other assumptions (such as history of nuclear power use) for each notional country may be based on another nation's historical information.

³ More details on can be found in Appendix A.

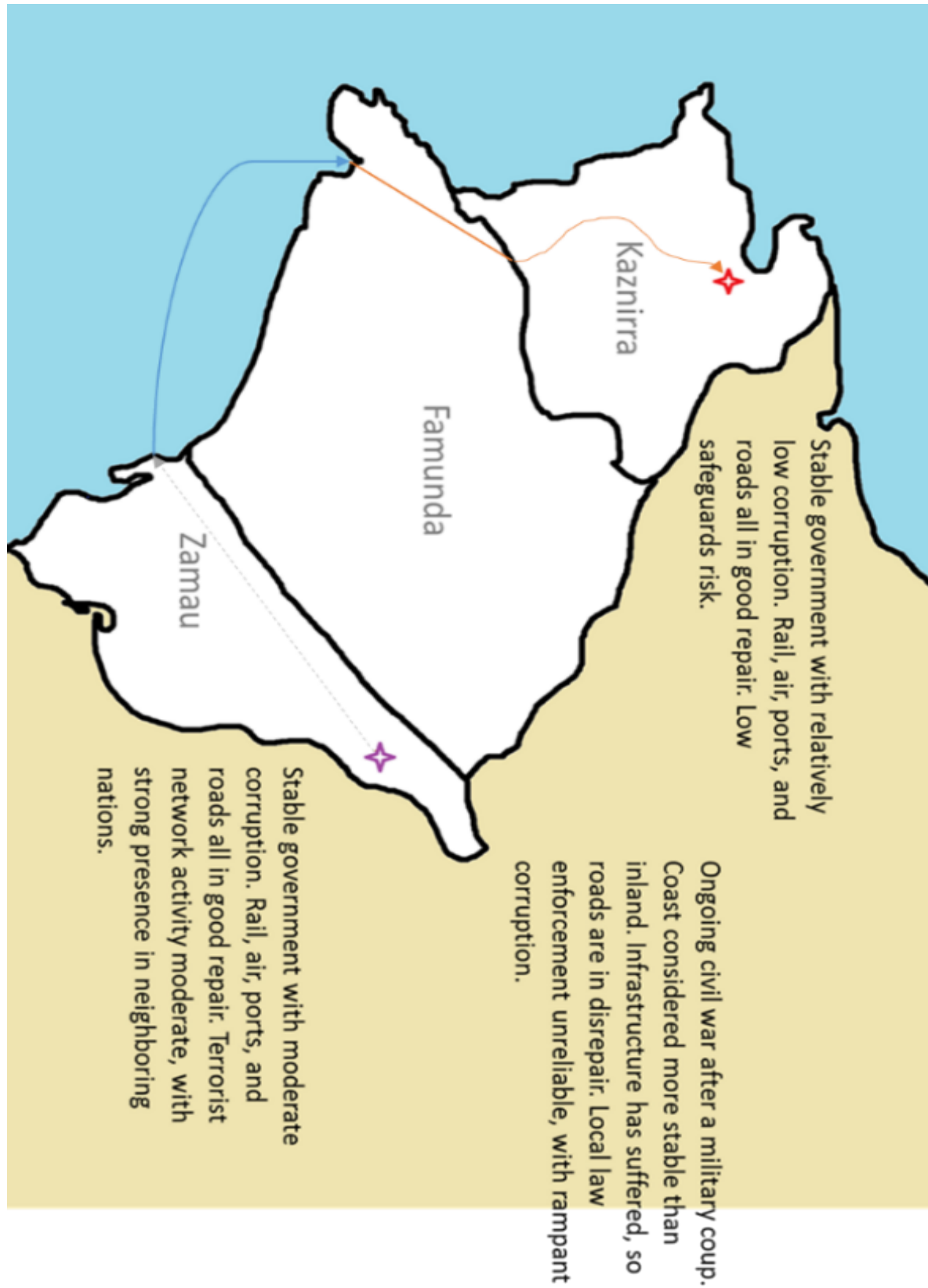


Figure 1. A Notional Region and Route for the Transport Scenario

2.1.1. Kaznirra

Kaznirra has a semi-arid climate, with some subtropical areas along the coast. The interior is a flat plateau, but is surrounded by rugged hills and a very narrow coastal plain. Because of this rugged costal terrain, there are no ports that can readily support transfer of the fuel from barge to truck, therefore the SNF must be offloaded from the barge in Famunda.

Kaznirra is a parliamentary republic with 5 provinces. Each province has a 10-member delegation appointed by the provincial legislature. There is a president who serves as chief of state and head of government, who is elected by the national assembly.

Kaznirra has 20,000 km of railways. The roadways in Kaznirra are about 65% unpaved.

Military units often need to be placed along the border to control poaching and smuggling. Illicit drug shipments are also an issue for this nation, as is money laundering.

Kaznirra has a well-developed nuclear (both commercial and governmental) enterprise—including the SNF disposal facility. Approximately 5% of Kaznirra’s electrical power comes from nuclear fuel. Kaznirra signed The Treaty on the Non-Proliferation of *Nuclear Weapons* (NPT) as a non-nuclear weapons state. Kaznirra also signed the Additional Protocol and is a member of the Nuclear Suppliers Group (NSG).

All employees with a security responsibility for securing SNF while it’s transited inside Kaznirra undergo a vigorous background investigation prior to being hired. To date, there have been no disputes over labor issues and no attempts to breach Kaznirran nuclear facilities or transports. The border security officers are instructed to prioritize protecting the border (and completing those related job tasks) over assisting in the security of any shipment (including SNF) temporarily held onsite.

Kaznirra received the following scores for the 2016 Nuclear Threat Initiative’s Nuclear Security Index⁴:

Table 1. National Security Index for the Country of Kaznirra.

Nuclear Security Index (2016) Sub-Indicator	Score (0 = worst; highest = best)
Security & Control Measures Category	
On-site Physical Protection (0 to 5)	3
Control and Accounting Procedures (0 to 7)	5
Insider Threat Prevention (0 to 9)	3
Response Capabilities (0 to 7)	7
Cybersecurity (0 to 4)	4
Domestic Commitments & Capacity	
UNSCR 1540 Implementation (0 to 5)	5
Domestic Nuclear Security Legislation (0 to 3)	2
Independent Regulatory Agency (0 to 1)	1

⁴ More details on can be found in Appendix A.

2.1.2. Famunda

Famunda is tropical along the coast, with some semiarid areas in the far north near the border with Kaznirra. Most of Famunda is flat or rolling plains, with some mountains in the eastern part of the country. The country is 40% forest. Torrential flooding is possible during the rainy season, and heavy surf can occur along the coast.

Famunda is a presidential republic. It has a civil law system based on the French civil code. There is a President and a Prime Minister, and a Council of Ministers appointed by the president. The President is elected via a majority popular vote. The legislative branch is a National Assembly with 255 seats.

The roads in Famunda are 90% unpaved. Intercity and urban roads can be unpaved, in addition to rural ones. There is only one major seaport—the Port of Famunda. This port, however, serves as a major regional trading hub, as it boasts the closest capacity to host international cargo ships. The road from the Port of Famunda to the border with Kaznirra is also a major trade artery, which results in it being well-maintained and well-protected by the Famunda government.

Famunda is often used as a narcotics transshipment point to Europe, although the increasing political instability in the country has made it less favorable to cartels. Rampant corruption exists in the banking system and government. The financial system is considered undeveloped, even for the region.

None of Famunda’s power comes from nuclear fuel, so they do not have a developed safeguards system, but they have signed The Treaty on the Non-Proliferation of *Nuclear* Weapons (NPT) as a non-nuclear weapons state.

Famunda received the following scores for the 2016 Nuclear Threat Initiative’s Nuclear Security Index⁵:

Table 2. National Security Index for the Country of Famunda.

Nuclear Security Index (2016) Sub-Indicator	Score (0 = worst; highest = best)
Security & Control Measures Category	
On-site Physical Protection (0 to 5)	2
Control and Accounting Procedures (0 to 7)	3
Insider Threat Prevention (0 to 9)	5
Response Capabilities (0 to 7)	5
Cybersecurity (0 to 4)	1
Domestic Commitments & Capacity	
UNSCR 1540 Implementation (0 to 5)	5
Domestic Nuclear Security Legislation (0 to 3)	2
Independent Regulatory Agency (0 to 1)	1

⁵ More details on can be found in Appendix A.

2.1.3. Zamau

Zamau has a tropical climate, including the coast immediately surrounding its key port. Zamau shares a low mountainous region along its border with Famunda, but a majority of its interior flat to rolling coastal plains and some plateaus near the mountains.

Zamau is a presidential republic with 15 counties and a mixed legal system (e.g., common and customary law). The president serves as both chief of state and head of government and is directly elected by an absolute majority popular vote. Civil wars in Zamau resulted in a UN peacekeeping mission that ended just 5 years ago, and while the country currently has a stable government, it also has moderate levels of corruption and terrorist network activity in-country and along its borders. Zamau boasts a fairly robust nuclear (both commercial and governmental) enterprise, including hosting several facilities generating SNF that provides approximately 12% of Zamau's electrical power. Kaznirra signed The Treaty on the Non-Proliferation of *Nuclear* Weapons (NPT) as a non-nuclear weapons state.

Zamau has 5,000 km of railways, with the most used (and usable) stretch running from near a national SNF collection site to a port on the coast. The roadways in Zamau are about 15% unpaved and the country boasts one strong port facility. Military units often need to be placed along the border to control poaching and the smuggling of illicit drugs, people and terrorists. Military and the gendarmerie⁶ collaborate to mitigate the growing influence of corruption throughout the government stemming from both organized crime and terrorist networks.

All employees with a security responsibility for securing nuclear materials (of any form) while inside Zamau undergo a rigorous background investigation prior to being hired. There have been a growing number of low-level disputes over labor issues by contract-based security forces and a few rumored (and unconfirmed by officials) attempts to breach Zamauan nuclear facilities.

Zamau received the following scores for the 2016 Nuclear Threat Initiative's Nuclear Security Index⁷:

Table 3. National Security Index for the Country of Zamau.

Nuclear Security Index (2016) Sub-Indicator	Score (0 = worst; highest = best)
Security & Control Measures Category	
On-site Physical Protection (0 to 5)	3
Control and Accounting Procedures (0 to 7)	1
Insider Threat Prevention (0 to 9)	0
Response Capabilities (0 to 7)	2
Cybersecurity (0 to 4)	0
Domestic Commitments & Capacity	
UNSCR 1540 Implementation (0 to 5)	2
Domestic Nuclear Security Legislation (0 to 3)	3
Independent Regulatory Agency (0 to 1)	1

⁶ A term describing a military unit responsible for civil law enforcement, which are popular in the developing world.

⁷ More details on can be found in Appendix A.

2.3. Route Description

The scope of our analysis begins at inspection after loading the cask onto the first mode of transportation at the origin site, and ends with arrival inspection before unloading. Loading and unloading of the casks is considered out of scope for this analysis. Lastly, this analysis only considers a single cask being transported along the following route.⁸

From the storage site (Site A) in Zamau to the Port of Zamau, the cask will travel 434 km by rail. The rail transport begins on-site, so our analysis begins upon inspection when the cask has been loaded onto the railcar. The climate in Zamau is tropical, with dry winters and rainy monsoon summers. The terrain is mostly flat with rolling coastal plains. The daily average maximum temperature is 30°C with the average minimum 20°C. The wettest month is June. The railway in Zamau sustained significant damage during a period of unrest in the country. The rail infrastructure is being rebuilt along the route, but is still likely to be less reliable and more prone to accidents than in more industrialized nations (assume 20% higher risk of an accident than the assumption within the US).

When the train reaches the Port of Zamau, a portable crane will be used to load the cask onto the barge, where it must be secured onto the barge and inspected. It will then travel 335 nautical miles (620 km) to the Port of Famunda in the northwest corner of the country of Famunda. There are issues with piracy along the route.

Upon arrival in the Port of Famunda, the cask must be transferred to a truck, again via a portable crane. There will be another safety inspection at the same time as the customs inspection. Local authorities insist on being present for this inspection. Most roads in Famunda are unpaved, although this route uses the major (and well-maintained) trade route to move commercial goods between the Port of Famunda and Kaznirra. Suitable alternate paths, however, do not exist and any deviation would involve the use of unpaved roads. The condition of the roads in use is relatively poor and expected to increase accident risk by 15% over more developed nations.

The truck will then take a 566 km route to Site B in Kaznirra. After 97 km along the major trade route connecting Kaznirra to the Port of Famunda, the truck must cross the border between Famunda and Kaznirra. The route is primarily on small highways and only passes one major city (Cona) 230 km after crossing the border. It will come within 5km of the residential area of the city.

Based on average speeds of transport vehicles, speed input to RADTRAN, and previously decided distances, the following timeframe has been established as an estimate for the entirety of the trip.

- 434 km by rail: 10 hours
- Barge loading: 2 hours
- 620 km by barge: 62 hours
- Transfer of cask to truck: 2 hours
- Travel by truck 97 km to border of Kaznirra: 4 hours

⁸ It is understood that this is the most simplified case possible, suggesting that any associated elements of complexity will likely increase in severity when considering multiple casks in the same shipment.

- Border inspection: 2 hours
- Travel by truck 469 km to Site B: 19.5 hours

Figure 2 shows a map of the notional country with the grey line indicating SNF transport by rail, the blue line indicating transport by barge and the orange line indicating transport via heavy haul truck.

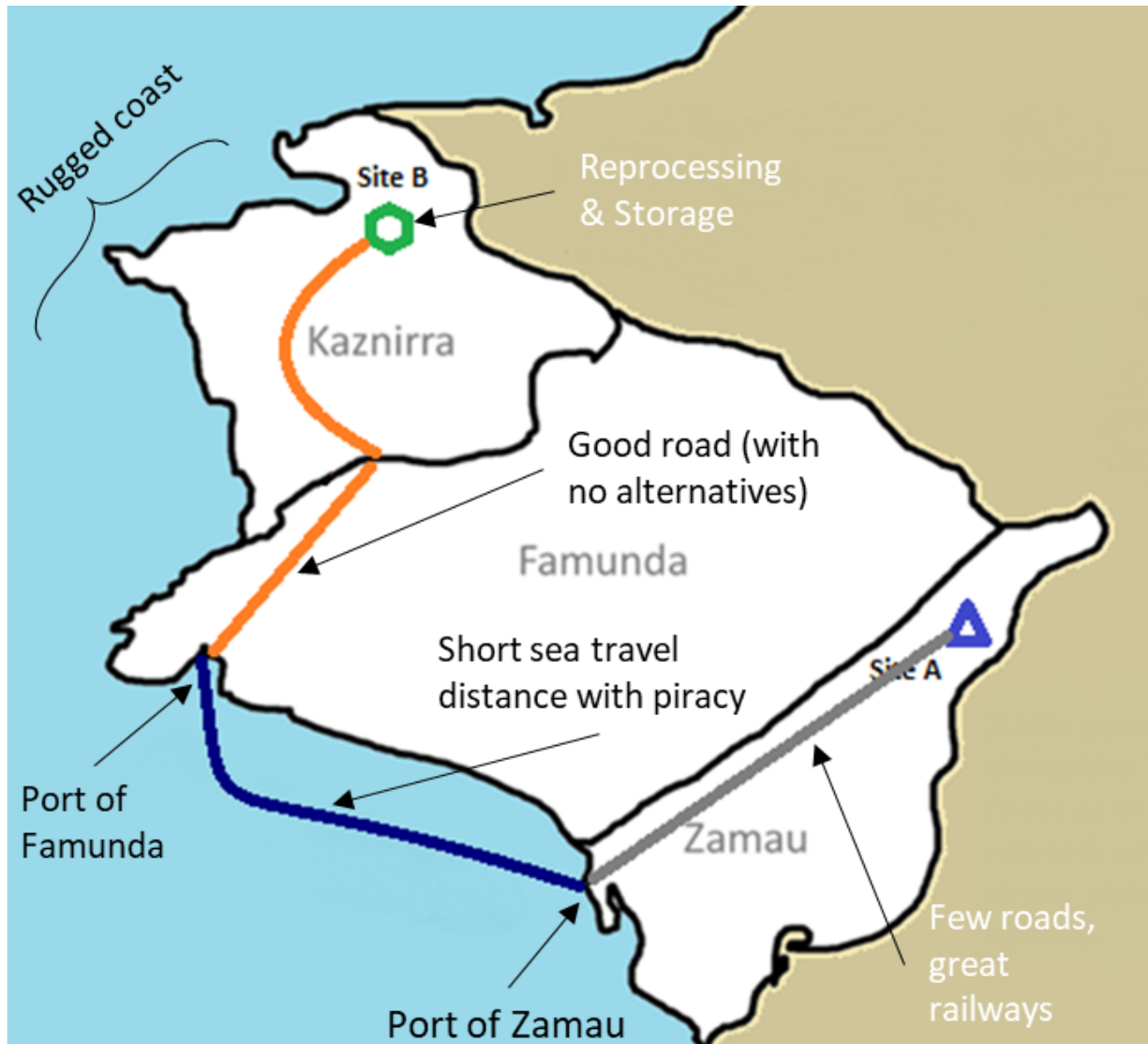


Figure 2. A Notional Region and Route for the Transport Scenario (with pertinent details from the text included)

[PAGE INTENTIONALLY LEFT BLANK]

3. TECHNICAL DESCRIPTION

3.1. Spent Nuclear Fuel

This analysis considered two generic SNF transportation casks – a pressurized water reactor (PWR) cask with a 24 fuel assembly capacity and a boiling water reactor (BWR) cask with a 52 fuel assembly capacity. The design of these generic casks is loosely based on the AREVA TN24 dual-purpose storage and transportation casks. Several PWR and BWR fuel burnups and discharge times were considered for this proof-of-concept. The inventory was calculated using ORIGEN (a point depletion and decay computer code from Oak Ridge National Laboratory [4]) for 3 characteristic burnup values (40, 50, and 60 GWD/MTU) and 4 fuel ages (5, 10, 25 and 50 years after discharge). The approach only considers once-through fuel from a PWR or BWR, therefore all cases involve SNF that has not been reprocessed and is being taken directly to long-term storage.

A large number of radionuclides are present in SNF (e.g., 204 radionuclides are found in 5-year-old, 60 GWD/MTU fuel). The approach used was to include all the radionuclides considered in NUREG-2125 [5] and any additional radionuclides (if present) that contribute to >90% of the human health effects.

Uranium ore contains 0.7% U-235 while the remaining 99.3% is composed of U-238, a fissionable material responsible for the production of Pu-239; however, it is non-fissile and cannot sustain a chain-reaction. Generally, nuclear reactors are designed to use uranium enriched to 3 - 5% U-235, a level suitable for energy production and unusable in weapons manufacture. Because the level nuclear reactors can operate at is driven by the hottest region of the reactor core, a technique to flatten the power distribution is used by utilities. This power-shaping technique uses non-uniform enrichments of the fuel to increase reactor power near the edges of the core and reduce power near the center of the reactor core. As such, each load of discharged fuel from a given reactor will often contain fuel assemblies with different enrichments.

Attractiveness assessed from an international safeguards and security perspective is calculated empirically as a metric to describe weapons utility of the nuclear material in review. It is found by comparing properties of the radioactive material (RAM) to current IAEA standards [5]. The first standard is that all RAM should be within the 20% threshold for low enriched uranium. The second is that Pu-238 enrichment is greater than 80%, and the third being that the RAM in question may have a regulatory-defined self-protecting dose rate. If fewer standards are met, the spent fuel is potentially more dangerous and the attractiveness increases.

In this hypothetical scenario, the attractiveness is effected mostly by the SNF burnup value and age. The burnup value of nuclear fuel is the amount of energy extracted from fuel while undergoing fission, and this analysis uses burnup values of 40, 50, and 60 GWD/MTU. Lower burnup values are more attractive because they contain greater amounts of U-235 and Pu-239.

When nuclear fuel cannot produce sufficient fission any longer it must be removed from the reactor core. Initially SNF is too irradiated to transport or keep in dry storage, so it is stored in a spent fuel pool which both lowers the temperature and shields radioactivity. After removal from the reactor core, each assembly is highly radioactive due to the presence of a higher quantities of

fission products, transuranic elements, and activation products. The most lethal ionizing radiation is emitted mainly from short-lived fission products, with half-lives of around 30 years (or less). Even though the remaining radiation from long-lived actinides have half-lives of hundreds of thousands of years, the radioactivity of the SNF drops quickly, therefore the age of SNF heavily influences attractiveness. Because new fuel is highly irradiated, it is much more difficult to handle or divert, while older fuel is easier to manage and more attractive to malevolent groups. Testing different burnup values and ages of SNF for PWR and BWR assemblies demonstrates a broad range of possibilities between safety hazards and security threats in this scenario.

An example of calculated inventories is provided in Table 4 for 60 GWD/MTU PWR and BWR fuel assemblies⁹. The additional radionuclides (the ones not considered in NUREG-2125) represent 22-26% of the total activity. However, the normalized activity of these radionuclides is less than 0.02%. The normalized activities were calculated by dividing the actual activities by the corresponding A_2 (radiotoxicity) values [6] and expressing these obtained values as percent of total normalized activity.

⁹ For similar SNF cask inventories with different burnup values and ages of PWR and BWR assemblies, please see Appendix C.

Table 4. Example of Calculated Inventories for 60 GWD/MTU PWR & BWR Assemblies, from [6].

Isotope	Assembly Activity (Tera Becquerel)							
	PWR				BWR			
	5yr	10yr	25yr	50yr	5yr	10yr	25yr	50yr
Radionuclides considered in NUREG-2125								
Am241	19.22	31.58	54.187	67.246	8.95	14.41	24.384	30.136
Am242	0.11001	0.10734	0.09971	0.08819	0.05	0.05	0.04466	0.03950
Am242m	0.11052	0.10783	0.10017	0.08859	0.05	0.05	0.04487	0.03968
Am243	1.0333	1.0328	1.0313	1.0289	0.39	0.39	0.39416	0.39323
Ce144	176.08	2.0771	3.41E-	7.79E-	55.95	0.66	1.08E-	2.47E-
Cm243	0.61188	0.54323	0.38011	0.20964	0.25	0.22	0.15259	0.08415
Cm244	226.81	187.33	105.55	40.566	66.49	54.92	30.942	11.892
Co 60	18.353	9.5135	1.3252	0.04959	15.75	8.16	1.137	0.04255
Cs134	1142.2	213.51	1.3945	0.00031	350.87	65.59	0.42837	9.78E-
Cs137	2837.7	2529.1	1790.4	1006.8	1019.7	908.76	643.33	361.75
Eu154	133.06	88.956	26.578	3.5491	49.91	33.37	9.9697	1.3313
Eu155	60.312	29.103	3.27	0.08555	23.13	11.16	1.2539	0.03280
Kr 85	200.64	145.4	55.34	11.062	69.13	50.10	19.069	3.8116
Pu238	137.87	132.53	117.74	96.653	46.18	44.40	39.439	32.379
Pu239	3.9103	3.91	3.9089	3.9071	1.96	1.96	1.9616	1.9605
Pu240	8.3927	8.4972	8.7094	8.8655	4.52	4.55	4.6076	4.648
Pu241	1767.3	1386.9	670.32	199.55	780.81	612.75	296.15	88.157
Pu242	0.08410	0.08410	0.08410	0.08410	0.03	0.03	0.02781	0.02781
Ru106	341.4	11.365	0.00041	1.71E-	113.32	3.77	0.00013	5.69E-
Sb125	61.621	17.558	0.40615	0.00076	20.75	5.91	0.13674	0.00025
Sr 90	1942.4	1722.3	1200.5	657.86	685.32	607.64	423.55	232.1
Te125m	15.089	4.2994	0.09945	0.00018	5.08	1.45	0.03348	6.29E-
U234	0.01808	0.01999	0.02528	0.03281	0.01	0.01	0.00988	0.01240
Y90	1942.9	1722.7	1200.8	658.03	685.49	607.79	423.66	232.16
Additional Radionuclides								
Ba137m	2687.30	2.40E+0	1695.5	953.39	965.60	861	609.23	342.57
Cm242	0.66	8.92E-	0.08246	0.07293	0.29	0.04	0.03693	0.03266
Np239	1.03	1.03	1.0313	1.0289	0.39	0.3.95	0.39416	0.39323
Pr144	176.09	2.08	3.41E-	7.79E-	55.96	0.660	1.08E-	2.47E-
Pr144m	1.68	0.0198	3.25E-	7.43E-	0.53	6.30E-	1.03E-	2.36E-
Rh106	341.40	11.4	0.00041	1.71E-	113.32	3.77	0.00013	5.69E-
Te127	0.00	6.82E-	5.17E-	0	0.00	2.80E-	2.12E-	0
Te127m	0.00	6.96E-	5.27E-	0	0.00	2.86E-	2.17E-	0
TOTAL	14245.3	10658.1	6938.86	3710.25	5140.1	3903.5	2530.39	1343.99
% additional	22.52	22.61	24.45	25.73	22.10	22.17	24.09	25.52

Figure 3 shows the total activity of generic PWR and BWR casks as a function of age and burnup. Also shown in this figure is the total activity of the cask considered in NUREG-2125. Note that the NUREG-2125 cask had 26 assemblies while the generic PWR cask has 24 assemblies. The total activity spans over a large range with PWR cask activity being about 1.3 higher than BWR cask activity.

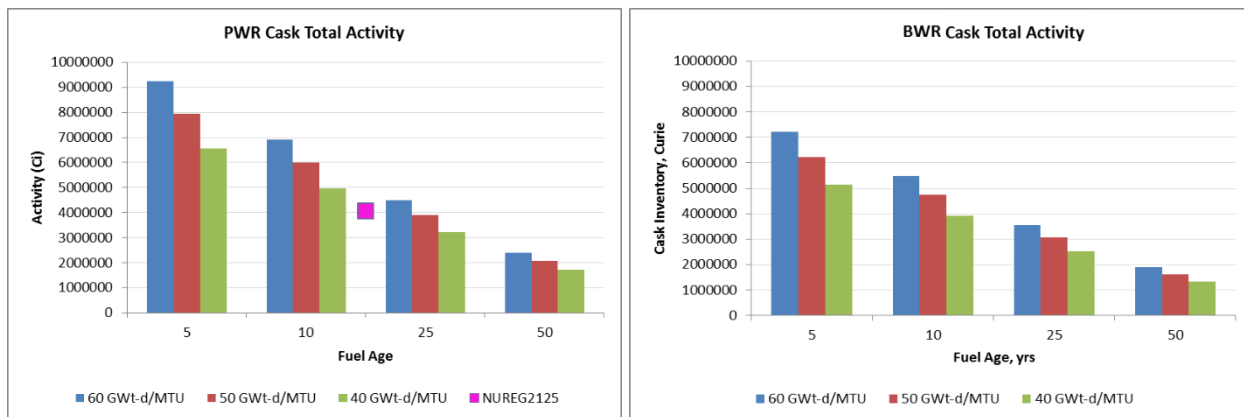
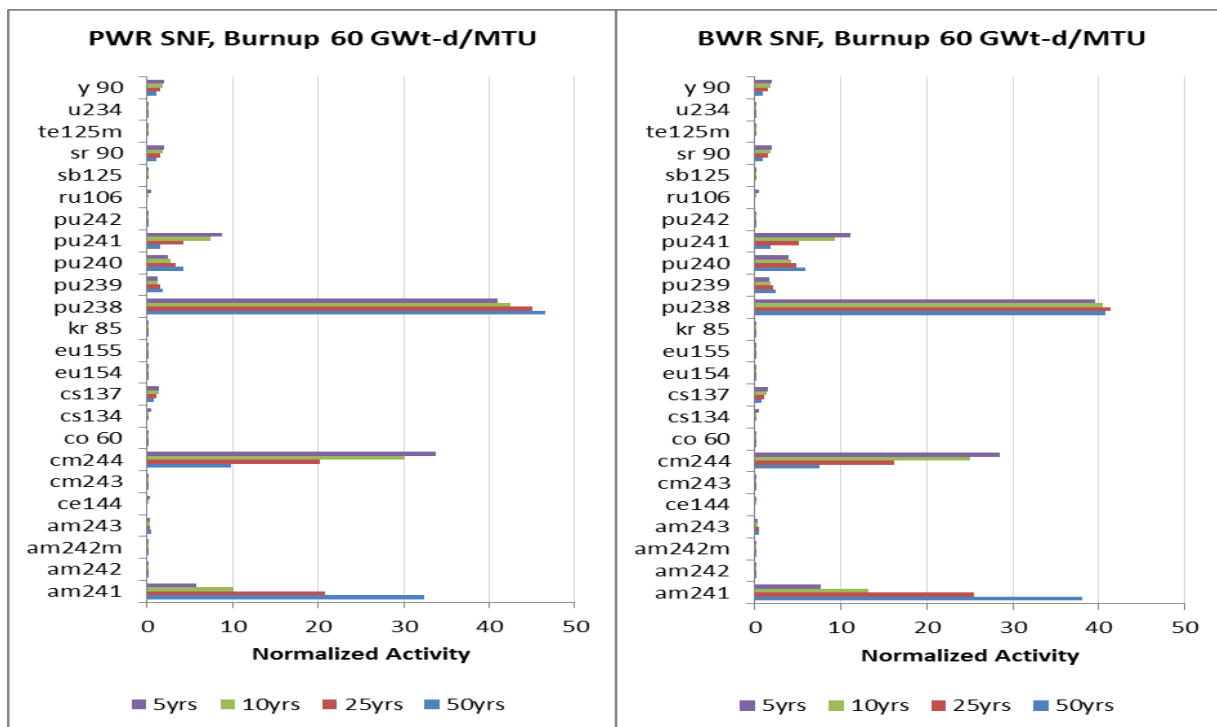


Figure 3. **Generic Transportation Cask Inventory, from [6].**

Figure 4 shows the normalized activities of 60 GWD/MTU PWR and BWR fuel assemblies. In both cases (PWR and BWR), the major contributors with regard to radiotoxicity are Pu-238, Am-241, and Cm-244 (76%-89% of radiotoxicity). Cs-137, Pu-241, Pu-240, Pu-241, Sr-90, and Y-90 are smaller contributors (11%-22%) and their contribution decreases with time. The total



contribution from the remaining radionuclides is 0.75% to 2% and it decreases with time as well.

Figure 4. Normalized Inventory of PWR & BWR Assemblies, from [6].

3.2. Cask

The generic transportation cask (like AREVA TN casks) are dual purpose casks designed for storage and transportation. The AREVA TN casks are compliant with both NUREG-2125 and IAEA best practices.

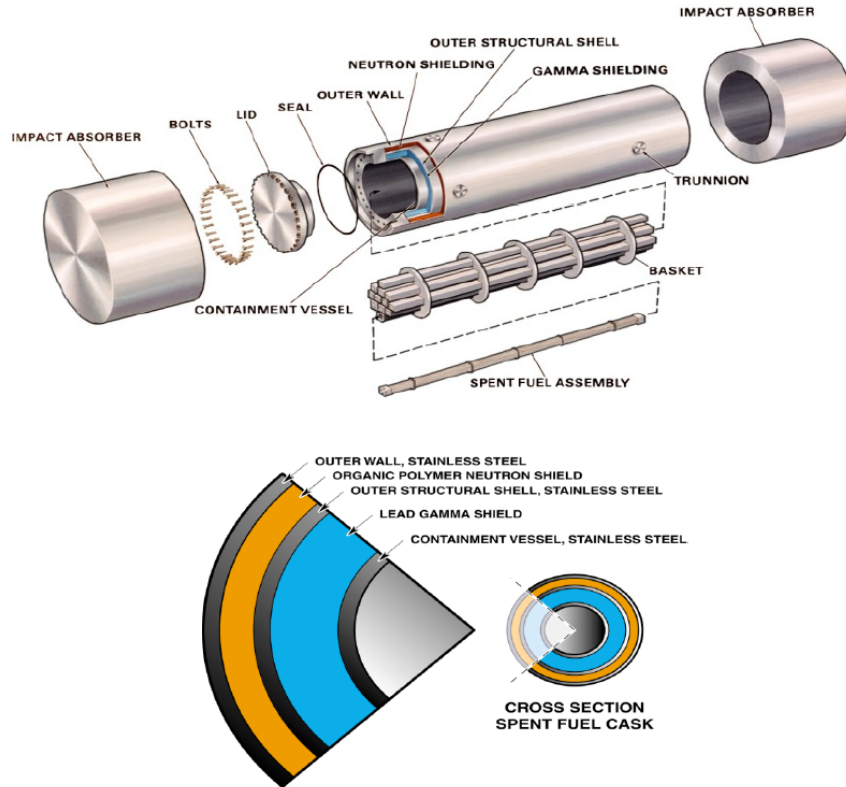


Figure 5. A Generic Spent Fuel Cask from Fig. 2-1 in [7, p. 17].

The TN-24 cask body is a cylinder made of SA-350, Grade LF3 forged steel with a wall thickness of 248 mm (9.75 in.) and a 286 mm (11.25 in.) thick welded closure on the bottom end. The top of the cask is sealed by a lid which is 292 mm (11.5 in.) thick. The cask is 5105 mm (201 in.) long and 2407 mm (94.75 in.) in diameter. When fully loaded with fuel, the cask weighs 103 tonne (113 tons); unloaded it weighs 75 tonne (83 tons).

The fuel basket is designed to hold 24 PWR or 52 BWR fuel assemblies. The basket is made of 11 mm thick copper plated borated stainless steel plates formed into 221 mm square cavities. The spacing of the plates provides water flux traps for criticality control during fuel loading.

A protective cover is bolted to the cask body to provide weather protection for the lid penetrations. The lid uses a double barrier seal system with two metallic O-rings forming the seal. The annular space between the O-rings is maintained above the pressure in the cask to prevent flow into or out of the cask. The TN-24 cask has three containment penetrations; one cask cavity drain, one cask cavity vent, and one interseal overpressure port. Each of these penetrations is in

the lid. Neutrons from the fuel are attenuated by a 137 mm (5.38 in.) thick borated polymer material encased in a steel shell on the outside of the cask.

3.3. Transportation Vehicles

The cask will travel by rail from the storage site (Site A) in Zamau to the Port of Zamau. Each railcar is designed to carry 140 ton loads and equipped with a canopy for physical protection. Railcars are designed to be compatible with any freight train [8]. To reduce 3S risk the cars have built-in real-time location monitoring and buffer cars to further isolate the cask car [9]. The cask will be transported on a dedicated train to avoid preventable stops and delays, and to reduce potential security and safety risk involving commercial shipments [10]. The Ministry of International Trade and Industry is responsible for regulations concerning SNF railcars, and standards for the railcars used for SNF transport are based on Association of American Railroads (AAR) Standard S-2043. Zamau's Atomic Energy Agency is responsible for cask standards.

The cask will travel by barge from the Port of Zamau to the Port of Famunda. At both the origin facility and the Port, there will be dedicated terminals owned and operated by the shipping organization which includes indoor facilities for inspections. All workers will be qualified and trained in the transport of SNF by the shipping organization. The barge is dedicated to the transport of radioactive material (RAM). There will not be a crane on the barge itself, partly to deter theft while the cask is at sea. There will be a crane onsite at the maritime terminal for transfer to the barge. Since Zamau is the flag state of the vessel, it is responsible for approving the radiation protection program for the shipment [11]. Famunda would be allowed approval by its competent authority for its port of call, but has declined to perform a review since this is not an active area of regulation for Famunda outside of research or medical waste. Stowage locations and occupancy factors for the planned maximum duration of the sea voyage will observe requirements in IAEA SSR-6. The requirements in the Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships (INF Code) for safety and emergency planning will be observed

The cask will travel by truck from the Port of Famunda to Site B in Kaznirra. The trucks used for transport will be specially manufactured vehicles with converters for low speed operations that can hold 150-250 tons. Drivers are qualified and trained by the shipping organization. In accordance with IAEA SSG-26: "During transit, there should be no unloading or entering into the enclosed area of a vehicle. If the vehicle is being held in the carrier's compound for any period, it should be parked in an area where access is controlled and where people are not likely to remain in close proximity for an extended period. If maintenance work is required to be done on the vehicle for an extended period, then arrangements should be made with the consignor or the consignee to ensure adequate radiation protection, for example, by providing extra shielding and radiation monitoring." [12] Famunda's Ministry of Transportation is responsible for regulating the transport of spent nuclear fuel. Packaging of nuclear material is regulated by the Ministry of Energy, but since they do not have a developed nuclear energy sector this is not an active area of regulation beyond research or medical waste. Kaznirra's National Nuclear Regulator reports to the Minister of Energy. It controls safety of nuclear installations and waste, and the protection of workers and the general public. In Kaznirra, the Committee on Radioactive Waste Management and Disposal is responsible for implementation of policies developed by the NNR. An inspection by trained shipping organization personnel will take place before the truck

leaves the port, and will include inspection of brakes, cask tie-downs, and other mechanical items. In the event of a nuclear disaster, the Ministry of Energy would be responsible, in partnership with the Provincial and local governments.

4. SCENARIOS

To focus the analytical scope of the associated LDRD 17-0969 research, the following three scenarios are described in more hypothetical, but realistic, detail.

4.1. Scenario 1: Train Derailment + Attack

During transit through Zamau, the train is derailed due to a 40-foot section of missing track. The derailed train is then opportunistically attacked by a state actor posing as a terrorist organization, in which the train's security force engages the attackers in a short firefight. In this scenario, if the attack is thwarted, the SNF shipment continues to its destination. However, if the attackers are successful, they quickly divert one significant quantity (SQ) of Pu from the fuel assembly, replace any missing material with dummy fuel rods, re-apply the containment seal and create a radiological release by detonating TNT attached to a fuel rod to make the diversion appear to be an act of terrorism. Lastly, the remains of the SNF assembly in the cask will eventually be shipped back to Site A and Zamau will send a special report to the IAEA detailing the incident. An IAEA inspector will subsequently inspect and examine the SNF shipment cask at Site A.

4.2. Scenario 2: Transfer of Cask from Famunda to Kaznirra at the Border

Because of the ongoing civil unrest in Famunda, the Kaznirran government has established a lengthy SNF responsibility transition process that includes more detailed SNF vehicle and cask inspections, as well as approval from several Kaznirran federal government offices (including the competent security authority). On average, this approval process takes 24 hours to complete—therefore, the SNF transportation vehicle is left in the vehicle arresting area at the border crossing overnight. During this process, the armed Famunda security personnel who escorted the SNF transport vehicle through Famunda are housed in the guard barracks until they are officially relieved of their security responsibilities by Kaznirran security personnel. Here, the description includes insights provided by the World Nuclear Transport Institute (WNTI) and the World Institute for Nuclear Security (WINS)—specifically the importance of coordinating security responsibilities between entities along the route and at points of transfer.

4.3. Scenario 3: Port of Famunda Refuses to Receive SNF on Barge from Zamau

The Port of Famunda is a major trading hub for this region and boasts the largest capacity for handling and distributing trade goods for each country in the region. In addition, there is a major highway that runs from the port to neighboring Kaznirra, which is regularly used to transport that countries' import/export goods. For these reasons, Zamau, Famunda and Kaznirra have agreed to allow the SNF cask barge to dock at the Port of Famunda for transfer to the heavy-haul truck convoy that will deliver the cask to Site B. The economic importance of this port is also routinely used by Famunda in both explicit and implicit negotiations for more preferential political concessions across a range of topics—including closing the port to ships flagged from its neighbors until political terms are agreed upon. As such, despite the previously agreed upon SNF transportation arrangement to use the Port of Famunda, Famunda denies the SNF barge

access to dock, citing ‘reasons of company policy [13].’ This leaves the barge in a holding pattern in the waters off of Famunda until either it is granted access or receives word to return to Zamau.

5. CONCLUSION

This SAND report provides a subject matter expert-validated (and detailed) description of both technical and political influences on the international transportation of spent nuclear fuel. This hypothetical case description assigns various attributes related to international SNF transportation that are representative, illustrative and indicative of “real” characteristics of “real” countries—and any similarity with specific real-world events is purely coincidental. Further, this hypothetical case description (and associated scenarios) were used in support of SNL’s “System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle” LDRD project [1]. Based on the successful use of this data for evaluating complex issues in SNL’s Center for Global Security and Cooperation mission space, the SAND report is offered for others seeking to conduct more rigorous analysis on global security issues without using “real” data or identifying “real” vulnerabilities, hazards or geopolitically embarrassing shortcomings.

[PAGE INTENTIONALLY LEFT BLANK]

REFERENCES

- [1] A. D. Williams, D. Osborn, K. A. Jones, E. A. Kalinina, B. Cohn, M. Thomas, M. J. Parks, E. Parks, B. Jeantete and A. H. Mohagheghi, "System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle: FINAL REPORT (SAND2017-10243)," Sandia National Laboratories, Albuquerque, NM, 2017.
- [2] World Institute for Nuclear Security & World Nuclear Transportation Institute, "Nuclear Security Transport," World Institute for Nuclear Security, Vienna, 2015.
- [3] J. M. Corbin and A. Strauss, "Grounded theory research: Procedures, canons, and evaluative criteria," *Qualitative Sociology*, vol. 13, no. 1, pp. 3-21, 1990.
- [4] M. J. Bell, "ORIGEN - the ORNL Isotope Generation and Depletion Code," May 1973.
- [5] U.S. Nuclear Regulatory Commission, "Spent Nuclear Fuel Transportation Risk Assessment-Final Report (NUREG-2125)," U.S. Nuclear Regulatory Commission, Washington, D.C., 2014.
- [6] International Atomic Energy Agency, "Security of Nuclear Material in Transport: Implementing Guide (IAEA Nuclear Security Series No. 26-G)," International Atomic Energy Agency, Vienna, 2015.
- [7] E. Kalinina, B. Cohn, D. Osborn, J. Cardoni, A. D. Williams, M. J. Parks, K. Jones, N. Andrews, E. Johnson, E. Parks and A. Mohagheghi, "Example of Integration of Safety, Security, and Safeguard Using Dynamic Probabilistic Risk Assessment Under a System-Theoretic Framework," in *International High-Level Radioactive Waste Management Meeting*, Charleston, 2017.
- [8] M. Valenzano, "The Future of Used Fuel Transportation in the U.S. (presentation)," in *INMM 30th Spent Fuel Management Seminar*, 2015.
- [9] Bipartisan Policy Center, "Transporting Spent Nuclear Fuel in the United States: An Assessment of Current Capabilities and Future Challenges," Bipartisan Policy Center, Washington, D. C., 2015.
- [10] U.S. Department of Transportation, Federal Railroad Administration, "Use of Dedicated Trains for Transportation of High-Level Radioactive Waste and Spent Nuclear Fuel: Report to Congress," U.S. Department of Transportation, Washington, D.C., 2005.
- [11] International Atomic Energy Agency, "Regulations for the Safe Transport of Radioactive Materials (2012 Ed.): Specific Safety Requirements No. SSR-6," International Atomic Energy Agency, Vienna, 2012.
- [12] "Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)," Vienna, 2014.
- [13] C. A. Chopra, "Handling and Transportation of Radioactive Materials by Maritime Carriage," in *Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials*, Kobe, Japan, 2016.
- [14] G. Corera, "A Secret Journey to Take Serbian Nuclear Fuel to Safety," BBC, 22 December 2010. [Online]. Available: <http://www.bbc.com/news/world-europe-12049784>. [Accessed 18 September 2017].
- [15] Nuclear Threat Initiative, "African Nuclear-Weapon-Free-Zone (ANWFZ) Treaty (Pelindaba Treaty)," Nuclear Threat Initiative, 30 June 2017. [Online]. Available: <http://www.nti.org/learn/treaties-and-regimes/african-nuclear-weapon-free-zone-anwfz->

- treaty-pelindaba-treaty/. [Accessed 18 September 2017].
- [16] International Atomic Energy Agency, "Convention on the Physical Protection of Nuclear Material (INFCIRC/274)," International Atomic Energy Agency, Vienna, 1979.
 - [17] Central Intelligence Agency, "The World Factbook," Central Intelligence Agency, 18 September 2017. [Online]. Available: <https://www.cia.gov/library/publications/the-world-factbook/>. [Accessed 18 September 2017].
 - [18] Fund for Peace, "Fragile States Index," The Fund for Peace, 18 September 2017. [Online]. Available: <http://fundforpeace.org/fsi/>. [Accessed 18 September 2017].
 - [19] Vision of Humanity, "Global Peace Index 2017," The Institute for Economics and Peace, 18 September 2017. [Online]. Available: <http://visionofhumanity.org/indexes/global-peace-index/>. [Accessed 18 September 2017].
 - [20] International Atomic Energy Agency, "Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols (IAEA Services Series 21)," International Atomic Energy Agency, Vienna, 2016.
 - [21] Nuclear Threat Initiative, "NIT Nuclear Security Index: Theft|Sabotage," Nuclear Threat Initiative, 2016. [Online]. Available: <http://www.ntiindex.org/>. [Accessed 18 September 2017].
 - [22] Republic of South Africa Department of Energy , "Nuclear Energy: Nuclear Safety," Republic of South Africa's Department of Energy , 2017. [Online]. Available: http://www.energy.gov.za/files/esources/nuclear/nuclear_safety.html. [Accessed 18 September 2017].
 - [23] H. A. Munera, M. B. Canal and M. Munoz, "Risk Associated with Transportation of Spent Nuclear Fuel Under Demanding Security Constraints: The Colombian Experience," *Risk Analysis: An International Journal*, vol. 17, no. 3, pp. 381-389, June 1997.
 - [24] A. A. Brown, "Sea Transport of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes," in *Safe and Security Transport and Storage of Radioactive Materials*, Amsterdam, Woodhead Publishing, 2015, pp. 155-169.
 - [25] International Atomic Energy Agency, "Return of Research Reactor Spent Fuel to the Country of Origin: Requirements for Technical and Administrative Preparations and National Experiences (IAEA-TECDOC-1593)," in *Technical Meeting*, Vienna, 2006.

APPENDIX A: CASE DESCRIPTION & ROUTE ASSUMPTIONS

In building this hypothetical international SNF case, Sandia subject matter experts (SMEs) in nuclear energy, spent fuel transportation, physical security, and safeguards were consulted. In addition, an extensive open source literature review was performed.

Based on the SME consultations and literature review, it was determined that three countries with two border crossings and multiple modes of transportation would be the most appropriate case to represent future SNF transport scenarios. Using only two countries would reduce the problem to a bilateral relationship, and three countries should be sufficient to explore the impact of a multi-lateral relationship on risk. Multiple modes of transportation were included to account for the various transportation modes identified as common in the literature when countries of differing levels of development are transporting SNF.

Related assumptions are identified, grounded in a real-world ‘equivalent’ and linked to a reference in the table below.

Table 5. Summary of case description and route assumptions.

Hypothetical Case Characteristic	Real-World ‘Equivalent’	Reference
Regional Context		
Significant regional influence on route selection	Example of 2010 shipment of HEU & SNF from Serbia to Mayak in Russia (see map) ‘Negotiating the route & gaining permission for the material to pass through countries that would accept it took five years of planning, and close co-operation between US, Russian officials and International Atomic Energy (IAEA) officials’	[14]
CONA Treaty establishing a regional nuclear-weapon-free zone	Loosely based on the ‘African Nuclear-Weapon-Free-Zone (Pelindaba) Treaty)	[15]
All three countries are parties to the Convention on the Physical Protection of Nuclear Material (CPPNM).	South Africa (one of the example countries) is a party to this Convention, as is Kazakhstan	[16]
Zamau Description		
Political/governance stability, terrorist activity, transportation infrastructure	Loosely related to characteristics of Liberia & Bangladesh	[17], [18], [19]
Zamau is responsible for the SNF until Kaznirra receives it. The first nation reports the reduction in inventory and the receiving nation reports the increase in their inventory to the IAEA.	Current IAEA best practice	[20]
Zamau NTI Nuclear Security Material Index scores ¹⁰	Tabulated & averaged NTI’s Nuclear Material Security Index theft values for the following areas: - Security & Control Measures: On-site Physical Protection (0 to 5); Control and Accounting Procedures (0 to 7); Insider Threat Prevention (0 to 9); Response Capabilities (0 to 7); Cybersecurity (0 to 4) - Domestic Commitments & Capabilities: UNSCR 1540 Implementation (0 to 5); Domestic Nuclear Security Legislation (0 to 3); Independent Regulatory Agency (0 to 1)	[21]

¹⁰ First, we identified the location on the Fragile States & Global Peace Indexes of the country on which the hypothetical country description was based. Then, we identified the nearest countries with nuclear material (according to the real NTI analysis). Once identified, the Nuclear Security Material Index values for those countries were then assigned to the hypothetical country.

Famunda Description		
Political/governance stability, terrorist activity, transportation infrastructure	Loosely related to characteristics of Cote d'Ivoire & Pakistan	[17], [18], [19]
Famunda's NTI Nuclear Security Material Index scores ¹¹	Tabulated & averaged NTI's Nuclear Material Security Index theft values for the following areas: • Security & Control Measures: On-site Physical Protection (0 to 5); Control and Accounting Procedures (0 to 7); Insider Threat Prevention (0 to 9); Response Capabilities (0 to 7); Cybersecurity (0 to 4) • Domestic Commitments & Capabilities : UNSCR 1540 Implementation (0 to 5); Domestic Nuclear Security Legislation (0 to 3); Independent Regulatory Agency (0 to 1)	[21]
Famunda's Ministry of Transportation is responsible for regulating the transport of spent nuclear fuel. Packaging of nuclear material is regulated by the Ministry of Energy, but since they do not have a developed nuclear energy sector this is not an active area of regulation beyond research or medical waste.	Modeled after US division of responsibility between Transportation and Energy is for nuclear international transport	[7]
Kaznirra Description		
Political/governance stability, terrorist activity, transportation infrastructure	Loosely related to characteristics of South Africa, Kazakhstan, Brazil & Turkey	[17], [18], [19]
Kaznirra NTI Nuclear Security Material Index scores ¹²	Tabulated & averaged NTI's Nuclear Material Security Index theft values for the following areas: • Security & Control Measures: On-site Physical Protection (0 to 5); Control and Accounting Procedures (0 to 7); Insider Threat Prevention (0 to 9); Response Capabilities (0 to 7); Cybersecurity (0 to 4) • Domestic Commitments & Capabilities : UNSCR 1540 Implementation (0 to 5); Domestic Nuclear Security Legislation (0 to 3); Independent Regulatory Agency (0 to 1)	[21]
	South Africa's National Nuclear Regulator (NNR) reports to the Minister	

¹¹ Ibid.

¹² Ibid.

	of Energy. It controls safety of nuclear installations and waste, and the protection of workers and the general public. The Committee on Radioactive Waste Management is responsible for implementation of policies developed by the NNR. In the event of a nuclear disaster, the Department of Energy would be responsible, in partnership with the Department of Provincial and Local government.	
Route Description		
Multimodal transportation route (road—rail—water)	Example of 2010 shipment of HEU & SNF from Serbia to Mayak in Russia (see map) • Direct road travel not available because some countries did not want materials in their borders	[14]
Transport takes months Using the distances offered in the text: • Rail travel ~ 7-9 hours (assuming 48-65 kmh, max speed 80 kmh) • Barge travel ~ 62 hours (assuming 8-12 kmh) • Heavy haul road travel ~ 3-4 hours/ 29-59 hours (assuming 8-16 kmh)	Example of 2010 shipment of HEU & SNF from Serbia to Mayak in Russia • One day to drive to rail station • Overnight at rail station • One day to rail travel to port/coast • Overnight at port • Several days/week at sea • Overnight at port • Several days/week by rail to Mayak • Almost 7000 mile journey	[10], [14]
Transportation modes modified to account for guerilla or terrorist activity	Example in Colombia (though they chose air transport)	[23]

APPENDIX B: TECHNICAL SNF & CASK ASSUMPTIONS

Additionally, a number of technical assumptions regarding SNF fuel characteristics, history, usage and expected movement patterns were made. Similarly, assumptions regarding the technical capabilities of the transportation cask were also made. Related assumptions are identified, grounded in a real-world ‘equivalent’ and linked to a reference in the table below.

Hypothetical Case Characteristic	Real-World ‘Equivalent’	Reference
Technical Description		
Radioactivity of material has lessened, making SNF attractive ‘dirty bomb’ target	Example of 2010 shipment of HEU & SNF from Serbia to Mayak in Russia (see map) - Fuel rods shipped were easier to handle - Ideal for production of a ‘dirty bomb’	[14]
No crane on barge	Example of shipping MOX to Japan: ‘the MOX transported to Japan is typically in flasks weighing over 100 Te in the hold of vessels that have no deck crane capable of opening the holds or removing the flasks’, pg. 166)	[24]
Cask characteristics (e.g., dual transportation and storage use)	AREVA TN-series type casks	[7]
Truck convoy notionally includes 4 escort vehicles of security forces and two more with responsible personnel from responsible agency	From IAEA Argentina documented example: The transport convoy departed from CAE on 13 December 2000 at 3:30 AM to the selected harbor that was about 750 km away, close to Bahía Blanca city. The convoy was formed by 7 trucks each one transporting an ISO container, 5 for the LWT casks and two for the transfer systems and associated tools and hardware. Besides, there were four escort vehicles of security forces and two more vehicles with CNEA personnel responsible for the transport. On the same day, the ISO containers were loaded in an exclusive-use transport vessel that departed for Charleston at 19:02 PM.	[25]
The barge has a military ship escorting it during transport and the ship will have its own crane facilities for transfer to the truck.	From the Portugal to US takeback program (IAEA doc): The truck transport of the cask from ITN to this base was done overnight in a military convoy, via a route that included the Vasco da Gama Bridge, avoiding areas of large population density. The ship had its own crane facilities and left less than 3 hours after the arrival of the convoy. It was escorted by a Navy vessel while in Portuguese waters.	[25]

Table 6. Summary of nuclear material and SNF cask technical assumptions.

APPENDIX C: CALCULATED INVENTORIES FOR PWR & BWR ASSEMBLIES

Table 7. Example of Calculated Inventories for 50 GWD/MTU PWR & BWR Assemblies.

Isotope	Assembly Activity (Tera Becquerel) – 50 Burnup							
	PWR				BWR			
	5yr	10yr	25yr	50yr	5yr	10yr	25yr	50yr
Radionuclides considered in NUREG-2125								
am241	18.784	30.648	52.438	65.019	8.252	13.28	22.473	27.773
am242	.11454	0.11176	0.10382	0.091825	0.045536	0.044431	0.041274	0.036504
am242m	0.11507	0.11228	0.1043	0.0922477	0.045745	0.044635	0.041464	0.036672
am243	0.65385	0.65354	0.65262	0.65109	0.23594	0.23583	0.2355	0.23495
ce144	181.69	2.1432	3.5E-06	8.03E-16	58.153	0.68597	1.13E-06	2.57E-16
cm243	0.42473	0.37707	0.26385	0.14552	0.15972	0.1418	0.099221	0.054721
cm244	108.5	89.615	50.491	19.406	31.259	25.817	14.546	5.5906
co 60	14.982	7.7664	1.0818	0.040491	13.37	6.9306	0.96537	0.036133
cs134	851.21	159.11	1.0392	0.000237	265.14	49.561	0.3237	7.39E-05
cs137	2389.1	2129.2	1507.3	847.58	860.74	767.12	543.06	305.37
eu154	111.28	74.39	22.227	2.968	41.031	27.43	8.1957	1.0944
eu155	48.909	23.601	2.6517	0.069376	18.524	8.9388	1.0044	0.026276
kr 85	181.37	131.44	50.027	9.9996	62.889	45.575	17.346	3.4673
pu238	98.852	95.03	84.423	69.31	32.305	31.056	27.59	22.652
pu239	4.0421	4.0417	4.0404	4.0381	2.0188	2.0186	2.0179	2.0166
pu240	7.6563	7.7044	7.8001	7.8652	4.0072	4.0202	4.0449	4.0589
pu241	1703.8	1337.1	646.25	192.37	719.47	564.62	272.89	81.227
pu242	0.057119	0.057119	0.057118	0.057117	0.018987	0.018987	0.018987	0.018986
ru106	281.49	9.3704	0.000346	1.41E-11	96.557	3.2143	0.000119	4.85E-12
sb125	52.476	14.952	0.34588	0.00065	18.099	5.157	0.11929	0.000224
sr 90	1734.7	1538	1072.1	587.49	612.12	542.74	378.31	207.31
te125m	12.85	3.6613	0.084695	0.000159	4.432	1.2628	0.029212	5.49E-05
u234	0.021403	0.02277	0.026563	0.031965	0.008497	0.008944	0.010183	0.011949
y 90	1735.1	1538.4	1072.4	587.64	612.27	542.88	378.41	207.36
Additional Radionuclides								
ba137m	2262.4	2016.4	1427.4	802.66	815.11	726.46	514.28	289.18
cm242	0.5695	0.092848	0.085863	0.075939	0.23051	0.036913	0.034134	0.030189
np239	0.65385	0.065354	0.65262	0.65109	0.23594	0.23583	0.2355	0.23495
pr144	181.7	2.1433	3.85E-06	8.03E-16	58.155	0.68599	1.13E-06	2.57E-16
pr144m	1.7348	0.020463	3.36E-08	7.67E-18	0.55524	0.00655	1.08E-08	2.45E-18
rh106	281.49	9.3704	0.000346	1.41E-11	96.557	3.2143	0.000119	4.85E-12
te127	0.000759	6.92E-09	5.24E-24	0	0.000308	2.81E-09	2.13E-24	0
te127m	0.000775	7.07E-09	5.35E-24	0	0.000315	2.87E-09	2.17E-24	0
TOTAL	12266.68	9226.19	6004.05	3198.25	4432.00	3373.44	2186.32	1157.82
% additional	22.24	21.99	23.79	25.12	21.91	21.66	23.53	25.00

Table 8. Example of Calculated Inventories for 40 GWD/MTU PWR & BWR Assemblies.

Isotope	Assembly Activity (Tera Becquerel) – 40 Burnup							
	PWR				BWR			
	5yr	10yr	25yr	50yr	5yr	10yr	25yr	50yr
Radionuclides considered in NUREG-2125								
Am241	16.757	27.414	46.904	58.158	6.9401	11.221	19.05	23.565
Am242	0.1033	0.10079	0.093631	0.082809	0.03628	0.0354	0.032885	0.029085
Am242m	0.10377	0.10125	0.094061	0.08319	0.036447	0.035563	0.033037	0.029218
Am243	0.34323	0.34307	0.34259	0.34178	0.11674	0.11669	0.11652	0.11625
Ce144	183.99	2.1703	3.56E-06	8.13E-16	5.99E01	0.70652	1.16E-06	2.65E-16
Cm243	0.22989	0.2041	0.14281	0.078764	8.23E-02	0.073106	0.051155	0.028213
Cm244	40.753	33.659	18.964	7.2886	1.14E01	9.4563	5.3279	2.0477
Co 60	11.755	6.0936	0.84879	0.031769	1.09E01	5.6576	0.78806	0.029496
Cs134	583.15	109	0.71194	0.000162	1.85E02	34.598	0.22597	5.16E-05
Cs137	1930.9	1720.9	1218.2	685.03	6.97E02	621.51	439.98	247.4
Eu154	84.069	56.203	16.792	2.2424	3.03E01	20.236	6.0462	0.80738
Eu155	35.733	17.243	1.9374	0.050687	1.34E01	6.4446	0.72411	0.018944
Kr 85	156.94	113.73	43.287	8.6525	5.48E01	39.748	15.128	3.0239
Pu238	61.029	58.671	52.124	42.798	1.96E01	18.838	16.737	13.742
Pu239	4.1584	4.1578	4.1562	4.1536	2.0484	2.0481	2.0473	2.046
Pu240	6.5496	6.5656	6.5958	6.6106	3.3088	3.3125	3.3187	3.319
Pu241	1524	1196	578.05	172.06	6.13E02	480.69	232.32	69.152
Pu242	0.033918	0.033918	0.033918	0.033917	1.14E-02	0.011368	0.011368	0.011368
Ru106	221.38	7.3696	0.000272	1.11E-11	7.87E-1	2.6212	9.67E-05	3.95E-12
Sb125	42.963	12.241	0.28318	0.000532	15.164	4.3207	0.099949	0.000188
Sr 90	1482.6	1314.5	916.3	502.12	5.24E02	464.83	324.01	177.56
Te125m	10.52	2.9976	0.069341	0.00013	3.7132	1.058	0.024474	4.6E-05
U234	0.25095	0.025939	0.02828	0.031615	9.66E-03	0.00993	0.010681	0.011752
Y 90	1483	1314.9	916.53	502.25	5.24E02	464.95	324.1	177.6
Additional Radionuclides								
Ba137m	1.83E03	1629.7	1153.7	648.72	6.60E02	588.56	416.65	234.29
Cm242	4.18E-01	0.083692	0.077432	0.098483	1.57E-01	0.029399	0.027196	0.024053
Np239	3.43E-01	0.34307	0.34259	0.34178	1.17E-01	0.11669	0.11652	0.11625
Pr144	1.84E02	2.1704	3.56E-06	8.14E-16	5.99E01	0.70654	1.16E-06	2.65E-16
Pr144m	1.7568	0.020722	3.4E-08	7.77E-18	5.72E-01	0.006746	1.11E-08	2.53E-18
Rh106	2.21E02	7.3696	0.000272	1.11E-11	7.87E01	2.6212	9.67E-05	3.95E-12
Te127	7.66E-04	0	5.29E-24	0	3.06E-04	2.79E-09	2.11E-24	0
Te127m	7.82E-04	7.13E-09	5.4E-24	0	3.12E-04	2.85E-09	2.16E-24	0
TOTAL	10117.49	7644.31	4976.61	2641.23	3654.02	2784.57	1806.98	954.97
% additional	22.10	21.45	23.19	24.58	21.89	21.26	23.07	24.55

DISTRIBUTION

1	MS0748	Brian Cohn	8852
1	MS0748	Doug Osborn	8852
1	MS0779	Elena Kalinina	8845
1	MS0789	M. Jordan Parks	6835
1	MS0789	Ethan Parks	6835
1	MS1188	Katherine Jones	8831
1	MS1371	Amir Mohagheghi	6833
1	MS1373	Maikael Thomas	6832
1	MS0779	Sylvia Saltzstein	8845
1	MS0747	Ken Sorenson	8843
1	MS0899	Technical Library	9536 (electronic copy)

