Abstract

ANGELL, JAMES ROSS. Practical Perspectives on Spent Nuclear Fuel Transportation Risks. (Under the direction of Man-Sung Yim)

Transportation of spent nuclear fuel is essential for relocation of used fuel assemblies from temporary storage facilities to a geological repository. There has been a great deal of publicized concern over the hazard of shipments of radiological materials in recent years due to the proposed Yucca Mountain repository. This concern over the radiological material transport is commonly based on a public perception of extreme fear or dread associated with radiological material.

The goal of this work is to provide some insight into the practical understanding and relative significance of the risk values presented in a transportation risk assessment. This will be achieved by performing a transportation risk assessment for shipment of spent nuclear fuel, by both truck and rail, for four specific routes. An investigative analysis into the possibility of a successful sabotage attack will also be performed. Finally, a comparison between the transportation and sabotage analysis results will be made to the transportation of other materials. This will include comparison against transport of hazardous chemicals and gases, transport of materials used in the production of electricity, and a comparison against previous work on a potential radiological dispersal device.

This work will show that the transportation risk presented by shipment of spent nuclear fuel is comparable to or less than other hazardous materials. This work will also demonstrate that the transportation risk is less for spent nuclear fuel than for other electrical power producing materials.

Practical Perspectives on Spent Nuclear Fuel Transportation Risks

By

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Biography

James Ross Angell was born in Salmon ID on January 23, 1974. He graduated high school from South Fremont High School in 1992. He received an Associate of Applied Science degree in Electronics from the Eastern Idaho Technical College in 1994. He received a Bachelor of Science Degree in Mechanical Engineering from the University of Idaho in 2002. Research interests included application and teaching techniques for problem solving methods. He received a Master of Science degree in Nuclear Engineering from North Carolina State University in 2005. Research interests included nuclear fuel transportation, nuclear waste policy, radiological dispersal devices, and particle size effects.

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Table of Contents

List of Tables

List of Figures

1 Spent Nuclear Fuel Transportation

1.1 Introduction

Transportation of spent nuclear fuel (SNF) is essential for relocation of used fuel assemblies from temporary storage facilities located at the power plant site to geological repositories, such as the Yucca Mountain facility, for permanent storage. Numerous factors must be considered prior to spent fuel transportation from a temporary storage facility to a permanent repository. A shipping container, called a cask, must be designed and tested for safe reliable transportation. The spent fuel usually requires a cooling period of more than 150 days and often several years after being removed from the reactor core before shipment to a repository is made. However, a large number of spent fuel assemblies have been in temporary storage at various power plant facilities for long time periods and will be suitable for shipment immediately.

The spent fuel assemblies will need to be inspected and organized into groups for insertion into a shipping cask. After the spent fuel assemblies are inserted into a shipping cask, the cask is further inspected before loading onto either truck or rail transports. During transport, the vehicle is continuously monitored for location through a global positioning system (GPS) tracking system with armed security for most of the truck transport routes. Upon reaching the repository, the shipping cask is inspected, unloaded from the transport vehicle, the spent fuel assemblies are removed from the shipping cask and prepared for permanent storage. The shipping cask is then cleaned and possibly used for future shipments. Detailed record keeping is prominent throughout the entire process.

There has been a great deal of publicized concern over the hazard of shipments of radiological materials in recent years due to the proposed Yucca Mountain repository.

This concern over the radiological material transport is commonly based on a public perception of extreme fear or dread associated with radiological material, especially the term ‘radioactive waste’. This perception of dread is easily associated with a lack of knowledge about radiological materials. This lack of knowledge may be the result of inadequate explanation by researchers or by a lack of ‘need to know’ by the general public. Simply put, if something (radiological material transport) is not an issue then people rarely take the time to learn about it. This is due in a large part to the exceptional safety record of previous radiological material shipments. Unfortunately, this relative lack of knowledge the public currently has about radiological materials makes sabotage of transportation or storage locations an ideal choice for terrorist activities.

1.2 Spent Nuclear Fuel Description

Spent nuclear fuel refers to the uranium fuel assembly after it has been removed from a reactor. Spent nuclear fuel contains uranium along with other radioactive material resulting from the reactor operation. Once removed from the reactor, the fission process has stopped. However, the spent fuel continues to generate significant radiation and release heat, commonly known as ‘radioactive decay’. There can be some variation in the type and amount of radioactive material contained in spent nuclear fuel depending on factors such as the type of reactor, reactor burnup rate, or initial fuel design.

The spent fuel used for this study is a pressurized water reactor (PWR) assembly. This is the most common type of reactor assembly used for electrical power generation in the United States. Table 1.1 lists the more significant parent nuclides and activity level for a cooled PWR spent fuel assembly.

Table 1.1: Key parent nuclides for PWR three year cooled spent fuel

Nuclide	Curies (1 PWR Assembly)	
	3 Year Cooled	20 Year Cooled
Co-60	5.78E+01	6.20E+00
Kr-85	5.87E+03	1.96E+03
Sr-90	5.36E+04	3.55E+04
Ru-106	4.43E+04	0.00E+00
Cs-134	6.99E+04	2.31E+02
Cs-137	7.90E+04	5.35E+04
Ce-144	3.87E+04	0.00E+00
Pm-147	2.58E+04	2.89E+02
Eu-154	8.42E+03	2.21E+03
Pu-238	4.81E+03	4.21E+03
Pu-239	2.14E+02	2.14E+02
Pu-240	4.28E+02	4.28E+02
Pu-241	6.52E+04	2.88E+04
Am-241	4.36E+02	3.69E+04
Am-242m	1.33E+01	1.23E+01
Cm-242	3.76E+02	0.00E+00
Am-243	2.51E+01	2.51E+01
Cm-243	2.88E+01	1.91E+01
Cm-244	5.62E+03	2.93E+03

1.3 Cask Description

Due to the radioactive decay inherent in the spent nuclear fuel, measures must be taken to ensure the safety of workers and the general public. A shipping cask is used for this purpose. The shipping cask ensures protection of the spent nuclear fuel during the transportation process. The cask also significantly reduces or completely prevents the release of radioactive material during an accident or sabotage attack.

Transportation of spent nuclear fuel is primarily accomplished with road and rail routes. Each mode of transportation uses a different shipping cask based on similar design considerations. The truck casks used for roadway routes are small, weighing approximately 22.5 – 36 tons with an overall length of approximately 5 m and a diameter of 1.75 m. Depending on cask dimension and design, one to three PWR spent fuel assemblies could be encased inside the cask. A truck transport cask can carry approximately 1.5 tons of spent fuel. The cask construction usually involves an inner and outer layer of stainless steel, with a layer(s) of lead, depleted uranium, or polymer shielding materials for both gamma and neutron shielding. One cask design for truck transport is shown in Figure 1.1.

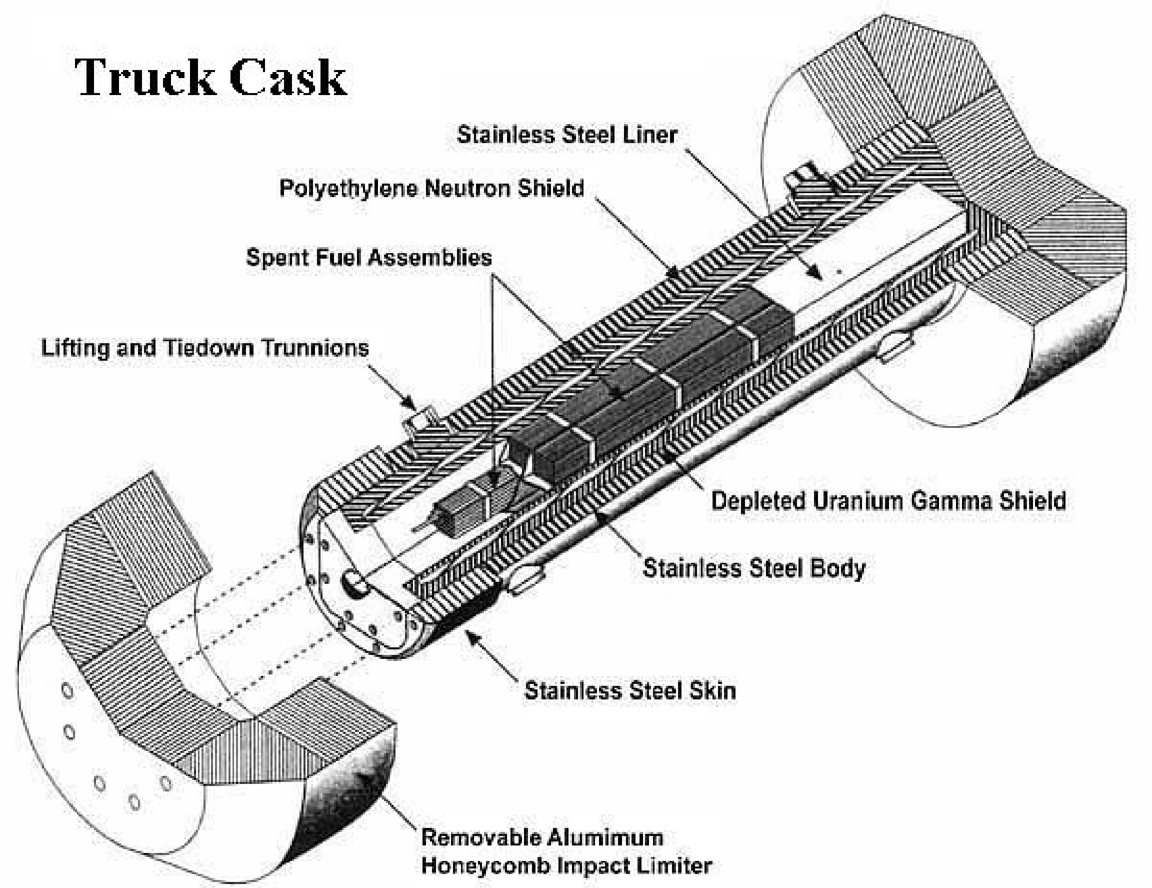

Figure 1.1: Truck transport cask cutaway diagram (Source: Dept. of Energy)

Larger load weights are capable of being transported on railway cars allowing the rail casks to be much larger. Rail casks can weigh approximately 67.5 to 120 tons, with an overall length of approximately 5 – 6 m and a diameter of 2.4 – 3 m. Depending on cask dimensions and design, 10 - 24 PWR spent fuel assemblies could be encased inside the cask. A rail transport cask can carry approximately 5 - 12 tons of spent fuel. Rail cask construction is similar in shape and materials to the truck cask with larger dimensions. One cask design for rail transport is shown in Figure 1.2.

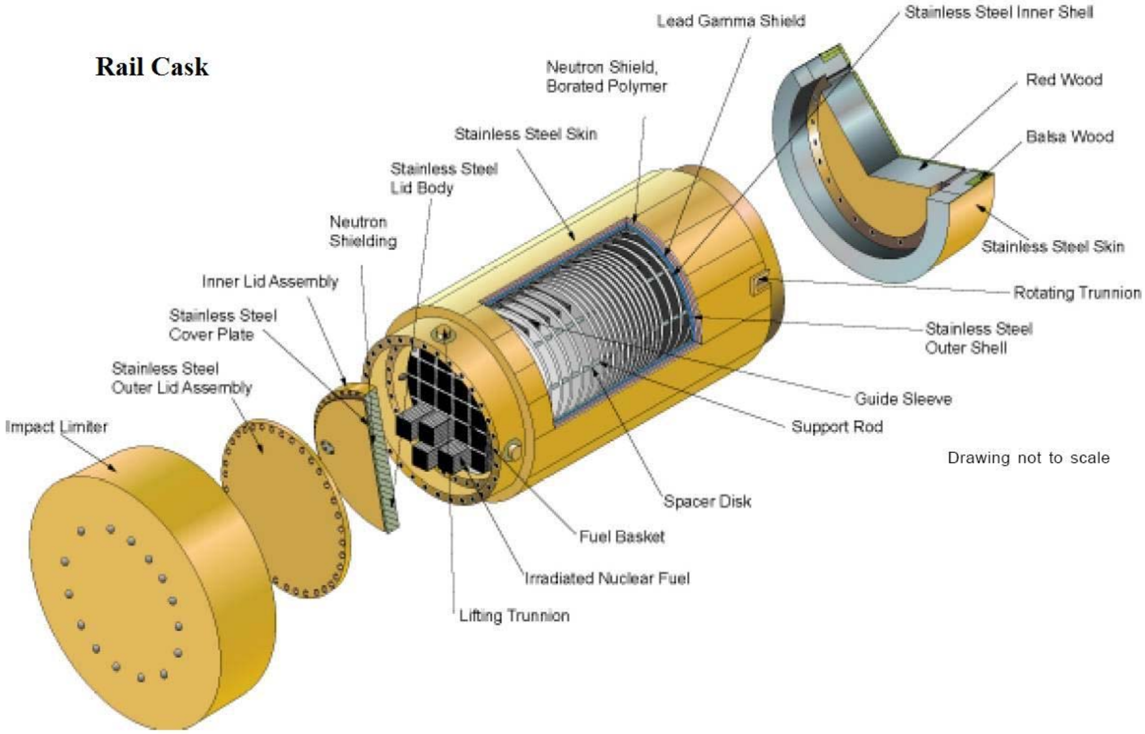

Figure 1.2: Rail transport cask cutaway diagram (Source: OCRWM)

1.4 Cask Testing

A spent fuel transport cask must meet strict specifications before the cask is certified by the Nuclear Regulatory Commission (NRC). All cask designs must have a Safety Analysis Report (SAR) which requires approval from the NRC for licensing.

Cask designs are tested to verify cask integrity and performance criteria. Tests concerned with cask performance in normal operation and possible accident situations include:.

- a 30 ft free fall in the most damaging orientation onto an unyielding surface: simulates a 120 mph crash into a concrete bridge abutment
- a 40 in free fall onto a 6 in diameter steel spike: simulates a puncture scenario
- 30 minutes completely engulfed in an open flame fire at 1,475˚F
- 8 hr submergence in water at a depth of 3 ft

These tests are performed and must be passed in sequence.

There have been further tests performed, primarily at Sandia National Laboratory (SNL), to evaluate the cask performance under the conditions of a deliberate sabotage attack which include:

- the cask engulfed in a propane gas explosion
- a jet engine rotor launched at the cask at near supersonic speed
- both 60 and 80 mph crash tests of truck and cask into 700 ton reinforced concrete walls
- an 80 mph crash test of a rail car and cask into a 700 ton reinforced concrete wall
- a rail cask broadsided by a 120 ton locomotive traveling at 80 mph
- 90 minutes engulfed in a 2000˚F fire (the fire burned 9000 gal. of aviation fuel)
- a truck cask dropped in a 2000 ft free fall onto hard ground
- a 140 ton locomotive broadsided a 48 ton rail cask attached to a derailed rail car
- impact from several high energy density devices (HEDD): this is a military anti-tank, penetrating explosive projectile

In all the above tests, except for the HEDD scenario, the cask maintained structural integrity with no release of radiation material. The HEDD tests did puncture the cask and result in an environmental release of spent fuel material. From these tests it is apparent the spent fuel shipping cask performed well above initial design expectations.

Furthermore, spent nuclear fuel is now shipped entirely in casks using “dry” materials, meaning no liquid is contained in the shipping cask. The spent fuel is a solid material that is not flammable or explosive making accident potential further reduced.

There have been over 3,000 shipments of spent fuel assemblies throughout the U.S. with no physical release of the spent fuel material in transport. This safety record is a direct result of the robust nature, careful engineering, and strict inspection requirements placed on the shipping cask designs.

1.5 Involved Agencies

Numerous organizations are involved with the spent fuel shipping cask design, testing, and transportation. The NRC sets cask certification design and performance standards. These standards must be met and verified through modeling or testing prior to cask use. The NRC also sets guidelines for cask safeguards and security against attacks, diversion, or theft of spent fuel shipments. The U.S. Department of Transportation (DOT) is the leading body for safe transportation of spent fuel shipments in the U.S. The DOT regulates and test items such as driver or other personnel training, and shipping cask packaging, labeling, and handling. Tasks such as transport security, route planning to minimize hazards, and transport communication between involved agencies are also led by the DOT.

The Office of Civilian Radioactive Waste Management (OCRWM) under the Department of Energy (DOE) was established to develop and manage a federal system for disposing of all spent nuclear fuel from commercial nuclear reactors and high-level radioactive waste resulting from atomic energy defense activities. Radiation waste management and transportation information and updates for both federal and public arenas are also a large responsibility of the OCRWM with support from the NRC and other organizations. Other organizations such as the Federal Emergency Response

Agency (FEMA) and state and local emergency response crews are also involved in the planning and preparation for possible accident scenarios.

1.6 Incident Free Risk

Incident-free (expected or normal) transportation events occur when no accident, packaging, or handling abnormality and no deliberate attack occurs during the transportation process. All methods of radiological material transportation are regulated in the United States by the NRC and DOT. Specifics can be found in the Code of Federal Regulations (CFR), Title 10 CFR Parts 71-73 and Title 49 CFR Parts 171-178. Topics such as the maximum permissible dose rates (both from the shipping cask and to crew members), packaging criteria and certification, as well as many other regulations for radiological material transportation are discussed.

Incident-free transportation does involve a risk to both the occupational workers and the general public. These risks include vehicle related risks caused by the motion of transport vehicles (such as a risk of accident and exposure to exhaust emissions) and an additional risk due to the nature of the radioactive material cargo.

For spent fuel transportation, the cargo related risk is primarily related to the low level of ionizing radiation being emitted by the spent fuel through the shipping cask during transport or the exposure of radioactive material released during a severe traffic accident. In both cases, the possibility of an increase risk of developing a latent cancer is the primary area of concern. A latent cancer, like a radiation induced cancer, typically develop years after the adverse (radiation) exposure.

1.7 Accident Risk

Accidents, although avoided, do occur during the transportation process. Accidents vary in both likelihood of occurrence (probability) and severity (consequence). Historical data of previous accidents along with estimation about postulated accident scenarios are used to establish a data set of accident probability and consequence pairs.

The 18 and 20 accident cases, for truck and rail respectively, are established for various extreme accident conditions that could lead to release of radiological material. The accident cases are determined from different types of accidents, impact velocity ranges, and temperature ranges. The additional accident category, #19 for truck and #21 for rail, accounts for all other types of accidents that will not lead to release of radiological material.

For each of these probability/consequence pairs, an effect on the shipping cask, possible radiological release, and potential adverse radiation exposure can be determined. This study relies on the ‘Reexamination of SNF Shipment Risk: NUREG/CR-6672’ [Sprung et al, 2000] for the probability of occurrence for a given set of accident categories. Table 1.2 lists the conditional probabilities for each accident category for both truck and rail. The consequence of each accident category is addressed by a corresponding release fraction. The release fraction describes the amount and conditions of spent fuel material released from the cask during a given accident category.

Table 1.2: Transportation accident severity fractions

Estimated Severity Fractions for Spent Nuclear Fuel Shipments		
Case	**Truck Cask** [a]	**Rail Cask** [b]
1	1.53E-08	8.20E-06
2	5.88E-05	5.68E-07
3	1.81E-06	4.49E-09
4	7.49E-08	2.96E-05
5	4.65E-07	8.24E-07
6	3.31E-09	1.10E-07
7	0.00E+00	6.76E-08
8	1.13E-08	1.88E-09
9	8.03E-11	2.51E-10
10	0.00E+00	4.68E-09
11	1.44E-10	1.31E-10
12	1.02E-12	1.74E-11
13	0.00E+00	3.70E-11
14	7.49E-11	1.03E-12
15	0.00E+00	1.37E-13
16	0.00E+00	4.15E-10
17	0.00E+00	2.51E-13
18	5.86E-06	1.74E-14
19	0.99993	1.37E-16
20	N.A.	4.91E-05
21	N. A.	0.99991
Total	1.0000	1.0000

a) Cask design: Steel-DU-Steel
Cask contains 3 PWR assemblies
b) Cask design: Steel-Lead-Steel
Cask contains 24 PWR assemblies

1.8 Sabotage Risk

The general public often perceive a malevolent act (or sabotage attack) on a spent nuclear fuel shipment as both easily achieved and extremely harmful. However, a sabotage attack would be difficult to achieve, require trained personnel, have no guaranteed effect, and the resulting health effects are considerably below current public belief [Wolff, 1984].

Due to the robust design of the shipping cask, a significant event is necessary to breach the cask. This would require a large amount of high explosives or a large high energy density device (HEDD) such as a military anti-tank projectile. Even with these sabotage devices, the amount of radioactive material released from the cask is low. For this type of sabotage attack, the estimated number of fatalities resulting directly from the attack (not related to the cask contents) could easily exceed the number of fatalities due to the spent fuel cargo that may be released. It is interesting that for a maximally successful HEDD attack, the estimated number of fatalities is below the number of fatalities estimated in the worst-case accident scenarios.

1.9 Scope of Work

The goal of this work is to provide some insight into the practical understanding and relative significance of the risk values presented in a transportation risk assessment. This will be achieved by performing a transportation risk assessment for shipment of spent nuclear fuel, by both truck and rail, for four specific routes. An investigative analysis into the possibility of a successful sabotage attack will also be performed. Finally, a comparison between the transportation and sabotage analysis results will be made to the transportation of other materials. This will include comparison against transport of hazardous chemicals and gases, transport of materials used in the production of electricity, and a comparison against previous work on a potential radiological dispersal device (RDD).

There have been numerous papers written about the risks due to the transportation of radiological materials over the past several decades. This work will rely on these previous reports when possible. The target of this work is to provide insight about the transportation of spent nuclear fuel rather than to actually be a complete, in-depth transportation risk analysis.

The transportation of radiological materials addresses an engulfing number of topics. This work will focus on the human risk associated with the transportation process and transportation cargo. While topics such as policy, public perception, stakeholder communication, or the relevance or justifiable use of radiological materials are of important interest and may be touched on briefly, they are beyond the scope of this work.

2 Transport Routes

2.1 Introduction

Four sample routes were selected for the analysis based on four power plant locations and Yucca Mountain. One power plant location was selected for the northwest, southwest, northeast, and southeast regions of the United States. This provides a sample route for short and long distance routes, rural and urban population settings, and various geographic and climatic regions.

The routes were selected using the Transportation Routing Analysis Geographic Information System (TRAGIS) program developed at Oak Ridge National Laboratory (ORNL) [ORNL, 2003]. The TRAGIS model is used to calculate highway, rail, or waterway routes within the United States. The selected nodes and program options used for route calculation are listed in Table 2.1.

Table 2.1: Selected TRAGIS input values

Origin	Highway Node Name	Node Number	Rail Node Name	Node Number	Railroad Company
Diablo Canyon, CA	Diablo Canyon NP	61100318	San Luis Obispo	62103227	UP
Millstone, CT	Millstone NP	91100126	Millstone NP	92100382	PW
Trojan, OR	Trojan NP	411100006	Trojan NP	412101807	WPRR
Turkey Point, FL	Turkey Point NP	121100445	Kendall	122102632	FEC
Destination	**Highway Node Name**	**Node Number**	**Rail Node Name**	**Node Number**	**Railroad Company**
Yucca Mountain NV	Yucca Mountain	321100084	Yucca Mountain	322100902	USG
Options Used	HRCQ		Commercial Line		
	Two Drivers		Include Nevada County Population Data		
	Prohibit Use of Road that restricts		No Blocked Nodes or Links		
	commercial truck, ferry crossings		No rail service: Diablo Canyon, Turkey Point		
	hazmat and radiological material		Nearest likely used node was selected		
	Include Nevada County Pop. Data				
	No Blocked Nodes or Links				

The shipment of highway route-controlled quantities (HRCQ) of radioactive materials are all based on DOT routing regulations in the Code of Federal Regulations, 49 CFR 397.101. The Diablo Canyon and Turkey Point sites do not currently have rail access. The nearest likely rail node was used for the routing calculations. The short distance of heavy-haul truck transport between the sites and the rail head are not addressed in this analysis.

2.2 Route Information

The TRAGIS calculated routes for truck shipments are shown in Figure 2.1. The calculated route information is listed in Table 2.2. The routes are separated into three population density regions: rural, suburban, and urban. These regions are determined based on a population density of: <54, 54 - 1300, >1300 people / sq. km, respectively. The population regions were determined based on an 800 m wide corridor on either side of the selected route.

The population data for TRAGIS is derived from the LandScan USA 15-arc second (approximately 360 m by 460 m) grid cell population database [Bhaduri, 2002]. This database represents nighttime population distributions developed from the 2000 U.S. Census Bureau block group population, roads from the Census TIGER data, slope from the NIMA Digital Terrain Elevation Data, and land cover from the USGS National Land Cover Database.

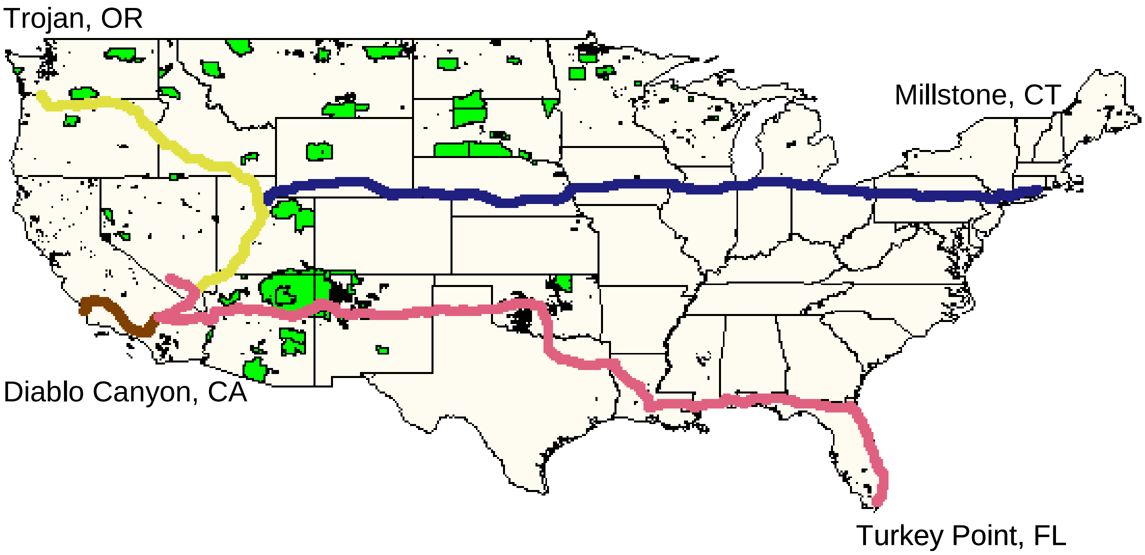

Figure 2.1: Truck routes calculated by TRAGIS

Table 2.2: Truck route data calculated with TRAGIS

		Diablo Canyon, CA	**Millstone, CT**	**Trojan, OR**	**Turkey Point, FL**
Total Distance	km	987.7	4497.8	2136.5	5004.2
Distance by Category					
Rural	km	727.5	3351.6	1690.6	3762.8
Suburban	km	176.9	986.9	362.5	1018.7
Urban	km	83.3	159.6	83.6	222.6
Weighted Population Density					
Rural	/sq km	7.5	11.5	8.6	10.0
Suburban	/sq km	405.3	332.9	361.4	367.1
Urban	/sq km	2822.7	2478.3	2442.0	2430.6
Trip Time	hr	13.4	48.3	23.3	53.3
Stop Time	hr	1.4	6.3	3.0	7.0
Total Pop (800m)	person	512307	1093914	467487	1400794

The calculated routes for rail shipments are shown in Figure 2.2. The calculated route information is listed in Table 2.3.

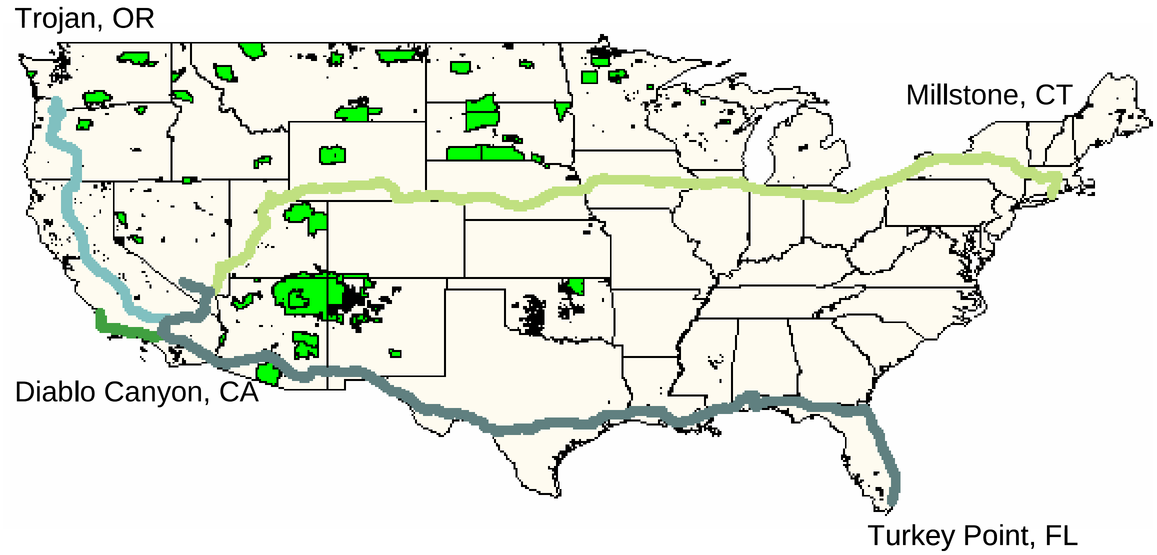

Figure 2.2: Rail routes calculated by TRAGIS

Table 2.3: Rail route data calculated by TRAGIS

		Diablo Canyon, CA	**Millstone, CT**	**Trojan, OR**	**Turkey Point, FL**
Total Distance	km	1057.6	4910.3	2294.7	5276
Distance by Category					
Rural	km	752.4	3748.7	1643.1	3815.6
Suburban	km	170.8	943.6	483.5	1148.7
Urban	km	134.6	218.4	168.4	311.9
Weighted Population Density					
Rural	/sq km	5.3	9.1	8.7	7.9
Suburban	/sq km	471.2	300.5	413.4	434.8
Urban	/sq km	3012.4	2448.4	2569.7	2424.6
Stop Time	hr	34.9	162.1	75.7	174.1
Total Pop (800m)	hr	874908	1328899	871603	1902963
Railroad Transfers	person	1	4	2	4

3 Spent Nuclear Fuel Transportation Risk

3.1 Introduction

For this study, the transportation risk analysis was performed using the RADTRAN 5 code developed at Sandia National Laboratory [Neuhauser, 2000]. RADTRAN was developed to estimate the risks associated with incident-free transportation of radiological materials and risks associated with accidents that might occur during transportation.

RADTRAN input values were taken from the Resource Handbook on DOE Transportation Risk Assessment [Chen, 2002], the RADTRAN/RADCAT User's Guide [Weiner, 2004], along with the route length and population density values generated with the TRAGIS program. The accident rate for each route was determined by a distance weighted average of the accident rate (accident/truck-km or accident/railcar-km) listed for each state using the Saricks and Tompkins 1999 data [Chen, 2002]. A similar method was used for the vehicle related fatality rate data. The truck and rail accident rate and vehicle related fatality rate for each route are listed in Table 3.1.

As expected, the accident rates are relatively consistent for both truck and rail which generates an increased risk of accident for an increased distance of travel. However, the fatality rate is nearly an order of magnitude larger for truck transport over the Diablo Canyon route, the shortest route. This is due to a significantly larger accident fatality rate for the state of California relative to other states. This results in an increased vehicle related fatality rate for the short distance Diablo Canyon route compared to the other three routes.

Table 3.1: Vehicle accident and fatality rate

		Diablo Canyon, CA	**Millstone, CT**	**Trojan, OR**	**Turkey Point, FL**
Truck					
Distance	km	988	4498	2137	5004
Accident Rate	acc/car-km	1.74E-07	3.58E-07	2.85E-07	2.20E-07
Accident Risk	per trip	1.72E-04	1.61E-03	6.10E-04	1.10E-03
Fatality Rate	veh-fat/car-km	9.82E-08	1.04E-08	8.18E-09	1.95E-08
Fatality Risk [a]	fatality/trip	1.94E-04	9.39E-05	3.49E-05	1.95E-04
Rail					
Distance	km	1058	4910	2295	5276
Accident Rate	acc/car-km	3.95E-08	1.34E-07	5.90E-08	4.93E-08
Accident Risk	per trip	4.18E-05	6.59E-04	1.35E-04	2.60E-04
Fatality Rate	veh-fat/car-km	2.76E-08	4.33E-08	2.78E-08	3.07E-08
Fatality Risk [a]	fatality/trip	5.84E-05	4.25E-04	1.28E-04	3.24E-04

a) Risk due to transport, regardless of cargo. Includes distance for return trip.

3.2 Transportation Risk

The truck transportation risk values estimated with the RADTRAN program are listed in Table 3.2.

Table 3.2: Estimated truck transportation risk values

	Diablo Canyon, CA		Millstone, CT		Trojan, OR		Turkey Point, FL	
	Dose Risk person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**
3 Year Cooled Spent Fuel								
Routine								
Crew	6.5E-02	2.6E-05	2.8E-01	1.1E-04	1.3E-01	5.1E-05	3.1E-01	1.2E-04
Off Link	5.4E-03		2.4E-02		9.5E-03		2.7E-02	
On Link	7.2E-02		2.0E-01		9.4E-02		2.5E-01	
Stop	1.1E-03		5.0E-03		2.4E-03		5.6E-03	
Total Public	7.8E-02	3.9E-05	2.3E-01	1.1E-04	1.1E-01	5.3E-05	2.8E-01	1.4E-04
Accident								
Rural	1.5E-08	7.7E-12	2.2E-07	1.1E-10	6.7E-08	3.3E-11	1.3E-07	6.7E-11
Suburban	2.0E-07	1.0E-10	1.9E-06	9.5E-10	6.0E-07	3.0E-10	1.3E-06	6.6E-10
Urban	4.2E-07	2.1E-10	1.5E-06	7.4E-10	6.0E-07	3.0E-10	1.2E-06	6.2E-10
Acc. Total	6.4E-07	3.2E-10	3.6E-06	1.8E-09	1.3E-06	6.4E-10	2.7E-06	1.3E-09
Acc. Ingest.	3.7E-08	1.9E-11	7.1E-07	3.5E-10	1.3E-07	6.3E-11	4.2E-07	2.1E-10
20 Year Cooled Spent Fuel								
Routine								
Crew	6.5E-02	2.6E-05	2.8E-01	1.1E-04	1.3E-01	5.1E-05	3.1E-01	1.2E-04
Off Link	5.4E-03		2.4E-02		9.5E-03		2.7E-02	
On Link	7.2E-02		2.0E-01		9.4E-02		2.5E-01	
Stop	1.1E-03		5.0E-03		2.4E-03		5.6E-03	
Total Public	7.8E-02	3.9E-05	2.3E-01	1.1E-04	1.1E-01	5.3E-05	2.8E-01	1.4E-04
Accident								
Rural	1.2E-08	6.1E-12	1.8E-07	8.9E-11	5.3E-08	2.7E-11	1.1E-07	5.3E-11
Suburban	1.6E-07	8.0E-11	1.5E-06	7.6E-10	4.8E-07	2.4E-10	1.1E-06	5.3E-10
Urban	3.4E-07	1.7E-10	1.2E-06	5.9E-10	4.8E-07	2.4E-10	9.9E-07	4.9E-10
Acc. Total	5.1E-07	2.6E-10	2.9E-06	1.4E-09	1.0E-06	5.1E-10	2.2E-06	1.1E-09
Acc. Ingest.	1.4E-08	7.2E-12	2.7E-07	1.4E-10	4.8E-08	2.4E-11	1.6E-07	8.1E-11
Vehicle Related Fatality Risk		1.9E-04		9.4E-05		3.5E-05		2.0E-04

The data presented are in the range of previous transportation risk studies. The estimated latent cancer fatality risk is similar to the vehicle related fatality risk (round trip). Again, the vehicle related fatality risk is slightly higher for the Diablo Canyon route because the truck fatality rate in California is several orders of magnitude higher than the other states where transportation occurs. Note the risk presented by routine transportation is the same for both the 3 year and 20 year cooled spent nuclear fuel. This is because the NRC dose rate limit of 10 mrem/h at 2 m from the lateral side of the transport vehicle (49 CFR 173 and 10 CFR 71) was used for the analysis. It is common to use the dose rate limit rather than adjust for the true lower dose rate created by 20 year cooled spent fuel, ensuring regulatory compliance and adding a level of conservatism.

The latent cancer fatality risk due to accident is significantly below that for routine transportation. This is due to the low probability of an accident occurring that can create a radiological release of material. The estimated accident ingestion risk values are presented here only for completeness. If an accident were to occur, the agricultural products and soil would be destroyed or cleaned before being reintroduced into the food chain. Thereby reducing the 'accident ingestion' risk value to near zero.

The rail transportation risk values estimated with the RADTRAN program are listed in Table 3.3.

Table 3.3: Estimated rail transportation risk values

	Diablo Canyon, CA		Millstone, CT		Trojan, OR		Turkey Point, FL	
	Dose Risk person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**
3 Year Cooled Spent Fuel								
Routine								
Crew	2.1E-02	8.6E-06	7.3E-02	2.9E-05	3.8E-02	1.5E-05	7.8E-02	3.1E-05
Off Link	6.3E-03		2.1E-02		1.5E-02		3.6E-02	
On Link	8.5E-04		2.6E-03		1.5E-03		3.2E-03	
Stop	1.5E-02		3.8E-02		2.9E-08		6.6E-02	
Total Public	2.3E-02	1.1E-05	6.2E-02	3.1E-05	1.6E-02	8.1E-06	1.1E-01	5.3E-05
Accident								
Rural	8.3E-08	4.2E-11	2.4E-06	1.2E-09	4.5E-07	2.2E-10	7.9E-07	3.9E-10
Suburban	1.7E-06	8.4E-10	2.0E-05	1.0E-08	6.2E-06	3.1E-09	1.3E-05	6.5E-09
Urban	5.5E-06	2.7E-09	2.4E-05	1.2E-08	8.7E-06	4.4E-09	1.3E-05	6.4E-09
Acc. Total	7.2E-06	3.6E-09	4.7E-05	2.3E-08	1.5E-05	7.7E-09	2.6E-05	1.3E-08
Acc. Ingest.	4.2E-07	2.1E-10	1.4E-05	7.2E-09	1.5E-06	7.5E-10	5.0E-06	2.5E-09
20 Year Cooled Spent Fuel								
Routine								
Crew	2.1E-02	8.6E-06	7.3E-02	2.9E-05	3.8E-02	1.5E-05	7.8E-02	3.1E-05
Off Link	6.3E-03		2.1E-02		1.5E-02		3.6E-02	
On Link	8.5E-04		2.6E-03		1.5E-03		3.2E-03	
Stop	1.5E-02		3.8E-02		2.9E-08		6.6E-02	
Total Public	2.3E-02	1.1E-05	6.2E-02	3.1E-05	1.6E-02	8.1E-06	1.1E-01	5.3E-05
Accident								
Rural	4.1E-08	2.1E-11	1.2E-06	6.0E-10	2.2E-07	1.1E-10	3.9E-07	1.9E-10
Suburban	8.3E-07	4.2E-10	9.9E-06	5.0E-09	3.1E-06	1.5E-09	6.4E-06	3.2E-09
Urban	2.7E-06	1.4E-09	1.2E-05	6.1E-09	4.3E-06	2.2E-09	6.3E-06	3.1E-09
Acc. Total	3.6E-06	1.8E-09	2.3E-05	1.2E-08	7.6E-06	3.8E-09	1.3E-05	6.6E-09
Acc. Ingest.	1.7E-07	8.4E-11	5.7E-06	2.8E-09	5.9E-07	2.9E-10	2.0E-06	1.0E-09
Vehicle Related Fatality Risk (3 rail cars)		1.8E-04		1.3E-03		3.8E-04		9.8E-04

The data for the rail transportation risk analysis are similar to the truck data. The estimated latent cancer fatality risk is below the vehicle related fatality risk (round trip). The rail and truck transport modes have similar vehicle related fatality rates, typically in the low 10^{-8} fatalities per vehicle-km. However, shipment by rail usually involves a further travel distance and a ‘cushion’ car is required by regulations, both in front and behind the SNF shipment car. This automatically raises the vehicle related fatality risk by a factor of three. Again, latent cancer fatality risk is higher for routine rail transport compared against rail accident latent cancer fatality risk. Notice that the risk of a cancer fatality is slightly higher for a rail accident than for a truck accident.

4 Sabotage Risk

4.1 Introduction

Study of a successful sabotage attack is somewhat different from incident-free or accident related transportation analysis. For a sabotage attack, there is no probability of occurrence. For this work, the sabotage related risk is based on the assumption that a successful sabotage attack has occurred. This shifts the unknown data from the chance of occurrence and amount of damage (as in an accident scenario) to only the amount of damage (or amount of radiological material released) due to the sabotage attack.

Review of both experimental tests and shipping cask analyses suggest that a substantial sabotage event is required to breach the shipping cask. The experimentally tested method of sabotage attack which could breach the shipping cask was a direct hit from a high energy density device [Luna, 1999]. This HEDD is similar to a large military anti-tank projectile or shape charge. It is expected that fatalities will result directly from a sabotage attack (not related to radiological material) in an urban area, however this work will not address this issue.

The risk addressed in this work focuses on the fatalities that may result from exposure to radiological material after a successful sabotage attack. This will occur if radiological material is released from confinement in the shipping cask. The amount of released radiological material used in this study is taken from experimental sabotage studies on actual shipping casks. The respirable release fractions from a truck and rail transportation cask for two different HEDD devices are listed in Table 4.1.

Table 4.1: Estimated release fraction for each physical-chemical group

Physical-Chemical Group	HEDD 1 Attack		HEDD 2 Attack	
	Truck	**Rail**	**Truck**	**Rail**
Co-60 (crud)	**7.5E-05**	**1.3E-06**	**9.1E-06**	**4.7E-08**
Radiocesium	**1.0E-03**	**1.7E-05**	**1.4E-04**	**7.2E-07**
Noble Gas	**2.0E-02**	**4.0E-04**	**6.2E-03**	**3.9E-05**
Matrix (particulates)	**1.2E-04**	**3.1E-06**	**1.8E-05**	**2.3E-07**

Values are suggested average, based on surrogate-to-true fuel material conversion factor of 3.

These release fractions were compared against previous source term experimental work in Germany [Luna, 2000] [Pretzsch, 1994]. The experimental results were found to be consistent. An uncertainty factor of approximately 2 for the release fractions listed in Table 4.1 has been suggested. The release fractions are based on a conversion factor of 3 when converting data from the experimental surrogate cask content material to spent nuclear fuel materials. This conversion factor is believed to be conservative but could range from 1 to 12 [Luna, 2001].

4.2 Sabotage Model Verification

The estimated dose and resulting cancer fatality for the models used in this work compared to previous studies, using similar input data, are listed in Tables 4.2 and 4.3 for truck and rail casks, respectively. This helps verify the sabotage scenarios in this work for both the RADTRAN and RISKIND models. Spent nuclear fuel transportation sabotage analysis results for a selected route can be compared to the spent nuclear fuel transportation incident-free and accident analysis results, as well as accident and sabotage scenarios for hazardous materials.

Table 4.2: Summary of truck sabotage analysis from various studies

Truck	**Population Exposure**				**Maximum Exposed Individual**	
	Total Dose person-rem	**Latent Cancer Fatalities**	**Acute Dose** Person-rem	**Acute Cancer Fatalities**	**Total Dose** rem (dist)	**Increased Cancer Risk**
YMEIS Max. Accident	1.1E+03	0.6	--	--	3 (150m)	--
YMEIS Sabotage Event	9.6E+04	48.0	--	--	110	6%
RWMA	3.1E+04	15.0	--	--	67 (150m)	7%
RADTRAN Code	9.2E+04	46.0	--	--	--	--
RISKIND Code	6.7E+04	33.3	6.2E+04	0	--	--
50% Stability [a]	5.7E+04	28.5	5.5E+04	0	--	--
95%Stability [a]	1.1E+05	54.2	1.1E+05	0	--	--
150 m	--	--	121	0	126 (150m)	13%
150 m Respirator	--	--	2.7	0	3.35 (150m)	0.17%
330 m	--	--	45.1	0	47 (330m)	4.70%

Shaded region represents new analysis for this paper.

a) Atmospheric stability. Stability is classified as ‘neutral’ throughout table, unless otherwise stated.

Table 4.3: Summary of rail sabotage analysis from various studies

Rail	**Population Exposure**				**Maximum Exposed Individual**	
	Total Dose person-rem	**Latent Cancer Fatalities**	**Acute Dose** Person-rem	**Acute Cancer Fatalities**	**Total Dose** rem (dist)	**Increased Cancer Risk**
YMEIS Max. Accident	9.9E+03	5.0	--	--	29 (330m)	--
YMEIS Sabotage Event	1.7E+04	9.0	--	--	40	2%
RWMA	4.9E+03	2.4	--	--	11 (140m)	0.60%
50% Stability [a]	5.3E+03	2.6	5.1E+03	--	11.1 (140m)	0.55%
95%Stability [a]	1.2E+04	5.8	1.1E+04	--	18.1 (140m)	0.90%
RADTRAN Code	1.9E+04	9.7	--	--	--	--
RISKIND Code	1.4E+04	6.9	1.3E+04	0	--	--
50% Stability [a]	1.2E+04	6.0	1.2E+04	0	--	--
95%Stability [a]	2.3E+04	11.3	2.2E+04	0	--	--
140 m	--	--	44.1	0	45.9 (140m)	4.60%
140 m Respirator	--	--	1.0	0	1.16 (140m)	0.06%
330 m	--	--	10.0	0	10.4 (330m)	0.52%

Shaded region represents new analysis for this paper.

a) Atmospheric stability. Stability is classified as ‘neutral’ throughout table, unless otherwise stated.

The ‘YMEIS Maximum Foreseeable Accident’ was used in the past to estimate the results of a sabotage event [DOE, 2002]. The maximum foreseeable accident is no longer used and is shown here for completeness only. The RWMA data, based on the Draft YMEIS, needs to have a factor of approximately 2 – 3 increase to correctly compare against the other studies [Halstead, 2000]. This is required to correct for a difference in the initial cask contents and the estimated population density.

The population total dose data show that for a truck or rail sabotage attack, the data agree well between the YMEIS Sabotage, RWMA (corrected by 3), and the RADTRAN and RISKIND data from this study. The truck and rail maximally exposed individual (MEI) data also agree well across the YMEIS Sabotage, RWMA (corrected by 2-3), and the RADTRAN and RISKIND data from this study. This demonstrates the models are established well enough to begin a further detailed analysis of a sabotage event.

The increased risk (above natural levels) of developing a latent cancer fatality is shown for MEI’s. Notice the increased cancer risk is not significantly high compared to common public belief. Of interest is the acute dose data (central column) comparison to the total MEI dose data. This shows the vast majority of radiation exposure occurs in the short time period during and immediately following the radiation cloud passage. Data is shown for a MEI following a successful truck sabotage at 150 m and a rail sabotage at 140 m, both with and without a respirator. The respirator was modeled by reducing the atmospheric air breathing rate down to 2.25% of normal. This clearly shows the dependence of the total dose on acute inhalation of radioactive particles.

4.3 Sabotage vs. Transportation Risk

Table 4.4 lists the incident-free, accident, and successful sabotage estimated dose risk and resulting cancer fatalities for the Diablo Canyon, CA route for both truck and rail transportation modes. Interestingly the risk due to sabotage on a truck cask is higher than sabotage on a rail cask. This is opposite of an accident event where the rail cask presents a higher risk than the truck cask. The detrimental health impact of a successful sabotage attack is quite dependent on the population density at or in the near downwind direction of the attack location.

Table 4.4: Transportation risk summary for the Diablo Canyon, CA route

	Truck		**Rail**		**Truck Sabotage**		**Rail Sabotage**	
	Dose Risk person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**Dose** person-rem	**LCF**	**Dose** person-rem	**LCF**
3 Year Cooled Spent Fuel								
Routine								
Crew	6.5E-02	2.6E-05	2.1E-02	8.6E-06				
Off Link	5.4E-03		6.3E-03					
On Link	7.2E-02		8.5E-04					
Stop	1.1E-03		1.5E-02					
Total Public	7.8E-02	3.9E-05	2.3E-02	1.1E-05				
Accident								
Rural	1.5E-08	7.7E-12	8.3E-08	4.2E-11	5.19E+02	2.6E-01	7.3E+01	3.6E-02
Suburban	2.0E-07	1.0E-10	1.7E-06	8.4E-10	2.8E+04	1.4E+01	6.5E+03	3.2E+00
Urban	4.2E-07	2.1E-10	5.5E-06	2.7E-09	1.2E+05	6.2E+01	2.7E+04	1.3E+01
Acc. Total	6.4E-07	3.2E-10	7.2E-06	3.6E-09				
20 Year Cooled Spent Fuel								
Routine								
Crew	6.5E-02	2.6E-05	2.1E-02	8.6E-06				
Off Link	5.4E-03		6.3E-03					
On Link	7.2E-02		8.5E-04					
Stop	1.1E-03		1.5E-02					
Total Public	7.8E-02	3.9E-05	2.3E-02	1.1E-05				
Accident								
Rural	1.2E-08	6.1E-12	4.1E-08	2.1E-11	3.8E+02	1.9E-01	5.3E+01	2.6E-02
Suburban	1.6E-07	8.0E-11	8.3E-07	4.2E-10	2.1E+04	1.0E+01	4.7E+03	2.3E+00
Urban	3.4E-07	1.7E-10	2.7E-06	1.4E-09	9.2E+04	4.6E+01	1.9E+04	9.7E+00
Acc. Total	5.1E-07	2.6E-10	3.6E-06	1.8E-09				
Vehicle Related Fatality Risk		1.9E-04		1.8E-04				

However, notice the largest public risk component for routine transportation is on-link (on-road travelers) for truck transport and rail stops (any public near stop area) for rail transport. This suggests shipping truck casks during low traffic flow times (possibly at night), rather than routing through low population zones, may help reduce routine public risk. Similarly for rail cask shipment, the use of dedicated trains, with few stops and a smaller crew, would reduce exposure risk better than routing through a low population area.

5 Sabotage Attack Parameter Investigation

5.1 Introduction

A sensitivity study was performed to discover the primary parameters that affect the risk presented following a successful sabotage attack. This will allow a parametric study to be performed on several of the sensitive parameters. The parametric study should allow a general bound for the risk presented by a sabotage attack. This can then be compared against a possible sabotage attack on hazardous materials or against a radiological dispersal device.

5.2 Sensitivity Study

Table 5.1 lists the results of a sensitivity study performed using the RISKIND code for a possible sabotage event on a truck cask containing three PWR, three year cooled, spent nuclear fuel assemblies. The RISKIND code was developed at Argonne National Laboratory (ANL) to analyze potential radiological health consequences [Yuan, 1995]. RISKIND was developed to address local aspects, scenario specific, and accident events. A 10% increase (10% decrease for ‘Fraction Respirable’) to the listed input values were made and the resulting change in radiological dose was recorded.

Table 5.1: Summary of truck sabotage sensitivity study to 10% change in input

Sensitivity Study for 10% change in input	**Base Case**	**Total Dose % Change**	**Acute Dose % Change**	**Variable Range**
Atmospheric Stability	D	**Significant**		A – F
Diffusion Parameters	---	**Significant**		Flat Terrain, Urban
Downwind Distance (km)	---	**Significant**		0.2 – 80
Fuel Age (yr)	3 yr cooled	Minimal		3 yr, 20 yr
Rainfall Rate (mm/hr)	0.0	Minimal		0.0 – 7.0
Respirable Fraction	1.0	**0.9**	**0.9**	0.0 – 1.0
Release Fraction (/cask content)	HEDD 1	**1.10**	**1.10**	HEDD 1
Particulates	1.20E-04	**1.07**	**1.10**	0 - 4.0E-5 - 4.8E-4
Cs, Ru	1.00E-03	1.01	1.00	0 - 3.3E-4 - 4.0E-3
Crud	7.50E-05	1.00	1.00	0 - 2.5E-5 - 3.0E-4
Noble Gas	2.00E-02	1.00	1.00	0 - 6.7E-3 - 8.0E-2
Population Density (/km^2)	2823	**1.10**	**1.10**	400 – 8000
Breathing Rate (m^3/yr)	8000	**1.07**	**1.10**	5000 – 20000
Wind Speed (m/s)	4	**0.94**	**0.94**	0.2 – 8
Particle Deposition Vel. (m/s)	0.01	1.01	**0.96**	0 – 0.1
Resuspension (1/m)	1.00E-05	1.02	1.00	---
Decay Time (yr)	0.137	1.02	1.00	---
Heated Release (cal/s)	5.00E+02	1.00	1.00	5E+02 – 2E+10
Atmosphere Mixing Height (m)	1000	1.00	1.00	400 – 2000
Ambient Temperature (°K)	283	1.00	1.00	255 – 310
Short Term Exposure (hr)	2	1.00	1.00	0.5 – 24
Total Exposure Time (yr)	50	1.01	1.00	1, 20, 50

The truck cask was selected because it presented a larger fatality risk over a rail cask sabotage. The input values used for the ‘base case’ are listed. The atmospheric stability, diffusion parameters, downwind distance, fuel age, and rainfall rate are listed at the top of Table 5.1 because they were believed to have a significant impact on the radiation exposure but were not evaluated with a single change sensitivity calculation. These parameters were each investigated with parametric studies.

The practical range considered for each input is listed on the far right of Table 5.1. Note the release fraction ranges are based on experimental data for the HEDD1 sabotage device described in Luna, 1999. Table 5.1 shows that only a handful of inputs significantly affect the results of a sabotage attack.

5.3 Study of Key Parameters

5.3.1 Atmospheric Stability

Atmospheric stability describes the state of atmospheric conditions which control the dispersion of a radioactive plume. Pasquill stability classes range from A – F for highly unstable to highly stable conditions, respectively [Faw, 1999]. Figure 5.1 shows the impact of changes in atmospheric stability, using a Gaussian model Pasquill-Gifford diffusion parameters for flat terrain [Eimutis, 1972], for individuals located at select distances directly downwind of a sabotage attack.

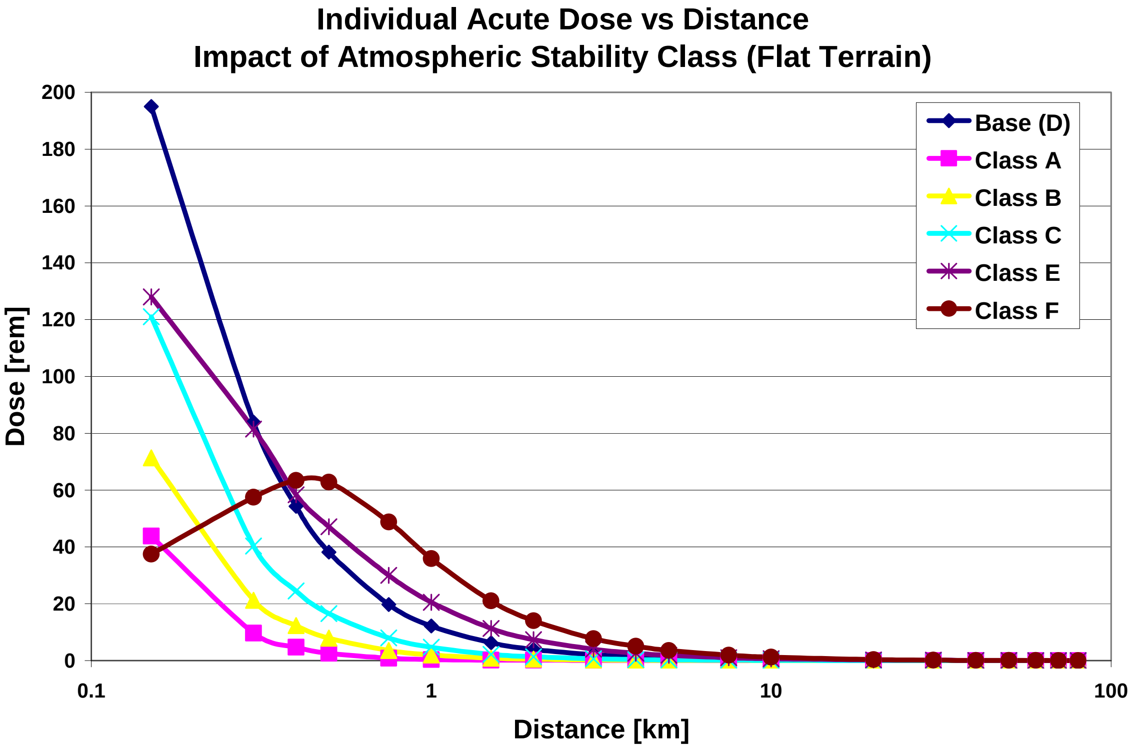

Figure 5.1: Impact of atmospheric stability on a sabotage attack (flat terrain)

A Class D (neutral) atmospheric stability condition was used for the base case. Class D is commonly used for atmospheric transport studies unless more specific local data is available. Class D clearly presents the greatest risk to an individual near the sabotage site. For less stable air (Class A- C) the dose is significantly reduced. Under these conditions, the plume can readily disperse and settle the radioactive particles out of the plume. For more stable air (Class E – F) the radiation dose near the sabotage site is reduced. However, the plume remains well formed much longer which allows a large portion of the radioactive cloud to be carried down range by the prevailing wind. This raises the possible radiation dose out near 1 km.

Figure 5.2 shows the impact of changes in atmospheric stability, using a Gaussian model Briggs diffusion parameters for urban terrain [Briggs, 1974], for individuals located at select distances directly downwind of a sabotage attack. It can be seen that the urban diffusion parameters have approximately a factor of 2 reduction on the radiological dose resulting from a successful sabotage attack.

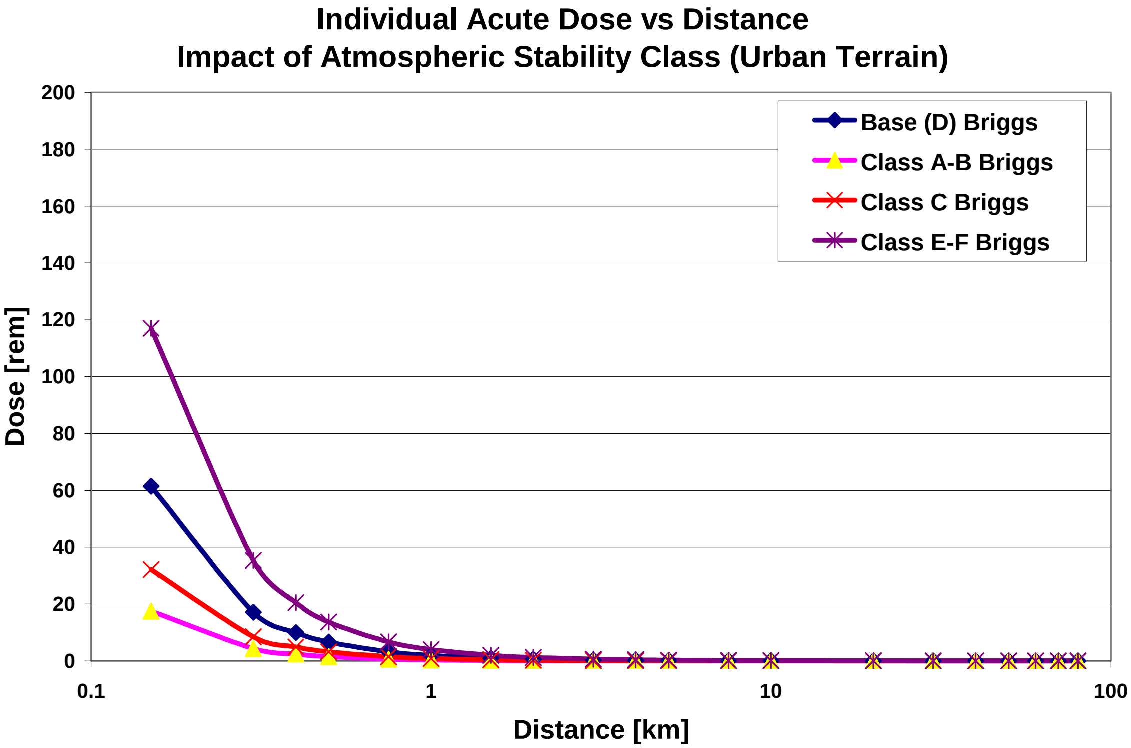

Figure 5.2: Impact of atmospheric stability on a sabotage attack (urban terrain)

5.3.2 Rainfall Rate

It is common for many atmospheric transport studies to neglect the effect of rainfall. This often presents a conservative case when looking at the airborne radiation exposure. When looking at routes, such as Trojan, OR or Turkey Point, FL to Yucca Mountain, NV, rainfall should be expected for segments of the route during portions of the year. Figure 5.3 show the effect of rainfall rates on radiation dose for individuals located at select distances directly downwind of a sabotage attack.

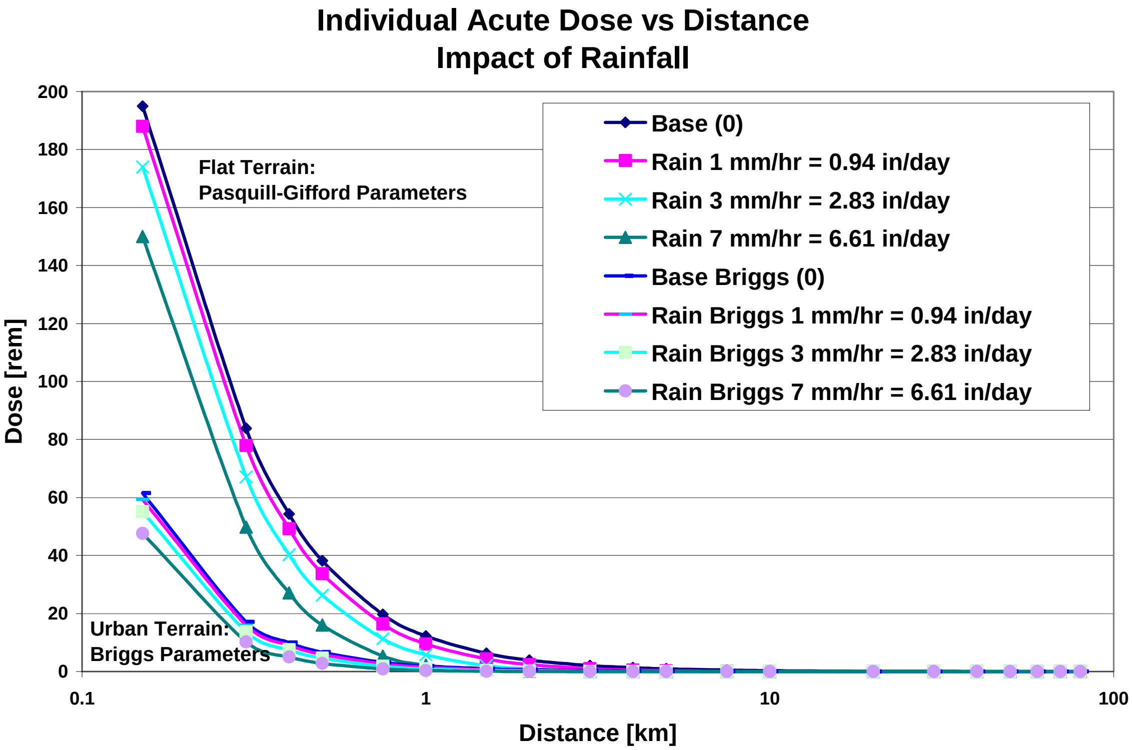

Figure 5.3: Impact of rainfall rate on a sabotage attack

The rainfall rate directly reduces the radiation dose at a given location. The effect of rainfall is not dramatic when the effects are compared against changes in the atmospheric stability class. It is easy to see why neglecting rainfall is a common occurrence for most transportation risk analysis for routine, accident, and sabotage events.

5.3.3 Wind Speed

Wind speed is modeled in this analysis as a constant value although it is a highly variable parameter. Wind speed can have a wide range of inputs from near zero to extremely large values during storms (~27 m/s or ~60 mph). This study considered only the most frequent wind speeds encountered. It is necessary to keep the wind speed up near 1 m/s for proper model application. This study considered wind speeds up to 7 m/s (~15.6 mph) although higher wind speeds commonly occur. Figures 5.4 and 5.5 show the effect of wind speed on radiation dose for individuals located at select distances directly downwind of a sabotage attack over flat and urban terrain, respectively.

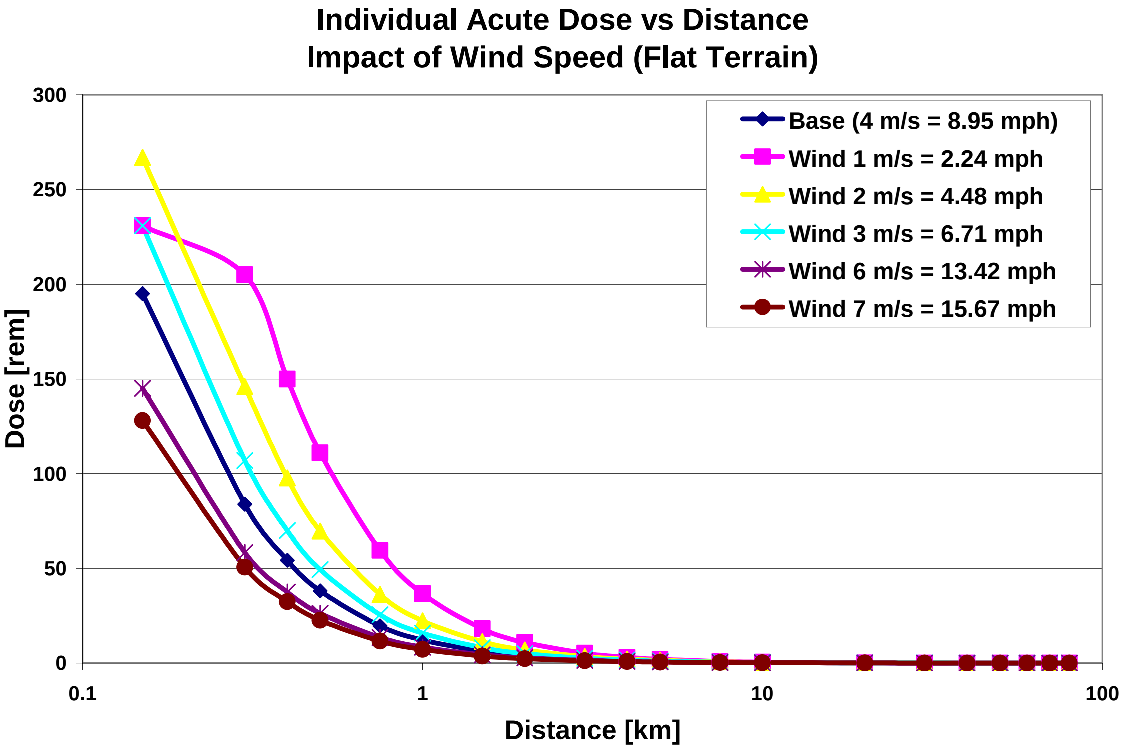

Figure 5.4: Impact of wind speed on a sabotage attack (flat terrain)

As the wind speed increases the radiation dose to individuals near the sabotage attack becomes less. This is due to the reduced time the individual is engulfed in the passing radioactive cloud. The data point for the radiation dose at 0.150 km downwind over flat terrain for the 1 m/s wind speed is somewhat curious. It is believed that such low wind speeds over flat terrain the diffusion process is allowed sufficient time to reduce the airborne concentration at the downwind distance.

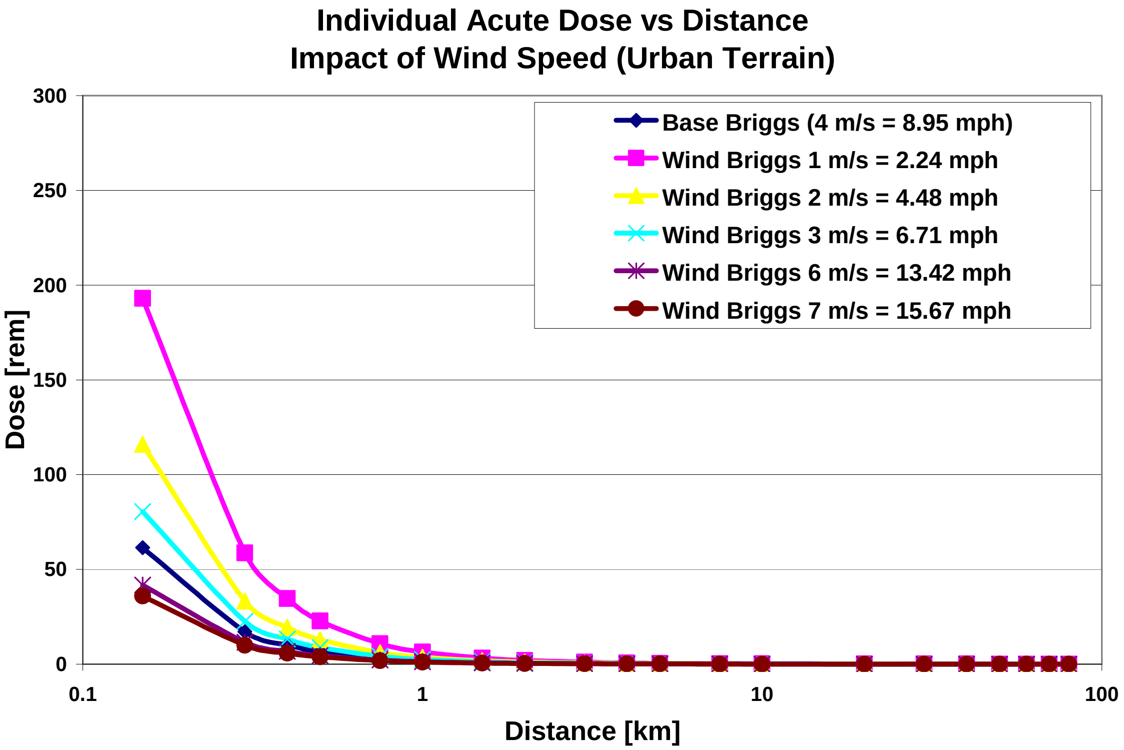

Figure 5.5: Impact of wind speed on a sabotage attack (urban terrain)

5.3.4 Release Fraction

The release fraction, by definition, creates the radiological source term that is available for atmospheric transport downwind out of the initial material contained in a shipping cask. For this reason, the release fraction data is often of interest when considering accident or sabotage events during spent nuclear fuel transportation. The respirable release fraction is the parameter of interest. Respirable refers to particulate material sufficiently small that it can be inhaled into human lungs (approximately < 5μm). The importance of inhaled radioactive material was demonstrated in Table 4.2.

The variation in the respirable release fraction created by a sabotage attack was addressed by developing a bounding region due to the uncertainty in the surrogate to spent fuel conversion factor used in the experimental tests. This bounded region was defined by replacing the suggested conversion factor of 3 (used for the base case release fractions of Table 4.1) with the experimental minimum and maximum values of 1 and 12, respectively. Table 5.2 lists these bounded minimum and maximum release fractions created from a HEDD1 sabotage attack for each material type along with other data of interest. This bounded release fraction creates a bounded MEI dose region, approximately a factor of 4 above and a factor of 3 below the average value. Notice this bounded release fraction region is valid for all atmospheric stability classes and downwind distances.

Table 5.2: Bounded region of release fraction and resulting consequences

Physical-Chemical Group	**Minimum**	**Average**	**Maximum**
Co-60 (crud)	4.33E-07	1.3E-06	5.20E-06
Radiocesium	5.66E-06	1.7E-05	6.80E-05
Noble Gas	1.37E-04	4.0E-04	1.64E-03
Matrix (particulates)	1.03E-06	3.1E-06	1.24E-05
Consequences			
MEI @ 118 m [rem]	4.2	12.4	49.2
Increased Cancer Risk	0.21%	0.62%	2.46%
Population Dose [a] [person-rem]	2620	7300	26500
Latent Cancer Fatalities	1.31	3.65	13.25

a) Based on the urban population density listed in Table 2.3

Figure 5.5 shows the range of estimated dose for individuals located at select distances downwind of a sabotage attack. The effect of the factor of 4 above and factor of 3 below the average release fraction is clearly seen. Note that for the maximum release fraction for the HEDD1 device has created a dose that can create a fatality due to acute radiation exposure. This has not happened anywhere in the study up to this point. The HEDD1 device is considered the upper limit to how effective a sabotage attack device could be. The HEDD2 device is considered to create release fractions that are more practical under a real sabotage attack. As Figure 5.5 shows, this significantly reduces the effectiveness of a sabotage attack to create fatalities.

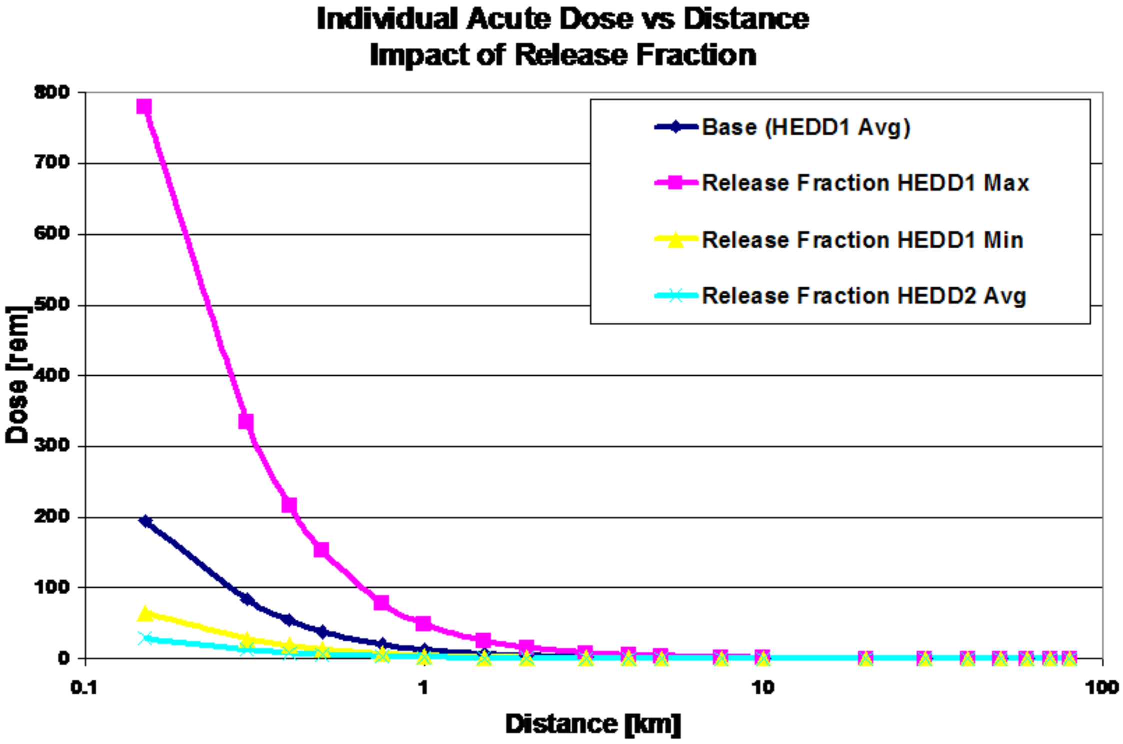

Figure 5.6: Impact of release fraction on a sabotage attack

5.3.5 Additional Parameters

The sensitivity study found that the breathing rate and population density were also parameters of interest for a sabotage attack. The deposition velocity of radioactive particulates was also found to have a slightly less important affect. The population density is quite easily understood. The population density would not affect the estimated radiation dose for an individual at a given location and would simply linearly increase the number of exposed people and thus the estimated number of possible latent cancer fatalities. The breathing rate also has a straight forward linear affect on the amount of inhaled dose a person receives.

The deposition velocity of particulate material affects the rate at which radioactive particles settle out of the air and deposit onto the ground [Hinds, 1999]. The particle size has an impact on the dose conversion factor (DCF). The dose conversion factor, which is not shown in the sensitivity study, is used to estimate the amount of radiation dose an individual receives from a given level of radiation exposure. The particle size controls how easily a radioactive particle is inhaled or attached to the lung surface. The RISKIND code is not able to accurately model wide ranges in the particle size (or deposition velocity) or DCF. The RISKIND code assigns inhalation DCF's independent of the particle size and breathing rate.

5.3.6 Dose Conversion Factor

The release fractions resulting from a sabotage attack are commonly debated in literature. However, parameters such as the DCF and the breathing rate are rarely included in a variability discussion. A comparison of the DCF and breathing rate variability against the variability of the release fraction for the HEDD1 sabotage device will be used to illustrate the relative importance of each parameter.

With the bounded region of the respirable release fraction determined earlier, a triangular distribution was defined for the release fractions of each material type, listed in Table 5.2. This triangular release fraction distribution applied to the point estimate model calculations will result in a triangular dose and cancer risk distribution with minimum, mode, and maximum values of approximately the values in Table 5.2.

A variability distribution was defined for the human inhalation rate and the dose conversion factor. The inhalation rate uncertainty distribution was taken from the RESRAD 6.21 radioactivity decontamination code. The DCF uncertainty distribution was taken from the National Council on Radiation Protection and Measurement Report No. 126 [NCRP 1997]. Table 5.3 lists the distribution for the inhalation rate and DCF, including the initial value used for the sensitivity study [Yuan, 1995]. These variability distributions were analyzed using the @RISK statistical software.

Table 5.3: Inhalation rate and DCF variability distribution

Human Inhalation Rate [m^3/yr]

Uncertainty Distribution Type	Minimum	Mode	Maximum	Initial Value
Triangular	4.38E+03	8.39E+03	1.31E+05	8.00E+03

Dose-Effect Conversion Factor (DCF) [cancer risk/rem]

Uncertainty Distribution Type	Geometric Mean	Geometric Standard Deviation	Mode	Initial Value
Lognormal	3.38E-04	1.83	2.36E-04	5.00E-04

Several combinations of distributions were made to illustrate the relative importance of the three defined distribution uncertainties. For case I, the respirable release fraction was set to the average release fractions listed in Table 5.2 with no uncertainty distribution while the inhalation rate and DCF were assigned the distributions in Table 5.3. This provides a probability distribution for the increased fatal cancer risk based on the inhalation rate and DCF distributions. For case II, release fractions, inhalation rate, and DCF were assigned the uncertainty distributions listed in Table 5.2 and Table 5.3, respectively. This provides a probability distribution for the increased fatal cancer risk based on all three distributions. A summary of statistics for each case are listed in Table 5.4.

Table 5.4: Statistics for the increased fatal cancer risk

	Case I: Point Estimate Release Fraction	**Case II: Triangular Distribution Release Fraction**
Statistic	**Fatal Cancer Risk [rem^{-1}]**	**Fatal Cancer Risk [rem^{-1}]**
Minimum	3.11E-04	1.70E-04
Maximum	7.66E-02	5.29E-02
Mean	7.10E-03	5.73E-03
Standard Deviation	5.73E-03	4.49E-03
Variance	3.28E-05	2.02E-05
Skewness	2.03	2.42
Kurtosis	11.8	13.7
Mode	1.18E-03	2.68E-03
5% Percentile	1.15E-03	1.32E-03
95% Percentile	1.79E-02	1.43E-02

Each case was performed using Latin Hypercube sampling with 5,000 iterations. The probability distribution for the excess cancer risk is shown for both cases in Figure 5.5. A quick glance yields the numerous similarities between Cases I and II.

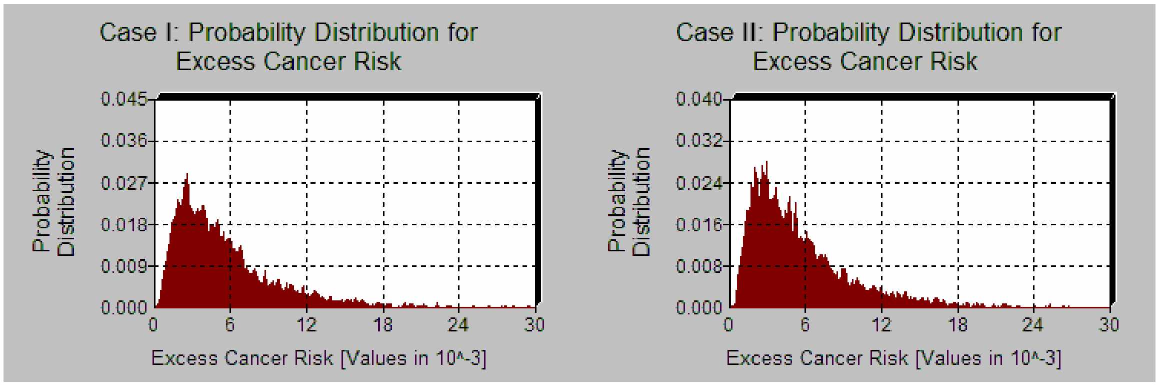

Figure 5.7: Excess cancer risk for point estimate (Case I) and triangular distribution (Case II) of the release fraction

The data analysis shows that the variability of the dose conversion factor is of the same importance as the variability of the respirable release fraction created in the sabotage attack. The inhalation rate does have some effect on the increased cancer risk but to a much less extent than the dose-effect conversion factor. This demonstrates that the often over dramatized potential for release from a sabotage attack may not be the single or dominant variable which should receive detailed consideration.

5.4 Sabotage Conclusion

Notice this study accepted that the sabotage event has occurred. This study, like any other study of a sabotage event, must be considered with care. This study is based entirely on the release fractions determined from earlier analytical and experimental work which were for specific HEDD or other sabotage devices. If different sabotage events occur on different radioactive targets, then there may be changes in the estimated release fractions which directly change the effects on the maximally exposed individual, population dose, and thus latent cancer fatalities. The fact that this and other analyses are based on numerous inputs that could have a significant effect on the cancer risk make careful understanding and application of these inputs essential.

A few examples of important parameter variability which were not mentioned in this sensitivity study include: package contents, exposure time, or different cask designs and sizes. There have been studies on this topic. A detailed literature search is recommended before any serious detailed analyses are performed or the analysis results applied in practice.

6 Practical Perspectives

6.1 Hazardous Material Transportation Comparison

Transportation of other hazardous materials, such as chemicals and gases, present an immediate risk to the general public due to the close proximity of passenger vehicles, residential and commercial areas, and large number of hazardous material shipments [Volpe, 1996]. For example, consider the tens of thousands of gasoline tanker truck deliveries each day in the United States.

Table 6.1 compares the results of an accident or sabotage event for chlorine gas, liquefied petroleum gas (LPG), and spent nuclear fuel for the urban population density (2823 people/km^2) estimated for the Diablo Canyon, CA truck route. Chlorine and LPG are commonly used to represent other dangerous commodities with similar properties [Saccomanno, 1989]. Chlorine is used as a surrogate for other highly toxic, heavier than air gases. Most bulk, ~90 ton, chlorine shipments take place on rail. Chlorine shipments by truck are usually ~27 ton. LPG serves as a surrogate for other highly flammable, potentially explosive pressure liquefied gases. LPG is commonly shipped in tankers with a capacity of ~63.5 ton for rail and ~18 ton for truck. As before, the spent nuclear fuel is three years cooled and contains 3 PWR and 24 PWR assemblies for the truck and rail casks, respectively.

Table 6.1: Summary of SNF, Chlorine, and LPG accident and sabotage transportation risk

	Truck Accident		Rail Accident		Truck Sabotage	Rail Sabotage
	Dose Risk person-rem	**LCF Risk**	**Dose Risk** person-rem	**LCF Risk**	**LCF**	**LCF**
3 Year Cooled Spent Fuel						
Urban	4.24E-07	2.12E-10	5.46E-06	2.73E-09	62.0	13.3
	Hazard Area (km^2)	**Fatality Risk**	**Hazard Area (km^2)**	**Fatality Risk**	**Fatalities**	**Fatalities**
Chlorine Gas						
Instantaneous						
LOW	0.804	1.14E-03	1.107	7.46E-04		
HIGH	1.072	8.66E-04	1.282	4.95E-04	246	296
Continuous						
LOW	0.001	4.74E-07	0.001	3.90E-07		
HIGH	0.650	4.50E-04	0.650	2.44E-04		
Liquefied Petroleum Gas (LPG)						
Instantaneous						
LOW	0.050	4.12E-05	0.160	1.07E-04		
HIGH	0.070	3.29E-05	0.230	8.75E-05	5.9	19.8
Continuous						
LOW	NA	NA	NA	NA		
HIGH	NA	NA	NA	NA		
Vehicle Related Fatality Risk		1.64E-05		7.43E-06		

The hazard area, for chlorine and liquefied petroleum gas, represents the distance from the accident site to a specified class of damage. For this comparison, the 50% fatality hazard area (fatality occurs in 50% of exposed population) was used. This is approximately a concentration value of 800 ppm for chlorine, fatal in a few breaths [Saccomanno, 1990].

For chlorine and LPG, ‘Instantaneous’ refers to an immediate release while a ‘Continuous’ release would occur over a few hours. The ‘Low’ and ‘High’ represent a difference in the release fraction of cargo based on the severity of accident. The continuous release scenario for LPG was found to have a negligible effect on the total risk [Saccomanno, 1990].

Notice the population fatality risk is orders of magnitude lower for spent nuclear fuel compared to both chlorine and LPG. In fact, the fatality risk, due to accident for chlorine and LPG, is often above the estimated vehicle fatality risk determined by the distance traveled for both truck and rail.

No sabotage data was available for the chlorine and LPG shipments. The chlorine and LPG tankers are not highly reinforced or designed to withstand a sabotage attack. For comparison, an instantaneous release of 100% of the tanker contents is assumed for these sabotage events. This results in a factor of 5 and 20 increase in the estimated number of fatalities due to chlorine gas relative to spent nuclear fuel for a truck and rail sabotage attack, respectively. The estimated number of fatalities for an LPG sabotage attack are more in the range of spent nuclear fuel.

6.2 Electrical Power Production Comparison

The primary use of spent nuclear fuel is for the generation of electricity. Of interest is the comparison of transportation risks of spent nuclear fuel to the transportation risks of other power generation sources. A simple calculation using a typical 35,000 MWD/MTHM burnup rate of spent nuclear fuel and 0.461 MTHM/PWR assembly yields a 48,405 and 387,240 MWD/Cask Shipment for the truck and rail cask, respectively.

Coal consumption for a 1,000 MWe power plant is approximately 7,300,000 kg/day. If a coal train-car contains 91 MT, then 3,883 and 31,064 train-cars of coal would need to be transported to produce the equivalent electricity of a truck and rail spent fuel shipment, respectively.

Table 6.2 compares the fatality risk between spent nuclear fuel and coal, due to transportation, for the Diablo Canyon route for an equivalent amount of electricity production. It is easy to see that the fatality risk of coal transport (due entirely to the motion of rail cars) is orders of magnitude above the fatality risk of spent fuel transport (due to vehicle motion, incident free radiological dose, and accidental radiological dose). There was no calculated radiological fatality due to a sabotage attack on a coal transport, while the spent fuel sabotage scenario radiological fatalities, seen in Table 6.1, were estimated at 62 and 13 for truck and rail, respectively.

Table 6.2: Summary of spent fuel and coal transportation risk for Diablo Canyon, CA route

Comparison of SNF and coal for equivalent electricity produced by contents of a truck or rail SNF cask	**Truck Cask** [a]	**Rail Cask** [b]
3 Year Cooled Spent Fuel		
Electricity Produced (MWD) [c]	48,405	387,240
Number of Transports	1 truck	1 railcar
Vehicle Related Fatality Risk [d]	1.94E-04	1.75E-04 [e]
Incident Free Radiological LCF Risk	6.50E-05	1.98E-05
Accident Radiological LCF Risk	3.20E-10	3.61E-09
Total Fatality Risk	**2.59E-04**	**1.95E-04**
Coal (transport by rail)		
Electricity Produced (MWD) [c]	48,405	387,240
Number of Transports (railcars)	3,883	31,064
Vehicle Related Fatality Risk [d]	2.27E-01	1.81E+00
Incident Free Radiological LCF Risk	0.00E-00	0.00E-00
Accident Radiological LCF Risk	0.00E-00	0.00E-00
Total Fatality Risk	**2.27E-01**	**1.81E+00**

a) 3 PWR assemblies
b) 24 PWR assemblies
c) Megawatt days electric
d) Includes return trip
e) Includes 1 cushion railcar on each side of cask railcar

To verify the validity of this analysis, a literature review was performed to collect transportation fatality risk data involved with electricity production. Table 6.3 lists the collective fatality risk from literature for four electrical power production methods. All data has been referenced to a 1,000 MWe-Yr.

Table 6.3: Transportation fatality risk summary for four electrical power producing fuels

	Fatality Risk for Transportation (1000 MWe-Yr)				
	Inhaber 1982	**Gotchy 1987**	**Comar and Sagan 1976**	**Hamilton 1974**	**Angell 2005**
Coal	2.4 – 6.9	2.2	0.61 – 1.7	1 – 3	1.81
Oil	0.04 – 0.14	---	0.03 – 0.1	0.1	---
Natural Gas	0.03 – 0.05	---	0.02 – 0.024	0.02	---
Nuclear	0.0028 – 0.012	0.01	0.002	---	0.0002

The analysis from this study agree well with the estimated fatality risk due to transportation for coal provided by the other studies. However, the risk for spent nuclear fuel transport is orders of magnitude below data from other studies. The primary cause for this is due to the difference in the expected population dose risk during an accident. The previous studies rely on the ‘Final Environmental Statement on the Transport of Radioactive Materials by Air and Other Modes’ [NRC, 1977]. While this paper uses the ‘Re-Examination of Spent Fuel Shipment Risk Estimates’ [Sprung, 2000]. The estimated accidental population dose risk based on the 2000 study is 1 - 3 and 1 - 4 orders of magnitude below that for the 1977 study for truck and rail, respectively. This will result in the accidental release fatality risk estimated in this paper to be several orders of magnitude below that listed for the previous studies.

6.3 Radiological Dispersal Device Comparison

A radiological dispersal device (RDD) is designed to project or release radioactive material in an area in an attempt to harm people and disrupt society. The relative lack of knowledge the public currently has about radiological materials makes an

RDD an ideal choice for terrorist activities. The release of radiological material from a spent nuclear fuel shipment, either through an accident or sabotage, is one method of creating an RDD event. The wide range of possible material choices, package designs, release methods, and target locations make the experimental study and computer modeling of an RDD event difficult and imprecise, at best.

Sandia National Laboratory performed a study which identified key materials of concern for use as possible RDD source materials [DOE/NRC, 2003]. Americium-241 (Am-241), californium-252 (Cf-252), cesium-137 (Cs-137), cobalt-60 (Co-60), iridium-192 (Ir-192), plutionium-238 (Pu-238), and strontium-90 (Sr-90) were listed as possible key RDD source materials, primarily because these materials can deliver a high radiological dose and/or the material can be obtained in sufficient quantity to present a health threat [Ferguson et al., 2003]. Figure 6.1, taken from Van Tuyle et al, 2003, shows the various sources and activity ranges for key nuclides of concern in an RDD attack.

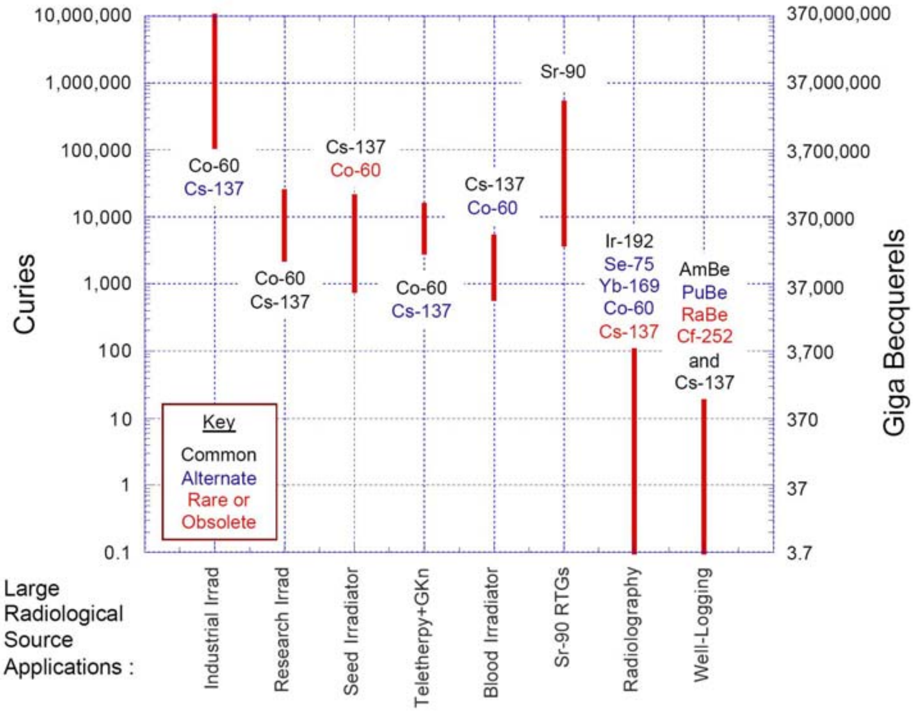

Figure 6.1: Source activity of possible RDD materials (from Van Tuyle et al, 2003)

Table 6.4 compares spent nuclear fuel to other potential sources for an RDD. Notice the available activity contained in a shipping cask is similar to some of the larger industrial sources. However, the shipping cask reduces the actual release amount during a sabotage attack by 3 – 5 orders of magnitude. Table 6.4 also compares the amount of initial activity before and the calculated number of fatal cancers following an event. Of interest is that the activity level considered for the RDD and SNF sources is very high. Death would likely occur in less than an hour of unshielded exposure.

Table 6.4: Summary of RDD source materials and consequence effects

Nuclide	**SNF Sabotage Release Amounts** (Curie)	**Other RDD Source Amount** [a] (Curie)
Sr-90	1.93E+01	1E+03 – 6E+05
Ru-106	1.33E+02	---
Cs-134	2.10E+02	---
Cs-137	2.37E+02	1E+03 – 1E+04
Pu-238	1.73E+00	1E+00 – 1E+02
Pu-239	7.70E-02	---
Pu-240	1.54E-01	---
Pu-241	2.35E+01	---
Am-241	1.57E-01	1E-01 – 2E+01
Cm-244	2.03E+00	---
Single Material RDD [b]	**Initial Activity** [d] (Curie)	**Fatal Cancers**
Cs-137	1.75E+03	0
Ir-192 [c]	2.70E+03	105
SNF Sabotage [e]	**Initial Activity** (Curie)	**Fatal Cancers**
Truck	9.71E+05	62
Rail	7.76E+06	13

a) Van Tuyle et al, 2003: Available activity, unsure about release amount
b) Ring, 2004: Designed to maximize radiological consequences
c) Ir-192 source is 10 times largest available industrial source
d) Unshielded exposure rate: approx. 900 rem/hr at 1m
e) 3 year cooled, assumes successful attack in urban region for Diablo Canyon, CA route

7 Conclusion

The estimated latent cancer fatality risk for routine transportation operations is similar to, or below, the vehicle related fatality risk (round trip). The latent cancer fatality risk due to an accident is significantly below that for routine transportation. This is due to the low probability of an accident occurring that can create a radiological release of material. This clearly places the transportation risk of spent nuclear fuel below other transportation risks commonly accepted by the general public.

Investigation into a possible sabotage attack requires careful selection and understanding of input parameters, modeling equations, and assumptions. Several noteworthy issues were discovered while applying the Riskind computer code to a possible spent nuclear fuel sabotage attack scenario.

- The dose conversion factor applied in Riskind is a fixed value. The dose conversion factor and inhalation factor for airborne nuclides does not account for changes in particle size.

- Care is needed to ensure correct diffusions parameters and dispersion schemes. Riskind suggests the Pasquill-Gifford diffusion parameters for a near surface release. However the urban Briggs diffusion parameters are more applicable to an urban sabotage event.

- Release fractions built into Riskind for accident scenarios are based on old research and should be updated. Riskind's built in release fractions are not appropriate when addressing a sabotage event scenario.

- Some modeling equations, such as effects of rainfall and select diffusion parameters, used in Riskind are not commonly found in literature. Care needs to be used when attempting to verify Riskind results with personal analysis.

- Riskind is a point estimate model. However, most processes and variables being modeled have significant variability and uncertainty. Care should be used when interpreting and drawing conclusions from Riskind analysis results.

Notice the population fatality risk is orders of magnitude lower for spent nuclear fuel compared to both chlorine and LPG, as shown in Table 6.1. In fact, the fatality risk, due to accident for chlorine and LPG, is often above the estimated vehicle fatality risk determined by the distance traveled for both truck and rail. Sabotage analysis data results in a factor of 5 and 20 increase in the estimated number of fatalities due to chlorine gas relative to spent nuclear fuel for a truck and rail sabotage attack, respectively. The estimated number of fatalities for an LPG sabotage attack are more in the range of spent nuclear fuel.

From Table 6.2, it is easy to see that the fatality risk of coal transport (due entirely to the motion of rail cars) is orders of magnitude above the fatality risk of spent fuel transport (due to vehicle motion, incident free radiological dose, and accidental radiological dose). There was no calculated fatality risk due to a sabotage attack on a coal transport, while the spent fuel sabotage scenario fatality risk was estimated at 62 and 13 fatalities for truck and rail, respectively. Nuclear power electrical production transportation risks are below that of other electrical power producing materials, as seen from literature summarized in Table 6.3

The available activity contained in a shipping cask is similar to some of the larger industrial sources that may be attempted to be obtained and used in a radiological dispersal device. However, the shipping cask reduces the actual release amount during a sabotage attack by 3 – 5 orders of magnitude. This demonstrates the effectiveness of the shipping cask for both sabotage attempts and radiation exposure safety for the general public.

The results of this work show that the transportation risk presented by shipment of spent nuclear fuel is comparable to or less than other hazardous materials. The results of this work also demonstrated that the transportation risk is less for spent nuclear fuel than for other electrical power producing materials. This work, along with other studies, indicate that methods are available that can perform technically defensible analysis for the safe transportation and handling of spent nuclear fuel.

NOTE: This study, like any other study of a sabotage event, must be considered with care. Notice this study accepted that the sabotage event has occurred. A detailed literature search and analysis were performed for a sabotage event. However, this analysis is for a hypothetical or postulated event and great caution and careful understanding is recommended before attempting to apply these results in practice.

8 Discussion of Recent Literature

There have been several recent federal government and scientific research reports written which address the risks involved with the shipment of spent nuclear fuel. The United States General Accounting Office (GAO) issued a report in July 2003 suggesting possible security and safety enhancements for spent nuclear fuel shipments [GAO, 2003]. The GAO report states that the likelihood of widespread harm from a terrorist attack or a severe accident involving spent nuclear fuel is low, causing little or no release of spent nuclear fuel.

Notice that the vehicle related fatality risk is the dominant risk associated with the shipment of spent nuclear fuel, as seen in Table 4.3. The GAO report recognizes reducing the number of shipments is a key method of reducing public risk from spent nuclear fuel shipments.

The GAO report suggests shipping older spent fuel first to help reduce radiological risk, neglecting contracting and policy issues. Table 4.3 shows the routine, accident, and sabotage risk resulting from 3 and 20 year cooled fuel. There is a small reduction in the possible accident or sabotage radiological risk by shipping older fuel first. However, there is no reduction in the routine risk due to the use of regulatory limits for this analysis. Shipping the older fuel first may require more shipments (contradictory to the above recommendation) and increase cost by requiring more frequent fuel handling and moving fuel from a cooling pool to dry storage more frequently.

The GAO report mentions ongoing efforts at Sandia National Laboratory to examine more severe terrorist attacks than the method considered during this analysis.

These more severe attack methods could have different release fractions and estimated radiological consequences than the values in Tables 4.1 and 4.2 of this analysis. The GAO report suggests the used of dedicated trains. This analysis uses accident probability and vehicle related fatality risks for general commercial trains. Appropriate data for the accident rate, fatality risk, and travel and stop times for dedicated trains should be considered when comparing to data from this analysis.

There is a current international effort to better understand the release fraction and particle size distribution resulting from a sabotage scenario directed at a spent fuel transportation or storage cask [Molecke, 2004]. The international Working Group for Sabotage Concerns of Transport and Storage Casks (WGSTSC) performs research to better protect people and the environment from potential radiological hazards resulting from sabotage of nuclear material storage and shipment casks.

This research is currently in the planning and experimental phase. Once the detailed data is available from these experiments, the data and results discussed in sections 5.3.4 and 5.3.6 of this analysis should be updated. This particle size data should allow for improved dose conversion factors. This needs to be considered manually outside of the Riskind code, due to the Riskind code’s lack of dose conversion input selection and coupling with particle size.

9 Future Works

The technical community has been working on modeling spent nuclear fuel transportation for decades. This is clear in how most literature and discussions focus on finding correct input data for models rather than improving modeling techniques. Several areas for improvement in the technical analysis area include understanding and integrating the particle size of released aerosol materials, the release fraction of material during an extreme accident or possible successful sabotage attack, and determining and applying appropriate diffusion parameters.

The international Working Group for Sabotage Concerns of Transport and Storage Casks (WGSTSC) is currently working on addressing the issues of particle size and release fraction from malevolent acts [Molecke, 2004]. Hopefully the research project will be completed on schedule in 2006 to allow a more accurate analysis to be performed.

The diffusion parameters used for modeling a release of radiological material requires additional research. A change in the diffusion parameters used to model the atmospheric transport can have significant effects on the simulated radiological dispersion and resulting health effects, as is shown in Figures 5.1 – 5.3. Improved diffusion parameters for various changes in topography and geography should be available. This would allow more representative diffusion parameters to be used for various urban or suburban settings.

The key shortcoming and greatest area for future work is in communication with the general public. This area has been largely ignored or addressed only for special cases by the technical community. Public communication is often mentioned as an area in need of attention but very little is pursued or accomplished until legislation forces the issue. This problem with public communication is decades old. The following quote from 'Evaluation of Methods to Compare Consequences from Hazardous Materials Transportation Accidents' [Rhoads, 1986], illustrates this point.

> "Relative comparisons are a useful communication tool only if unfamiliar things can be compared to familiar things. In general, non-technical people do not understand the potential consequences from any hazardous materials transportation accident. Comparison of consequences from several hazardous materials will probably not provide them with useful insight, because there is nothing familiar in the comparison on which to base an evaluation of any of the materials. In other words, it may show them that one material is inherently safer than another, but will not help them with the more basic question of whether or not any or all of the materials are 'safe enough' This tends to be the area in which the concerns of many people reside."

This statement is directly applicable to the analysis and data presented in this paper. The transportation risk for spent nuclear fuel is clearly shown to be below that of other hazardous materials or other electrical power producing materials, however, this does not explain to the public 'why' the risk analysis is being performed and what risk values are acceptable.

The public illusion that spent nuclear fuel is an unsolved problem without purpose must be corrected. Nuclear fuel must be described and discussed throughout the electrical power production process to allow the significant benefit and purpose of the resulting spent nuclear fuel to be realized by the public.

The separation between the technical communities which rely on calculated risk values and the public which rely on intuition about perceived risks can only be bridged with open and accurate communication. This requires the technical community to present sound data and analysis, but more importantly, listen to what the public thinks and feels about spent nuclear fuel transportation and nuclear science in general.

Establishing and maintaining public confidence should be a primary goal for any regulatory authority responsible for acting in emergency situations [Jörle, 2003]. The emergency response to a spent nuclear fuel accident or sabotage attack depend on the public confidence of the responsible agencies. Without trust in the communication about an event and the planned response, the public could perceive or even create a more dangerous situation than was created by the accident or sabotage event itself.

It is important that trust from the public be established now. Trust cannot be achieved directly following an emergency or crisis situation and is very difficult to establish in the years or even decades following an emergency. Strong public trust must begin and rely on honest open communication involving not only the presentation of information, but listening to the public and addressing public concerns.

Regulatory authorities have taken the initiative to communicate with select public groups about specific topics such as a nuclear/radiological accident, waste disposal, or transport of radioactive material [Wieland, 2000]. This shows that regulatory agencies recognize and are responding to the need for public communication. However, this communication process usually addresses these select topics in a defensive manner only after public trust is lost or questionable.

There is an immediate need for a comprehensive communication strategy which addresses all facets of nuclear and radiological sciences [Wieland, 2000]. The International Atomic Energy Agency (IAEA) and other international organizations have recognized the need for public communication with reports such as ‘Communications on

Nuclear, Radiation, Transport, and Waste Safety: A Practical Handbook' [IAEA, 1999]. Several suggested steps necessary for a successful communication strategy which apply across the full spectrum of nuclear science and policy include:

- Disseminate information on safety to the public in both routine and emergency saturations;
- Be attentive to public concerns, and address them;
- Maintain social trust and confidence by keeping society informed on the established safety standards and how they are enforced;
- Facilitate the decision making process on nuclear matters by promptly presenting factual information in a clear manner;
- Integrate and maintain an information network at both the national and international levels;
- Encourage the dissemination of factual information on nuclear issues in schools.

10 References

Bhaduri, B., Bright, E., Coleman, P., and Dobson, J., (2002), “LandScan – Locating People is What Matters”, GeoInformatics, April/May 2002, pg. 34-37.

Briggs, G.A., (1974), “Diffusion Estimation for Small Emissions”, Environmental Research Laboratory, Atmospheric Turbulence and Diffusion Laboratory 1973 Annual Report, No. ATDL-106, National Oceanic and Atmospheric Administration, Washington D.C.

Chen, S.Y. et al., (2002), “A Resource Handbook on DOE Transportation Risk Assessment”, Argonne National Laboratory.

Comar, C.L., and Sagan, L.A., (1976), “Health Effects of Energy Production and Conversion”, Annual Review of Energy.

Department of Energy (DOE), (2002), “Final Environmental Impact Statement for a Geological Repository for the Disposal of Spent Nuclear Fuel and High Level Radioactive Waste at Yucca Mountain Nye County Nevada”, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, DOE/EIS-0250, February 2002.

Department of Energy/Nuclear Regulatory Commission (DOE/NRC), (2003), “Radiological Dispersal Devices: An Initial Study to Identify Radioactive Materials of Greatest Concern and Approaches to Their Tracking, Tagging, and Disposition”, Interagency Working Group on Radiological Dispersal Devices, Report to the Nuclear Regulatory Commission and the Secretary of Energy.

Eimutis, E.C., and Konicek, M.G., (1972), “Derivation of Continuous Functions for the Lateral and Vertical Dispersion Coefficients”, Atmospheric Environment, Vol. 6, pg. 859-863.

Faw, R.E., and Shultis, J.K., (1999), Radiological Assessment: Sources and Doses, American Nuclear Society Inc., La Grange Park, IL, USA.

Ferguson, C.D., Kazi, T., and Perera, J., (2003), “Commercial Radioactive Sources: Surveying the Security Risks”, Center for Nonproliferation Studies at Monterey Institute of International Studies, Occasional Paper No. 11.

Government Accounting Office (GAO), (2003), “Spent Nuclear Fuel: Options Exist to Further Enhance Security”, Report to the Chairman, Subcommittee on Energy and Air Quality, Committee on Energy and Commerce, United States House of Representatives, GAO-03-426.

Gotchy, R.L., (1987), “Potential Health and Environmental Impacts Attributable to the Nuclear and Coal Fuel Cycles”, U.S. Nuclear Regulatory Commission, Report No. NUREG-0332

Halstead, B., (2000). “Use of RISKIND and RADTRAN to Estimate the Economic Consequences of a Sabotage Event.” Radioactive Waste Management Associates, Professional Memo, September 21, 2000.

Hamilton, L.D. (Editor), (1974), “The Health and Environmental Effects of Electricity Generation – A Preliminary Report, BNL-20582, Brookhaven National Laboratory.

Hinds, W.C., (1999), “Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles”, 2nd ed, John Wiley & Sons Inc.

Inhaber, H., (1982), “Energy Risk Assessment”, Gordon and Breach Science Publishers, New York, NY.

International Atomic Energy Agency (IAEA), (1999), “Communications on Nuclear, Radiation, Transport and Waste Safety: A Practical Handbook”, Report No. TECDOC-1076, Vienna, Austria.

Jörle, A., (2003), “Public Communication During Events and Threats Involving Radioactive Releases”, Proceedings entitled ‘Security of Radioactive Sources’ of the International Atomic Energy Agency, Vienna, Austria, Mar. 10-13, 2003, pg. 425-428.

Luna, R.E., Neuhauser, K.S., and Vigil, M.G., (1999), “Projected Source Terms for Potential Sabotage Events Related to Spent Fuel Shipments.” Report No. SAND99-0963, Sandia National Laboratory, Albuquerque, NM.

Luna, R.E., (2000), “Comparison of Results from Two Spent Fuel Sabotage Source Term Experiments”, International Journal of Radioactive Materials Transport, Vol. 11, Issue 3, pg. 261-265.

Luna, R.E., et al, (2001). “Perspectives on Spent Fuel Cask Sabotage”, Waste Management 01 Conference Proceedings, March 2001, Report Number SAND2001-0603C, Sandia National Laboratories, Albuquerque, NM, Abstract.

Molecke, M.A., et. al., (2004), “Spent Fuel Sabotage Aerosol Ratio Program and Surrogate Material Test Results” Proceedings of the Institute of Nuclear Materials Management, Orlando, Florida, July 18-22, 2004.

National Council on Radiation Protection and Measurements (NCRP), (1997). “Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection.” NCRP Report No. 126, National Council on Radiation, Bethesda MD, pg. 71-76.

Neuhauser, K.S., Kanipe, F.L., and Weiner, R.F., (2000a), “RADTRAN5: Technical Manual” Report No. SAND2000-1256, Transportation Safety and Security Analysis Department, Sandia National Laboratory, Albuquerque, NM.

Neuhauser, K.S., and Kanipe, F.L., (2000b), “RADTRAN5: User Guide” Report No. SAND2000-1257, Transportation Safety and Security Analysis Department, Sandia National Laboratory, Albuquerque, NM.

Nuclear Regulatory Commission (NRC), (1977), “Final Environmental Statement on the Transport of Radioactive Materials by Air and Other Modes”, U.S. Nuclear Regulatory Commission, Report No. NUREG-0170.

Oak Ridge National Laboratory (ORNL), (2003), “Transportation Routing Analysis Geographic Information System (TRAGIS) User’s Manual”, National Transportation Research Center, Report No. ORNL/NTRC-006 Rev. 0.

Pretzsch, G., and Lange, F., (1994), “Radiological Consequences of Radioactivity Release from a Spent Fuel Transport Cask After a Shaped Charge Attack”, GRS-A-2158e, Gesellschaft fur Anlagenund Reaktorsicherheit (GRS) mbH.

Rhoads, R.E., Franklin, A.L., and Lavender, J.C., (1986), “Evaluation of Methods to Compare Consequences from Hazardous Materials Transportation Accidents”, Sandia National Laboratory, Report No. SAND-86-7117.

Ring, J.P., (2004), “Radiation Risks and Dirty Bombs”, The Radiation Safety Journal, Volume 86, Supplement 1, February 2004, Pages S42-S47.

Saccomanno, F.F., Shortreed, J.H., and Aerde, M.V., and Higgs, J., (1989), “Comparison of Risk Measures for the Transport of Dangerous Commodities by Truck and Rail”, Transportation Research Record No. 1245, National Research Council.

Saccomanno, F.F., Shortreed, J.H., and Mehta, R., (1990), “Fatality Risk Curves for Transporting Chlorine and Liquefied Petroleum Gas by Truck and Rail”, Transportation Research Record No. 1264, National Research Council.

Sprung, J.L., et al., (2000), “Reexamination of Spent Fuel Shipment Risk Estimates – Volume 1: Main Report”, NUREG/CR-6672 Vols. 1 and 2, SAND2000-0234, Sandia National Laboratory.

Van Tuyle, G.J., Strub, T.L., O’Brien, H.A., Mason, C.F.V., and Gitomer, S.J., (2003), “Reducing RDD Concerns Related to Large Radiological Source Applications”, Los Alamos National Laboratory, report no. LA-UR-03-6664.

Volpe, J.A., (1996), “Truck Transport of Hazardous Chemicals: Phosphorus Pentasulfide”, Environmental Engineering Division, U.S. Department of Transportation, Research and Special Programs Administration, Report No. DOT-VNTSC-RSPA-96-3, National Transportation Systems Center, Cambridge, MA.

Weiner, R.F., Osborn, D.M., and Mills, G.S. (2004), “RADTRAN/RADCAT User Guide (DRAFT)”, Sandia National Laboratory.

Wieland, P., (2000), “IAEA Activities on Communication of Nuclear Safety Issues”, Proceedings entitled ‘Investing in Trust: Nuclear Regulators and the Public’ of the Nuclear Energy Agency, Paris, France, Nov. 29 – Dec. 1, 2000, pg. 287-292.

Wolff, T.A., (1984), “The Transportation of Nuclear Materials”, Sandia National Laboratory, Report No. SAND84-0062, TTC-0471.

Yuan, Y.C., Chen, S.Y., Biwer, B.M., and LePoire, D.J., (1995), “RISKIND – A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel”, ANL/EAD-1, Argonne National Laboratory.