CHAPTER 5

TRANSPORTATION ACCIDENTS

5.1 Types of Accidents and Incidents

The different types of accidents that can interfere with routine transportation of spent nuclear fuel are:

- Accidents in which the spent fuel cask is not damaged or affected.
  - Minor traffic accidents ("fender-benders," flat tires) resulting in minor damage to the vehicle. These are usually called "incidents."[1]
  - Accidents that damage the vehicle or trailer enough that the vehicle cannot move from the scene of the accident under its own power, but do not result in damage to the spent fuel cask.
  - Accidents involving a death or injury, but no damage to the spent fuel cask.
- Accidents in which the spent fuel cask is affected.
  - Accidents resulting in loss of lead gamma shielding or neutron shielding (or both), but there is no release of radioactive material.
  - Accidents in which there is a release of radioactive material.

Accident risk is expressed as "dose risk," a combination of the radiation dose that results from the accident and the probability of that dose. The units used for accident risk are dose units (Sv).

An accident happens at a particular spot on the route. When the accident happens, the vehicle carrying the spent fuel cask stops. Thus, there can be no more than one accident for a shipment; resumption of the shipment would essentially be a new shipment. Accidents can result in damage to spent fuel in the cask even if no radioactive material is released. While this would not result in additional exposure of members of the public, workers engaged in accident recovery operations, including unloading or subsequently opening the cask at a facility would be affected. Accidents damaging the fuel but not damaging the cask, and potential consequent risk to workers are not included in this study.

5.2 Accident Probabilities

Risk is the product of probability and consequence of a particular accident scenario. The probability, or likelihood, that a spent fuel cask will be in a particular type of accident is a combination of two factors:

- The probability that the vehicle carrying the spent fuel cask will be in an accident, and

[1] In Department of Transportation parlance, an "accident" is an event that results in a death, an injury, or enough damage to the vehicle that it cannot move under its own power. All other events that occur in non-routine transportation are "incidents." This document uses the term "accident" for both accidents and incidents.

- The conditional probability that the accident will be a certain type of accident. This is a conditional probability because it depends on the vehicle being in an accident.

The net accident probability is the product of the probability of an accident and the conditional probability of a particular type of accident. A few hypothetical examples are given in Table 5-1 to illustrate the probability calculation.

Table 5-1. Illustrations of net probability

Accident Probability for a 5000 km (3107-mile) Cross-Country Trip[a]	Accident Scenario	Conditional Probability[b]	Net Probability Of Accident
0.0099	Truck collision with a gasoline tank truck	0.82×0.003 = 0.00246	0.82×0.003×0.0099 = 0.0000244 = 2.44×10^{-5}
0.00066	Derailment into slope >80 kph (>50 mph), no fire	0.7355×0.9846× (0.06048+0.00005)× 0.9887×0.0011 = 0.0000476	0.0000476×0.00066 = 3.14×10^{-8}
0.00066	Railcar accident on a bridge at 48-80 kph (30-50 mph), no fire	0.7355×0.9846× 0.2665×0.0113 = 0.00218	0.00218×0.00066 = 1.44×10^{-6}

[a] Calculated from DOT, 2005, Table 1-32. [b] From event trees in Appendix V.

Accident probability is calculated from the number of accidents per kilometer (accident frequency) for a particular type of vehicle as recorded by the DOT and reported by the Bureau of Transportation Statistics. Large truck accidents and freight rail accidents are the two data sets used in this analysis. The DOT has compiled and validated national accident data for truck and rail from 1971 through 2007 (DOT, 2008), but the accident rates declined definitively between 1971 and the 1990s. For this analysis, rates from 1996 through 2007 are used: 0.0019 accidents per thousand large truck-km (0.0031 accidents per thousand large truck miles) and 0.00011 accidents per thousand railcar-km (0. 00018 accidents per thousand railcar miles).

Figure 5-1 shows the accidents per truck-km and per railcar-km for this period. The logarithmic scale is used on the vertical axis in order to show the entire range.

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Deleted: . The accident frequency varies somewhat from state to state. The U.S. average for large trucks for the period 1991 to 2007 is 0.0035 accidents per thousand kilometers (km). For rail accidents, the average is 0.00024 per thousand railcar-km (DOT, 2008)

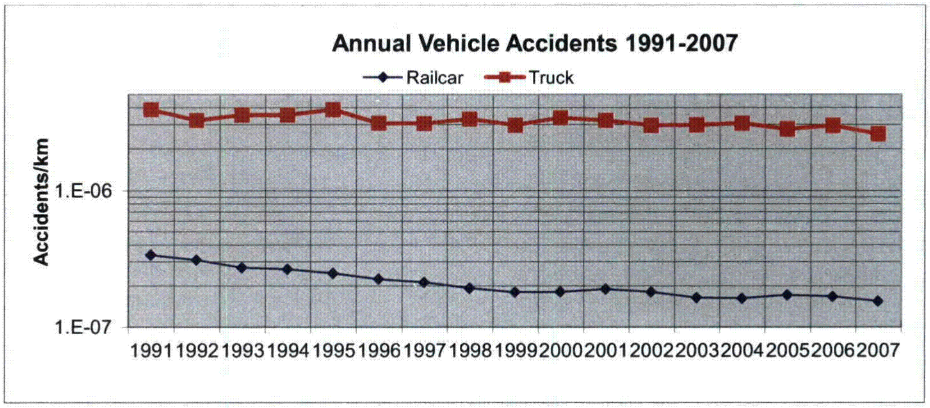

Figure 5-1. Accident frequencies in the U.S. from 1991 until 2007.

As Chapters 3 and 4 show, however, the only accidents that could result in either the loss of radiation shielding or release of radioactive material are rail accidents involving the Rail-Lead cask (when the fuel is directly loaded inside the cask, i.e. the fuel is not contained in a welded canister inside the cask). These are:

- Collisions with hard rock or equivalent at impact speeds greater than 97 km/hour (60 mph) that result in some loss of lead gamma radiation shielding or damage to the cask seals. Hard rock is not necessarily an unyielding target; however, collision of a cask with hard rock is the only type of collision along a transportation route that could damage the cask (in the absence of fire) sufficiently to result in release of radioactive material or loss of lead shielding.
- Fires of long enough duration to compromise the seals.

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Whether or not these accidents happen depends on the likelihood (conditional probability) of the accident scenario as well as on the accident frequency. The event trees for truck and rail, Figures V-1 and V-2 of Appendix V, show some of the elements of accident scenarios in each branch of the respective event tree. The dependence on probability is illustrated by Figure V-6, which shows the sequence of events needed for a pool fire that can burn long enough to compromise the seals and the lead shielding.

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Table 5-2 shows the conditional probabilities of accidents that could result in a radiation dose to a member of the public and of accidents in which there is neither loss of lead shielding nor a release of radioactive material. The analysis that results in these conditional probabilities may be found in Appendix V, Sections V.3 to V.5.

Table 5-2. Scenarios and conditional probabilities of rail accidents involving the Rail-Lead cask

Accident Scenario for the Rail-Lead Cask	Conditional probability of gamma shield loss or radioactive material content release exceeding 10 CFR 71.51 quantities[a]
Loss of lead shielding from impact[b]	8.3×10^{-10}
Loss of lead shielding from fire[c]	10^{-14} to 10^{-10}
Radioactive materials release from impact[d]	5.1×10^{-10}
Radioactive materials release from fire	0

[a]More than 99.999 percent of potential accidents would not result in either loss of lead shielding or a release of radioactive material.
[b]From the cases in Table V-2 of Appendix V with lead slump greater than 1%.
[c]From the fire event tree, Figure V-6 in Appendix V.
[d]From the sum of probabilities in the last row of Table 5-10 for the casks with metal seals. If the cask is shipped with elastomer seals the probability of release would be less.

5.3 Accidents with Neither Loss of Lead Shielding nor Release of Radioactive Material

The conditional probability that an accident involving a lead-shielded cask will be of the type with no release and no lead shielding loss is, as the footnote to Table 5-2 states, 99.999 percent. The only type of cask that could lose gamma shielding is a lead shielded cask like the Rail-Lead cask. The only type of cask that could release radioactive material in an accident is a cask carrying uncanistered spent fuel. Although the Truck-DU cask carries uncanistered fuel, this cask would not release any radioactive material under any scenario postulated in this report. The Rail-Steel cask carries only canistered fuel and would not release any radioactive material. Neither Truck-DU casks nor Rail-Steel casks are lead-shielded, therefore shielding loss would not occur.

The doses to emergency responders from an accident in which no material is released and there is no loss of lead gamma shield are shown in Table 5-3, and collective doses to the public from this type of accident are shown in Table 5-4 and

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Deleted: of collision scenarios at speeds greater than 113 kph into slope, embankment, tunnel, and on bridge from the rail event tree of Appendix V. In order for there to be any release, the impact speed would have to be greater than 145 kph. The event tree does not distinguish which of the impacts that are greater than 113 kph are also greater than 145 kph, so an assumption of 5% was made. This is extremely conservative because the analyses were for impacts onto a rigid target, and many of these impact surfaces are considerably softer
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Table 5-5. These radiation doses depend on:

- The external dose rate from the cask (**Error! Reference source not found.**).
- A ten-hour stop (DOE, 2002) at the scene of the accident, until the vehicle and/or cask can be moved safely. Ten hours is believed to overstate the stop time for most accidents.
- An average distance of five meters between the cask and the first responders and others who remain with the cask.
- For collective doses, the average rural, urban, and suburban population densities for each route.

The radiation doses in Table 5-3, Table 5-4, and

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Table 5-5 are the consequences of all Truck-DU accidents, all Rail-Steel accidents, and 99.999% of the Rail-Lead accidents.

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Table 5-3. Dose to an emergency responder[2] from a cask in a no-shielding loss, no-release accident

Cask	Dose in Sv	Ten-hour allowed dose in Sv derived from the one-hour dose in 10 CFR 71.51
Truck-DU	1.0 E-03	1.0 E-01
Rail-Lead	9.2E-04	1.0 E-01
Rail-Steel	6.9E-04	1.0 E-01

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Table 5-4 and

[2] Includes police, incident command, fire fighters, EMTs, and any other emergency responders.

Table 5-5 show collective doses in Sv for the ten-hour stop that follows the accident. Doses are shown for rural, suburban, and urban segments of each route, but an accident is only going to happen at one place on any route. Each listed dose is thus the collective dose that residents on that route segment could receive if the accident happened at any spot on that type of route segment.

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Table 5-4. Collective dose risks to the public from a no-shielding loss, no-release accident involving rail casks (person-Sv)

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban[a]	Total	Rural	Suburban	Urban[a]	Total
MAINE YANKEE								
ORNL	3.1E-06	5.3E-05	6.6E-06	6.3E-05	2.3E-06	4.0E-05	5.0E-06	4.8E-05
DEAF SMITH	2.3E-06	5.7E-05	6.8E-06	6.6E-05	1.7E-06	4.3E-05	5.2E-06	5.0E-05
HANFORD	5.7E-06	5.2E-05	6.3E-06	6.4E-05	4.3E-06	3.9E-05	4.8E-06	4.8E-05
SKULL VALLEY	2.8E-06	5.1E-05	5.3E-06	6.0E-05	2.1E-06	3.9E-05	4.0E-06	4.5E-05
KEWAUNEE								
ORNL	3.1E-06	5.7E-05	7.2E-06	6.8E-05	2.3E-06	4.3E-05	5.4E-06	5.1E-05
DEAF SMITH	1.5E-06	6.1E-05	7.2E-06	6.9E-05	1.2E-06	4.6E-05	5.4E-06	5.2E-05
HANFORD	1.5E-06	5.3E-05	6.6E-06	6.1E-05	1.2E-06	4.0E-05	5.0E-06	4.6E-05
SKULL VALLEY	2.0E-06	6.2E-05	6.0E-06	7.0E-05	1.5E-06	4.7E-05	4.5E-06	5.3E-05
INDIAN POINT								
ORNL	2.6E-06	7.2E-05	8.7E-06	8.3E-05	2.0E-06	5.4E-05	6.6E-06	6.3E-05
DEAF SMITH	1.9E-06	5.9E-05	7.5E-06	6.9E-05	1.4E-06	4.5E-05	5.7E-06	5.2E-05
HANFORD	1.9E-06	5.6E-05	7.2E-06	6.5E-05	1.4E-06	4.3E-05	5.5E-06	5.0E-05
SKULL VALLEY	2.2E-06	6.0E-05	6.6E-06	6.9E-05	1.7E-06	4.6E-05	5.0E-06	5.2E-05
IDAHO NATIONAL LAB								
ORNL	1.9E-06	6.0E-05	5.8E-06	6.8E-05	1.4E-06	4.6E-05	4.4E-06	5.2E-05
DEAF SMITH	8.0E-07	6.0E-05	5.3E-06	6.6E-05	6.0E-07	4.6E-05	4.0E-06	5.0E-05
HANFORD	1.0E-06	6.0E-05	6.7E-06	6.8E-05	7.5E-07	4.6E-05	5.1E-06	5.2E-05
SKULL VALLEY	2.0E-06	5.9E-05	7.1E-06	6.8E-05	1.5E-06	4.4E-05	5.4E-06	5.1E-05
AVERAGE	2.3E-06	5.8E-05	6.7E-06	6.7E-05	1.7E-06	4.4E-05	5.1E-06	5.1E-05

[a]The urban dose is less than the suburban dose because urban residences are 83% shielded, while suburban residences are 13% shielded.

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Table 5-5. Collective dose risks to the public from a no-shielding loss, no-release accident involving a truck cask (person-Sv)

FROM	TO	Truck-DU			
		Rural	Suburban	Urban[a]	Total
MAINE YANKEE	ORNL	4.2E-06	7.2E-05	9.1E-06	8.5E-05
	DEAF SMITH	3.9E-06	6.7E-05	8.4E-06	7.9E-05
	HANFORD	3.2E-06	5.9E-05	8.4E-06	7.1E-05
	SKULL VALLEY	3.5E-06	6.1E-05	8.6E-06	7.3E-05
KEWAUNEE	ORNL	4.1E-06	6.6E-05	8.3E-06	7.8E-05
	DEAF SMITH	2.8E-06	6.2E-05	8.4E-06	7.3E-05
	HANFORD	2.2E-06	5.8E-05	8.4E-06	6.9E-05
	SKULL VALLEY	2.6E-06	5.9E-05	8.6E-06	7.0E-05
INDIAN POINT	ORNL	3.6E-06	6.7E-05	8.2E-06	7.9E-05
	DEAF SMITH	3.6E-06	6.7E-05	8.2E-06	7.9E-05
	HANFORD	**2.7E-06**	**6.2E-05**	**8.4E-06**	7.3E-05
	SKULL VALLEY	3.0E-06	6.4E-05	8.5E-06	7.6E-05
IDAHO NATIONAL LAB	ORNL	2.6E-06	5.5E-05	7.9E-06	6.6E-05
	DEAF SMITH	1.6E-06	6.2E-05	6.8E-06	7.0E-05
	HANFORD	1.4E-06	3.6E-05	5.2E-06	4.3E-05
	SKULL VALLEY	2.1E-06	6.2E-05	8.4E-06	7.3E-05
AVERAGE		2.9E-06	6.1E-05	8.1E-06	7.2E-05

[a]The urban dose is less than the suburban dose because urban residences are 83% shielded, while suburban residences are 13% shielded

The average individual U.S. background dose for ten hours is 4.1×10^{-6} Sv. Average background doses during the 10-hour stop for the 16 truck routes analyzed are

- Rural: $(4.1\ 10^{-6}\ \text{Sv}) \times (16.8\ \text{persons/km}^2) \times\pi\times (0.8\ \text{km})^2 = 0.000138$ person-Sv
- Suburban: $(4.1\ 10^{-6}\ \text{Sv}) \times (463\ \text{persons/km}^2) \times\pi\times (0.8\ \text{km})^2 = 0.00382$ person-Sv
- Urban: $(4.1\ 10^{-6}\ \text{Sv}) \times (2682\ \text{persons/km}^2) \times\pi\times (0.8\ \text{km})^2 = 0.0221$ person-Sv

If the Truck-DU cask, for example, is in a no-shielding loss, no-release accident, the average collective dose (the sum of the background dose and the dose due to the accident) to residents for the 10 hours following the accident would be

- Rural: 0.000141 person-Sv
- Suburban: 0.003881 person-Sv
- Urban: 0.022108 person-Sv

The background and accident collective doses would be indistinguishable from the collective background dose. Any dose to an individual is well below the dose allowed by 10 CFR 71.51, as one would expect.

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5.4 Accidental Loss of Shielding

The details of the calculation of doses from shielding losses are provided in Appendix V, Section V.3.1 (loss of gamma shielding) and Section V.3.2 (loss of neutron shielding).

5.4.1 Loss of Lead Gamma Shielding

Type B transportation packages are designed to safely carry radioactive material and need shielding adequate to meet the external dose regulation of 10 CFR Part 71. Spent nuclear fuel is extremely radioactive and requires both gamma and neutron radiation shielding. The sum of the external radiation doses from gamma radiation and neutrons should not exceed 0.0001 Sv per hour at two meters from the cask, as stipulated by 10CFR71.47.

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Each spent-fuel transportation cask analyzed uses a different material to serve as the gamma shielding. Each may use different neutron shielding as well, but since no credit is taken for the neutron shield, it is not usually part of the accident analysis. The Rail-Steel cask has a steel wall thick enough to attenuate gamma radiation to acceptable levels. The Truck-DU cask uses metallic DU. Neither of these shields would lose their effectiveness in an accident. The Rail-Lead cask has a lead gamma shield which could have its effectiveness reduced in an accident. Lead is relatively soft compared to DU or steel, and melts at a considerably lower temperature (330°C) than either DU or steel.

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In a hard impact, the lead shield will slump, and a small section of the spent fuel in the cask will be shielded only by the steel shells.

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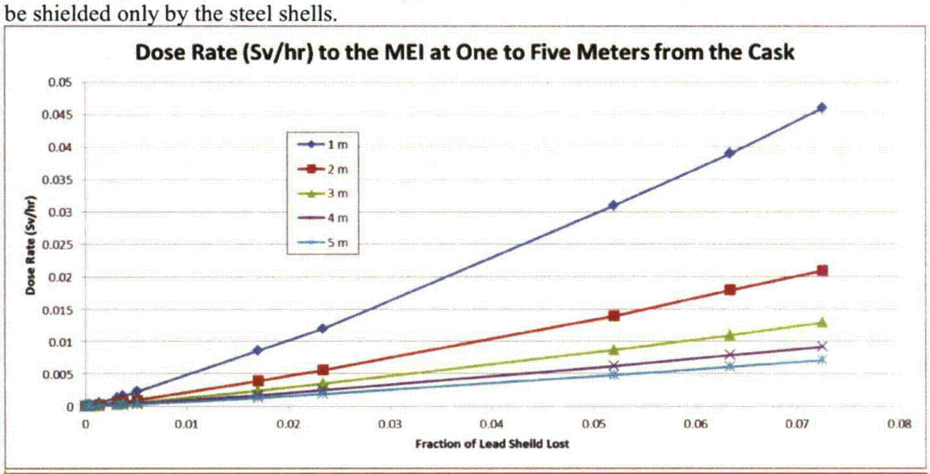

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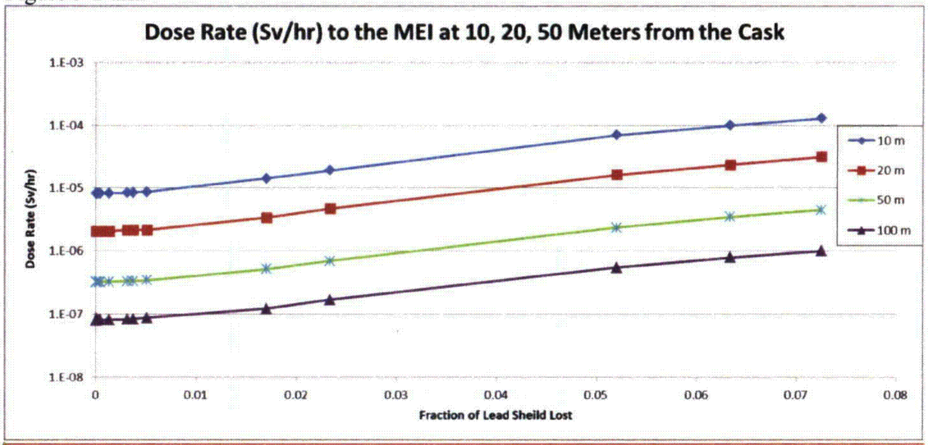

Figure 5-3 show the maximum individual radiation dose at various distances from the damaged cask for a range of gaps in the lead shield. In the figures, the dose estimates for the large gaps are depicted on the left end of the graph, and the fraction of lead shield lost (gap size) increases from left to right.

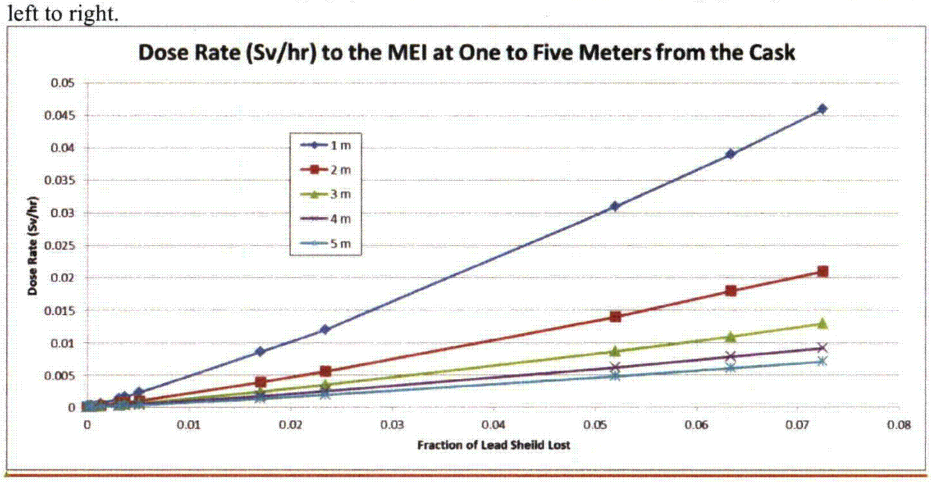

Figure 5-2 shows that doses larger than the external dose allowed by the regulation of 10 CFR 71.51 (0.01 Sv/hour at 1 meter from the cask) occur when the lead shielding gap is more than two percent of the shield.

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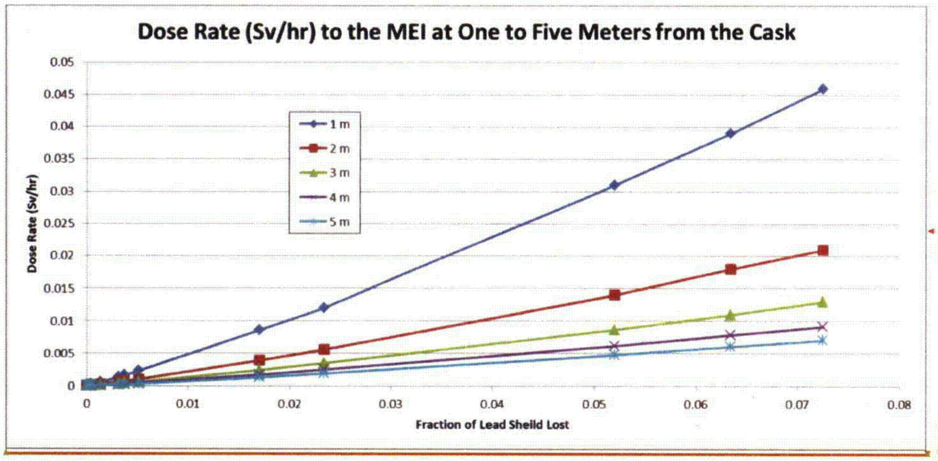

Figure 5-2. Radiation dose rates to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from one to five meters from the cask carrying spent fuel. The horizontal axis represents the fraction of shielding lost—the shielding gap.

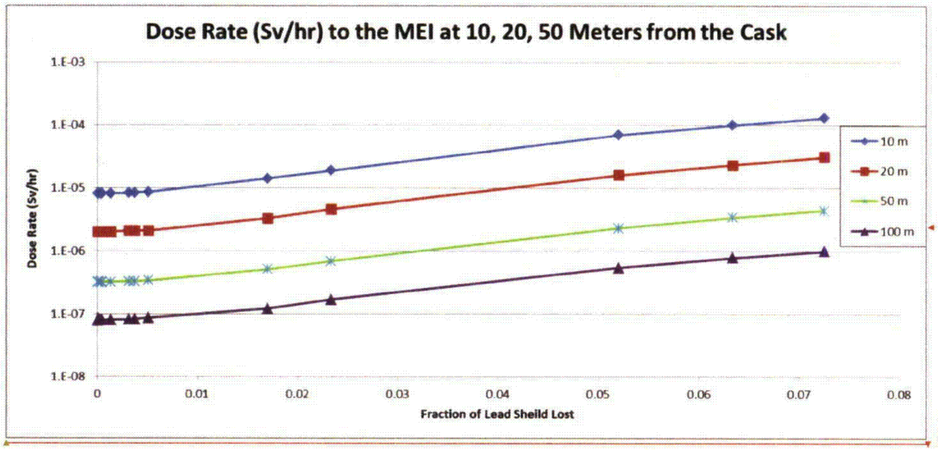

Figure 5-3. Radiation dose rates to the maximally exposed individual from loss of lead gamma shielding at distances from 10 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic so that all of the doses can be shown on the same graph. The horizontal axis represents the fraction of shielding lost—the shielding gap.

One in a billion accidents could be an impact accident that causes loss of lead shielding resulting in a dose rate that exceeds the regulatory dose rate from 10 CFR 71.51; the "one in a billion" is a

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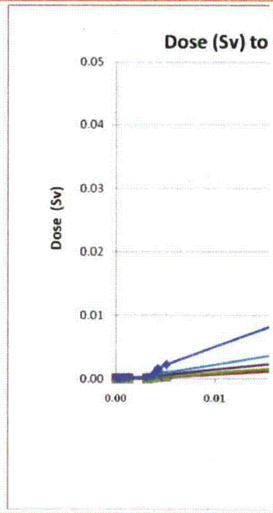

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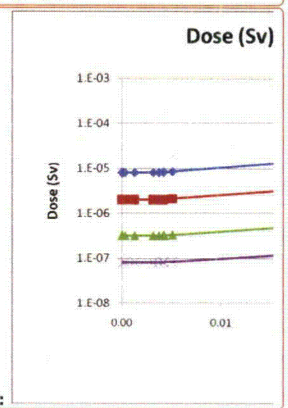

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conditional probability, conditional on an accident happening. The total probability of such an accident includes both this conditional probability and the probability that there will be an accident. The probability of an accident is shown in the right-hand column of Table 5-6. For example, the probability that an accident resulting in lead shielding loss leading to a dose rate greater than 0.01 Sv/hr will happen on the rail route from Maine Yankee Nuclear Plant site to Hanford is:

$$(1 \times 10^{-9})*(0.00214) = 2.14 \times 10^{-12}$$

or about twice in a trillion Maine Yankee to Hanford shipments.

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This very small probability indicates that severe accidents, which are more traumatic to the cask than the tests shown in Figure 1-1, are not likely to happen. The conditions that can cause enough loss of lead shielding to result in radiation doses to the public above those allowed by 10 CFR 71.51 are extreme conditions.

Table 5-6. Average railcar accident frequencies and accidents per shipment on the routes studied

ORIGIN	DESTINATION	AVERAGE ACCIDENTS PER KM	ROUTE LENGTH (KM)	PROBABILITY OF AN ACCIDENT FOR THE TOTAL ROUTE
MAINE YANKEE	ORNL	6.5×10^{-7}	2125	0.00139
	DEAF SMITH	5.8×10^{-7}	3362	0.00194
	HANFORD	4.2×10^{-7}	5084	0.00214
	SKULL VALLEY	5.1×10^{-7}	4086	0.00208
KEWAUNEE	ORNL	4.3×10^{-7}	1395	0.00060
	DEAF SMITH	3.3×10^{-7}	1882	0.00062
	HANFORD	2.4×10^{-7}	3028	0.00073
	SKULL VALLEY	3.7×10^{-7}	2755	0.00103
INDIAN POINT	ORNL	8.8×10^{-6}	1264	0.0112
	DEAF SMITH	6.2×10^{-7}	3088	0.00192
	HANFORD	4.4×10^{-7}	4781	0.00212
	SKULL VALLEY	5.5×10^{-7}	3977	0.00217
INL	ORNL	3.6×10^{-7}	3306	0.0012
	DEAF SMITH	3.5×10^{-7}	1913	0.00067
	HANFORD	3.2×10^{-7}	1062	0.00034
	SKULL VALLEY	2.8×10^{-7}	455	0.00013

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The overall collective dose risks to the resident population from a lead shielding loss accident on the sixteen rail routes studied are shown in Table 5-7. These include accidents whose resultant dose rates would be within regulatory limits. These doses are the totals of the rural, suburban, and urban doses from Table V-7. The expected dose to any member of the populations along the routes, at least 10 m. from the cask, is within the limits of 10 CFR 71.51. The Indian Point-to-ORNL collective dose risk is comparatively large because the suburban and urban populations along this route are about 20 percent larger than along the other routes, and the rail accident rate per km is an order of magnitude larger.

Table 5-7. Collective dose risks per shipment in person-Sv for a loss of lead shielding accident involving a lead-shielded rail cask.

SHIPMENT ORIGIN	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.5E-13	2.7E-13	2.7E-13	2.6E-13
KEWAUNEE	1.0E-13	6.3E-14	5.4E-14	1.1E-13
INDIAN POINT	3.5E-12	2.4E-13	2.5E-13	2.7E-13
IDAHO NATIONAL LAB	9.9E-14	4.1E-14	2.1E-14	1.5E-14

The conditional probability that a gap in lead shielding will occur after a fire involving the cask is about 10^{-19}. The conditional probability is so small because the following has to happen before a fire is close enough to the cask, and burns hot enough, and long enough, to do any damage to the lead shield.

- The train must be in an accident that results in a major derailment or else the location of the fire will be too far removed from the cask to damage the lead shielding.
- There must be at least one tank car of flammable material involved in the accident (either on the train carrying the spent fuel cask or on another train involved in the accident).
- The derailment must result in a pileup. By regulation, railcars carrying spent fuel casks are required to have buffer cars and will never be located directly adjacent to a railcar carrying hazardous or flammable material.
- The flammable material must leak out so that it can ignite.
- The pileup must be such that the resulting fire is no further from the cask than a railcar length.

The probability of a pileup and the probability that the cask is within a railcar length from the fire are very small. Assessing the conditional probability without these two events, and considering only the more likely events, results in a conditional probability of about 10^{-10}, or about one in ten billion.

The event trees and probabilities for fire accident are discussed in detail in Appendix V.

5.4.2 Loss of Neutron Shielding

The type of fuel that can be transported in the three casks considered has relatively low neutron emission but does require neutron shielding. This is usually a hydrocarbon or carbohydrate polymer of some type that often contains a boron compound. All three of the casks studied have polymer neutron shields. Table 5-8 shows the neutron doses to individuals who are about five meters from a fire-damaged cask for ten hours. The dose allowed by 10 CFR 71.51 is provided for comparison. Neutrons are absorbed by air much better than is gamma radiation, so that

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external neutron radiation would impact receptors close to the cask but not members of the general public.

Impacts caused by severe accidents, even those that cause breaches in the seals, will not damage the neutron shield significantly. However, the neutron shielding on any of the three casks is flammable and could be damaged or destroyed in a fire.

Table 5-8. Doses to an emergency responder or other individual five meters from the cask for 10 hours

Cask	Total Dose in Sv	Ten-hour allowed total dose in Sv from 10 CFR 71.51
Truck-DU	0.0073	0.1
Rail-Lead	0.0076	0.1
Rail-Steel	0.0076	0.1

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The neutron doses do not exceed the allowed dose cited in the regulation following an accident. Essentially, these are not extra-regulatory accidents. The conditional probability of this neutron dose is 0.0063 for a truck fire accident and 0.0000001 for a rail fire accident. The conditional probability of a fire for the Truck-DU cask is much higher than that for the two rail casks in part because truck accidents always include a potential source of fuel (the gas tanks of the truck) while many railcar accidents do not involve the locomotive, and in part because of the way the event trees were constructed. The truck event tree does not distinguish between minor fires and ones that are severe enough to damage the neutron shielding, while the rail event tree only considers severe fires. Therefore the conditional probability of a truck fire is quite conservative (overstated). Details are discussed in Appendix V Section V.3.2.

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5.5 Accidental Release of Radioactive Materials

Radioactive materials released into the environment are dispersed in the air, and some deposit on the ground. If a spent fuel cask is in a severe enough accident, spent fuel rods can tear or be otherwise damaged, releasing fission products and very small particles of spent fuel into the cask. If the cask seals are damaged, these radioactive substances can be swept from the interior of the cask through the seals into the environment. Release to the environment requires that the accident be severe enough to damage the fuel rods and release the pressure in the rods, or there will be no positive pressure to sweep material from the cask to the environment.

The potential accidents that could result in such a release are discussed in Chapters 3 and 4. This chapter discusses the probability of such accidents and the consequences of releasing these radionuclides.

5.5.1 Spent Fuel Inventory

Spent nuclear fuel contains a great many different radionuclides. The amount of each fission product nuclide in the spent fuel depends on the type of reactor fuel and how much ^{235}U was in the fuel (the enrichment) when it was loaded into the reactor. The amount of each fission product in the spent fuel also depends on how much nuclear fission has taken place in the reactor (the burnup). Finally, the amount of each radionuclide in the spent fuel depends on the time that has passed between removal of the fuel from the reactor and transportation in a cask (the cooling time) because the fission products undergo radioactive decay during this time. Plutonium, americium, curium, thorium, and other actinides produced in the reactor decay to a sequence of radioactive elements which are the progeny of the actinide. These progeny increase in concentration as the original actinide decays. However, there is never more radioactive material as a result of decay than there was initially.

The fuel studied in this analysis is PWR fuel that has "burned" 45,000 MWD/MTU and has been cooled for nine years[3].. The Rail-Lead cask, the only cask studied that could release radioactive material in an accident, is certified to carry 26 PWR assemblies.

The spent fuel inventory for accident analysis was selected by normalizing the radionuclide concentrations in the spent fuel by radiotoxicity (see Appendix V, Section V.4.1). The resulting inventory is shown in Table 5-9.

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Table 5-9. Radionuclide inventory for accident analysis of the Rail-Lead cask (TBq)

Radionuclide	Terabecquerels (TBq) 26 Assemblies
^{240}Pu	7.82E+03
^{239}Pu	1.84E+02
^{137}Cs	4.38E+04
^{238}Pu	7.18E+01
^{243}Cm	2.50E+01
^{60}Co	5.56E+01
^{154}Eu	9.01E+02
^{134}Cs	4.03E+02
^{85}Kr	2.26E+03
^{241}Am	1.58E-01
^{242}Cm	1.00E+00
^{155}Eu	2.63E+02
^{231}Pa	3.12E-02
^{106}Ru	7.50E+00
^{236}U	1.92E-01
^{63}Ni	8.99E+02
^{233}U	5.75E-01
^{241}Pu	6.13E-01
^{113m}Cd	5.24E+00

[3] This was approximately the shortest time needed for the fuel to cool sufficiently to meet the thermal requirements of the cask certification.

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The ^{60}Co inventory listed is not part of the nuclear fuel. It is the main constituent of a corrosion product, Chalk River unidentified deposits (CRUD), which accumulates on the outside of the rods, and is formed by corrosion of hardware in the fuel pool. It is listed here with the inventory because it is released to the environment under the same conditions that spent fuel particles are released.

5.5.2 Conditional Probabilities and Release Fractions

Seven accident scenarios involving the Rail-Lead cask, described in Chapter 3, could result in releases of material to the environment. The details of these scenarios that are important to calculating the resulting doses are shown in Table 5-10. A detailed description of the movement of radionuclide particles from fuel rods to the cask interior and from the cask interior to the environment is found in Appendix V, Section V.4.3.

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Table 5-10. Parameters for determining release functions for the accidents that would result in release of radioactive material[a]

	Cask Orientation	End	Corner	Side	Side	Side	Side	Corner
	Rigid Target Impact Speed (kph)	193	193	193	193	145	145	145
	Seal	metal	metal	elastomer	metal	elastomer	metal	metal
Cask to Environment Release Fraction	Gas	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	Particles	0.70	0.70	0.70	0.70	0.70	0.70	0.64
	Volatiles	0.50	0.50	0.50	0.50	0.50	0.50	0.45
	Crud	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Rod to Cask Release Fraction	Gas	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	Particles	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	2.40E-06
	Volatiles	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	1.50E-05
	Crud	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Conditional Probability	5.96E-12	3.57E-11	1.79E-11	1.79E-11	3.40E-10	3.40E-10	1.13E-10

[a]Discussion of the values in this table is given in §V.4.3 of Appendix V.

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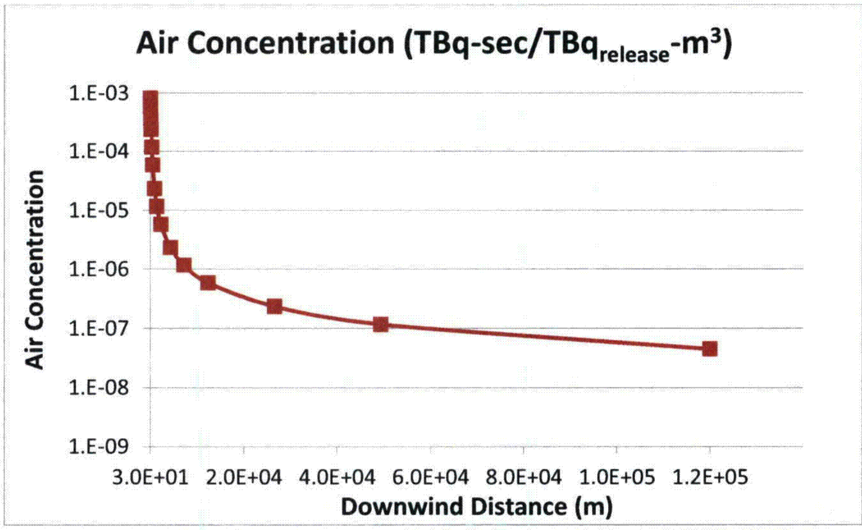
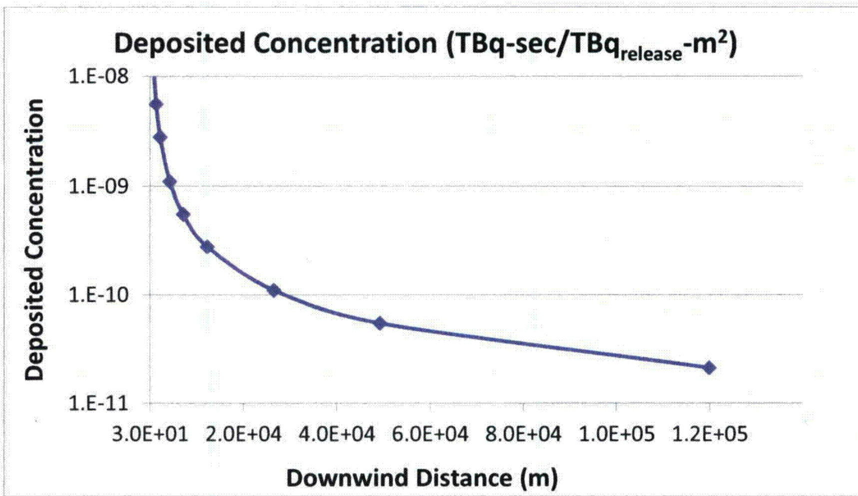
5.5.3 Dispersion

When material is swept from the cask and released into the environment, it is dispersed by wind and weather. The dispersion is modeled using the accident model in RADTRAN 6, which is a Gaussian dispersion model. The release would be at about 1.5 meters above ground level, since the cask is sitting on a railcar. The gas sweeping from the cask is warmer than ambient, so that the release is elevated. Under these conditions, the maximum ground level air concentration and deposition are 21 m downwind from the release. The dispersion was modeled using neutral weather conditions (Pasquill: stability D, wind speed 4.7 m/sec). It was repeated using very stable meteorology (Pasquill: stability F, wind speed 0.5 m/sec), but the difference was negligible because of the relatively low elevation of the release. The maximally exposed individual would be located directly downwind from the accident, 21 meters from the cask.

Figure 5-4 shows air and ground concentrations of released material as a function of downwind distance. The upwind side of the maximum concentration is short because the plume rise is very fast. Therefore the x-axis (downwind distance) is foreshortened so that the plume rise and gradual decay can be shown in the same graph. The concentrations shown are along the plume centerline and are the maximum concentrations in the plume. The figure shows the exponential decrease of airborne concentrations as the downwind distance increases. The ground (deposited) concentration also decreases in the downwind direction.



a. Airborne concentration of radioactive material released from the cask in an accident



b. Concentration of radioactive material deposited after release from the cask in an accident

Figure 5-4. Air and ground concentrations of radioactive material following a release.

5.5.4 Consequences and Risks from Accidents Involving Release of Radioactive Material

The dose from each of the accidents that would involve a release is shown in Table 5-11. Detailed discussion on how these values were obtained is provided in §V.4.3 of Appendix V.

Table 5-11. Doses (consequences) in Sv to the maximally exposed individual from accidents that involve a release

Cask Orientatio n	Impac t Speed (kph)	Seal Material	Inhalatio n	Re-suspension	Cloud-shine	Ground-shine	Total
End	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Corner	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	193	elastome r	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	145	elastome r	1.6	0.014	4.5E-06	3.6E-05	1.6
Side	145	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Corner	145	metal	0.73	0.0063	5.1E-05	9.0E-04	0.73

The doses listed in Table 5-11 are consequences, not risks. The dose to the maximally exposed individual is not the sum of the doses. Each cask orientation is a different accident scenario and results in a different set of inhalation and external doses. These doses would not result in either acute illness or death (Shleien et al., 1998, p. 15-3) and are in fact, similar to a single radiotherapy treatment for cancer. The inhalation and groundshine doses are listed separately because they have different physiological effects. External doses are exactly that, and the receptor would receive a dose only as long as he or she is exposed to the deposited or airborne material. If people near the accident are evacuated, and evacuation can take as much as a day, then they only receive an external dose for a day. The most significant dose is the inhalation dose. All exposures to the dispersed material last until the end of the evacuation time, which for this analysis was 24 hours.

Inhaled radioactive particles lodge in the body and are eliminated slowly through physiological processes that depend on the chemical form of the radionuclide. The inhaled dose is called a "committed" dose, because the exposure is for as long as the radionuclide is in the body, though the activity of the nuclide decreases exponentially as it decays (this is shown in the Inhalation column of Table 5-11). The resuspension dose is also an inhaled dose. The NRC considers the total effective dose equivalent: the sum of the inhaled and external doses, which allows the doses to be added (the total is shown in the last column of Table 5-11).

A pool fire co-located with the cask and burning for a long enough time could damage the seals severely. None of the fires analyzed in this report caused sufficient seal damage to result in a release of radioactive material. The conditional probability of the series of events required to produce the worst fire scenario analyzed is about 10^{-19}, as is discussed in detail in Appendix V,

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Section V.3.1.2, so analysis of a more severe fire is meaningless. Even a fire offset from the cask but close enough to damage lead shielding has a conditional probability of between 10^{-14} and 10^{-10}.

The total collective dose risk from the universe of release accidents is shown in Table 5-12. The accident with the most severe consequence results in a release of 50 times the amount of radioactive material that can be transported in a non-accident resistant container and a collective dose of 2.18 person-Sv (direct output from RADTRAN) using a population density of 41.46 persons/km^2 (the US average minus Alaska). Of the three casks in this study, only the Rail-Lead cask could result in a release in each kind of accident considered.

Table 5-12. Total collective dose risk (person-Sv) for release accidents per shipment for each route

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.4E-09	1.5E-09	1.3E-09	6.4E-10
KEWAUNEE	1.0E-09	4.9E-10	4.8E-10	3.4E-10
INDIAN POINT	4.0E-08	1.6E-09	1.6E-09	5.1E-10
IDAHO NATIONAL LAB	2.5E-10	4.0E-10	1.1E-10	7.3E-10

These dose risks are negligible by any standard.

The total dose risks from loss-of-lead shielding accidents are shown in Table 5-13 (which is the same as Table 5-7, repeated here for ease of comparison), and the sum of the two is shown in Table 5-14.

Table 5-13. Total collective dose risk (person-Sv) for each route from a loss of lead shielding accident

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.5E-13	2.7E-13	2.7E-13	2.6E-13
KEWAUNEE	1.0E-13	6.3E-14	5.4E-14	1.1E-13
INDIAN POINT	3.5E-12	2.4E-13	2.5E-13	2.7E-13
IDAHO NATIONAL LAB	9.9E-14	4.1E-14	2.1E-14	1.5E-14

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Table 5-14. Total collective dose risk (person-Sv) from release and loss of shielding accidents

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.4E-09	1.5E-09	1.3E-09	6.4E-10
KEWAUNEE	1.0E-09	4.9E-10	4.8E-10	3.5E-10
INDIAN POINT	4.1E-08	1.6E-09	1.6E-09	5.2E-10
IDAHO NATIONAL LAB	2.5E-10	4.1E-10	1.1E-10	7.3E-10

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Table 5-15 shows the total collective dose risk for an accident involving the Rail-Lead shielded cask in which there is neither loss of lead shielding nor a release. Since the collective dose risk for this type of accident depends in the TI, the collective dose risk from an accident involving the truck cask would be the same. For the Rail-Steel cask carrying canistered fuel, the collective dose risk would be slightly less because the TI is smaller. For this analysis, the cask was assumed to be immobilized for ten hours.

Table 5-15. Total collective dose risk (person-Sv) from no-release, no-loss of shielding accidents involving the Rail-Lead cask (see Table 5-4).

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	6.3E-05	6.6E-05	6.4E-05	6.0E-05
KEWAUNEE	6.8E-05	6.9E-05	6.1E-05	7.0E-05
INDIAN POINT	8.3E-05	6.9E-05	6.5E-05	6.9E-05
IDAHO NATIONAL LAB	6.8E-05	6.6E-05	6.8E-05	6.8E-05

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Table 5-16 shows the collective accident risk for the 16 rail routes from loss of neutron shielding for the Rail-Lead cask. This table is extracted from Table V-14 in Appendix V.

Table 5-16. Total collective dose risk (person-Sv) from loss of neutron shielding for accidents involving the Rail-Lead cask.

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	8.90E-14	1.16E-13	1.13E-13	1.12E-13
KEWAUNEE	3.48E-14	3.41E-14	3.72E-14	5.46E-14
INDIAN POINT	6.94E-13	1.13E-13	1.14E-13	1.22E-13
IDAHO NATIONAL LAB	5.88E-14	3.48E-14	1.09E-14	7.15E-15

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5.6 Chapter Summary

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The conclusions that can be drawn from the risk assessment as presented in this chapter, keeping in mind that these apply to the three types of casks studied, are:

- The sixteen truck and sixteen rail routes selected for study are an adequate representation of U.S. routes for spent nuclear fuel transportation, and there was relatively little variation in the risks per km over these routes.
- The overall collective dose risks are vanishingly small.
- The collective dose risks for the two types of extra-regulatory accidents, accidents involving a release of radioactive material and loss-of-lead-shielding accidents, are negligible compared to the risk from a no-release, no-loss-of-shielding accident. There is no expectation of any release from spent fuel shipped in inner welded canisters from any impact or fire accident analyzed.
- The collective dose risk from loss of lead shielding is comparable to the collective dose risk from a release, though both are very small. The doses and collective dose risks from loss of lead shielding are larger than were calculated in NUREG/CR-6672 as a result of better precision in the finite element modeling and a more accurate model of the dose from a gap in the lead shield.
- The conditional risk of either a release or loss of shielding from a fire is negligible.
- The consequences (doses) of some releases and some loss of shielding scenarios that occur with extremely low probability are larger than cited in the regulation of 10 CFR 71.51, and are significant, but are neither acute nor lethal.

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CHAPTER 6

FINDINGS AND CONCLUSIONS

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The health and safety impacts of spent fuel transportation were first assessed by NRC as part of NUREG-0170, *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes*, published in 1977. Based on NUREG-0170, NRC concluded that the regulations in force at the time of the environmental impact statement (1981) were "adequate to protect the public against unreasonable risk from the transport of radioactive materials" (46 FR 21629, April 13, 1981). The present document presents the most recent NRC assessment of the risks of transporting commercial spent nuclear fuel. Both NUREG-0170 and this document estimate the radiological impact for spent fuel transport conducted in compliance with the regulations of 10 CFR Part 71. Other NRC studies, including the Modal Study (Fischer, et al., 1987) and NUREG/CR-6672 (Sprung, et al., 2000), also provided spent fuel shipment risk assessments.

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Regulations and regulatory compliance analyses are different from risk assessments. A regulation must be conservative because its purpose is to ensure safety, and 10 CFR Part 71, which regulates transportation, requires a conservative estimate (i.e., overestimate) of the damage to a cask in an accident and the radiation emitted from the cask during routine transportation. The original environmental assessment for 10 CFR Part 71, NUREG-0170, was also conservative, but for a different reason: only limited data were available to perform the assessment, so NUREG-0170 deliberately used conservative parameter estimates. The NRC's conclusion was that NUREG-0170 showed transportation of radioactive materials, even with conservative assumptions, to provide adequate public safety.

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When an assessment is used to inform regulation, it should be as realistic as possible to provide information needed to confirm or revise the regulations it informs. Realistic assessment depends on the data availability and accurate and precise modeling techniques that have become increasingly available in the years since 1977. Consequently, the Modal Study and NUREG/CR-6672 made good progress in assessing transportation risks more realistically. As a result, both the calculated consequences and risks of radioactive materials transportation decreased. The decrease in risk means that the regulations provide for a greater level of safety than previously recognized.

The present study is a more accurate analysis than the previous analyses. Certified spent fuel casks are analyzed, rather than generic designs. Recent (2005 or later) accident frequency data and population data are used in the analyses, and the modeling techniques have been upgraded as well. This study, the Spent Fuel Transportation Risk Assessment, is another step in building a complete picture of spent nuclear fuel transportation radiological safety. Also, it represents the current state of the art for such analyses. The results of this study are compared with preceding risk assessments in the figures that follow.

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6.1 Routine Transportation

Figure 6-1 and Figure 6-2 show results of routine truck and rail transportation of a single shipment of spent nuclear fuel. Figure 6-1 plots average collective radiation dose (person-Sv)

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from truck transportation, and Figure 6-2 plots average collective radiation dose from rail transportation. These average doses include the doses to the population along the route, doses to occupants of vehicles sharing the route, doses at stops, and doses to vehicle crew and other workers. Also shown are the doses without the crew and worker dose (labeled public only).

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Collective doses from routine transportation depend directly on the population along the route and the number of other vehicles that share the route, and inversely on the vehicle speed. Doses to occupants of vehicles that share the route depend inversely on the square of the vehicle speed.

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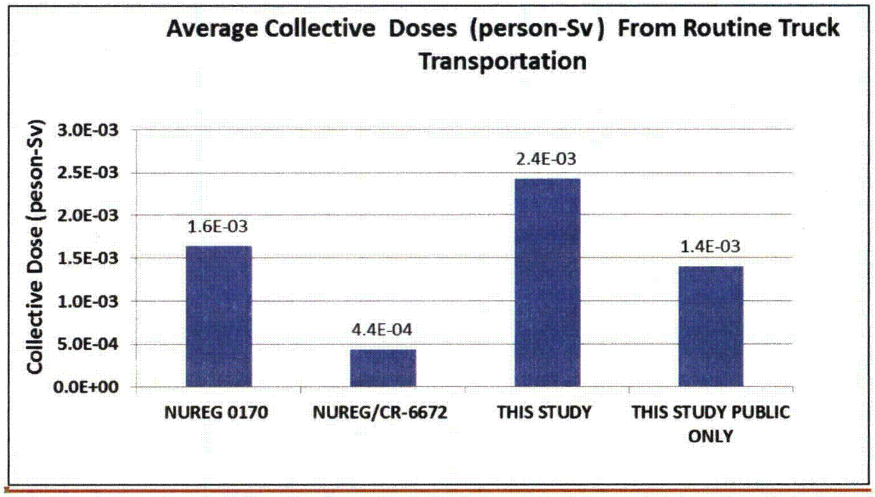

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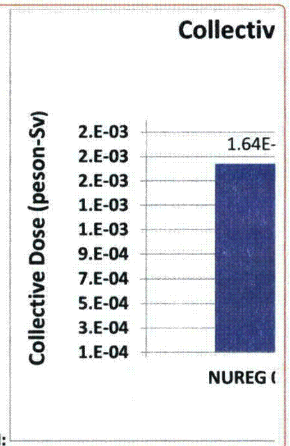

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Figure 6-1. Collective doses (person-Sv) from routine truck transportation.

The NUREG-0170 results for truck transportation were based on a single long route, constant values of rural, suburban, and urban population densities, on different and conservative vehicle speeds on rural, urban, and suburban roads, on a fixed rate of vehicle stops, and on 1975 estimates of vehicle density (vehicles per hour), all of which led to conservative results. NUREG/CR-6672 used more realistic distributed route lengths, population densities, vehicle occupancy and density, vehicle dose rate and stop time and used the means of the distributions as parameters. As shown in Figure 6-1, the conservatism was decreased by over a factor of three.

The collective average dose in the present study is larger than the NUREG/CR-6672 result because present populations are generally larger, particularly along rural routes, and the vehicle densities are much larger (see Chapter 2). These increases were offset by the greater vehicle speeds used in the present study. The largest contributor to higher doses in this study are the parameters used for stops. In this study stops were assumed to occur every 845 km vs. 1290 km and last for 50 minutes vs. 30 minutes. The combination of these two factors results in a 2.5 times increases in the stop dose. This is especially significant because the greatest contributor to the public collective dose is from people sharing the truck stops with the cask (56% of the collective dose). The second largest contributor is from people sharing the highway with the cask

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(38% of the collective dose). Residents along the route only receive 6% of the collective dose and residents near truck stops only 1%.

Figure 6-2 shows the differences between NUREG 0170, NUREG/CR-6672, and the present study for calculation of average doses to the public for routine rail transportation.

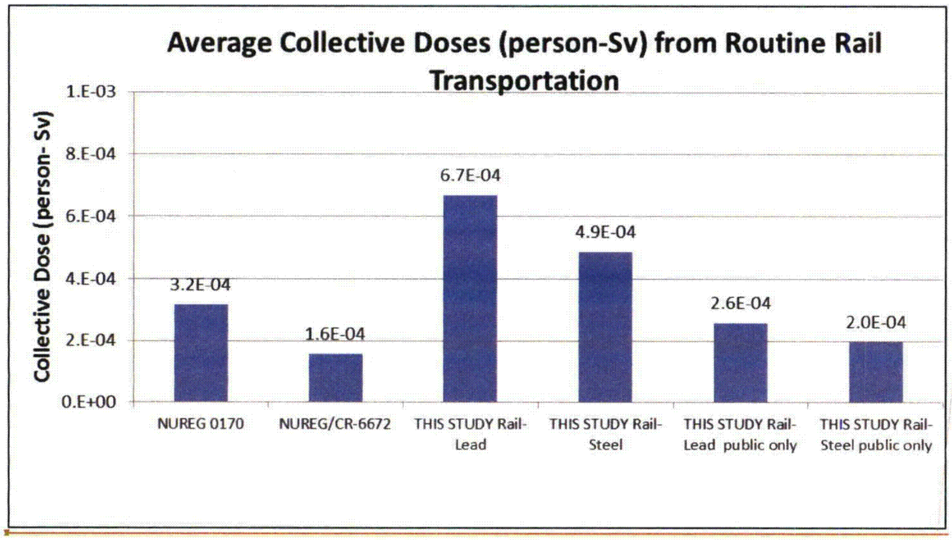


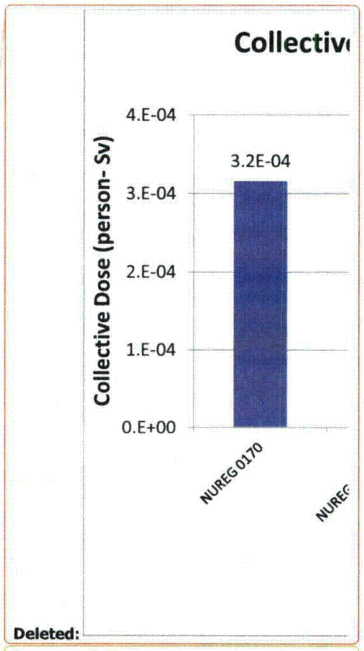
Figure 6-2. Collective doses (person-Sv) from routine rail transportation.

The difference in dose between the Rail-Lead cask and the Rail-steel cask occurs because the latter cask has a smaller external dose rate (Chapter 2). The differences in crew doses between the studies reflect the considerable difference between the methods used in the different studies.

The differences in the collective doses from routine transportation between the cited studies are not the result of differences in external radiation from the spent fuel casks. The 1975 version of 10 CFR Part 71[4] specified the same limit on external radiation (the transport index) as Part 71 specifies today.

The differences in results are due primarily to vehicle speed, population and vehicle densities, and differences in calculating train crew and railyard worker doses. These differences are summarized below.

- *Differences in vehicle speed.* The faster the cask moves past a receptor, the less that receptor is exposed. NUREG-0170 and NUREG/CR 6672 used 80 kph for all truck routes and 64 kph on rural rail routes, 40 kph on suburban rail routes, and 24 kph on urban rail routes. The truck



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speeds used in this study are 108 kph on rural routes, 102 kph on suburban routes, and 97 kph on urban routes, and the rail speed is 40 kph on rural and suburban routes and 24 kph on urban routes. The present speeds are based on data instead of the estimated values used in the previous studies.

- *Differences in populations along the routes.* NUREG-0170 used six persons per km^2 for rural populations, 719 per km^2 for suburban routes, and 3861 per km^2 for urban routes. NUREG/CR-6672 used 1990 census data provided by the codes HIGHWAY and INTERLINE and used the mean values of Gaussian distributions of population densities on 200 routes in the United States. This study uses 2000 census data provided by WebTRAGIS (Johnson and Michelhaugh, 2002), with some updates based on 2008 census data, for the rural, suburban, and urban truck and rail route segments in each state traversed for each of the sixteen origin/destination pairs studied. The variation from the NUREG-0170 values is considerable.

- *Differences in vehicles per hour on highways.* NUREG-0170 and NUREG/CR-6672 both used the 1975 values of 470 vehicles per hour on rural routes, 780 on suburban routes, and 2800 on urban routes. This study used 2002 state vehicle density data for each state traversed. The national average vehicle density is 1119 vehicles per hour on rural routes, 2464 on suburban routes, and 5384 on urban routes. This large difference in vehicle density contributes to the difference in collective doses for routine truck transportation between NUREG/CR-6672 and this study.

- *Differences in calculating doses to rail crew.* NUREG-0170 calculated doses to rail and railyard crew by estimating the distance between the container carrying radioactive material and the crew member. NUREG/CR-6672 used the Wooden (1980) calculation of doses to railyard workers, and did not calculate a dose to the crew on the train. This study calculated all doses using the formulations in RADTRAN 6, calculated an in-transit crew dose, used an updated value for the time of a classification stop (27 hours instead of 30 hours), and used in-transit stop times from WebTRAGIS rather than the stop dose formula, pegged to total trip length, used in NUREG/CR-6672. The in-transit crew dose calculated in this study was small enough that it contributed a negligible amount to these doses.

Dose to the maximally exposed individual is a better indication of the radiological effect of routine transportation than collective dose. The same event results in different collective doses depending on the population affected, which varies both spatially and temporally. The dose to the maximally exposed individual is shown in Figure 6-3 for NUREG-0170 and for the three cask types of this study. NUREG/CR-6672 did not calculate this dose for routine transportation.

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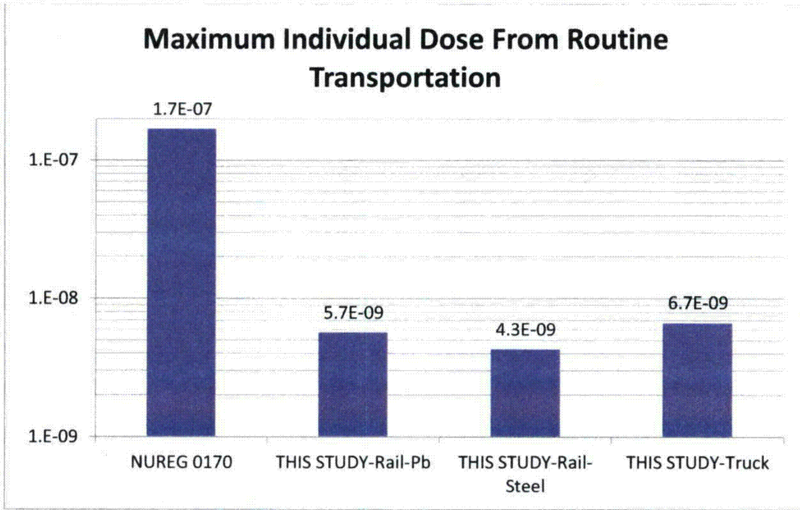

Figure 6-3. Maximum individual dose (Sv) from routine transportation.

6.2 Transportation Accidents

Radiological accident risk is expressed in units of "dose risk" that include the probability of an accident and the conditional probability of certain types of accidents. The units used are dose units (Sv) because probability is a unitless number. NUREG-0170, NUREG/CR-6672, and this study all used the version of RADTRAN available at the time of the study to calculate dose risk, but the input parameters differed widely. In addition, improvements in RADTRAN and in other modeling codes described in earlier chapters resulted in a more accurate analysis of cask behavior in an accident.

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The results shown in Figure 6-4 and Figure 6-5 for this study are averages over the 16 rail routes studied. As was discussed in Chapters 3, 4, and 5, a lead-shielded rail cask, the Rail-Lead cask in this study, is the only cask type of the three studied that resulted in either release radioactive material or can lose lead gamma shielding in an accident.

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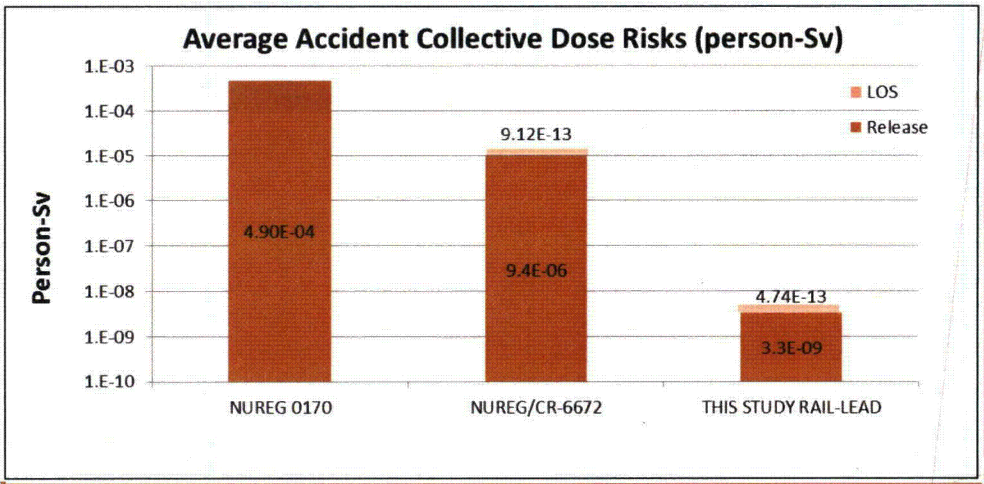

Figure 6-4. Accident collective dose risks from release and Loss of Shielding (LOS) accidents. The LOS bar representing the NUREG/CR-6672 collective dose is not to scale.

The results shown in Figure 6-4 reflect the different amounts of radioactive material released and different amounts of lead shielding lost as estimated in the respective studies. NUREG-0170 used a scheme of eight different accident scenarios, four of which postulated release of the entire releasable contents of the cask, two of which postulated no release, one postulated a ten percent release, and one postulated a one percent release. The range of conditional probabilities was from 1×10^{-5} for the most severe (100 percent release) accident to 80 percent for the two no-release accident scenarios. The NUREG-0170 "universe" of accidents and their consequences was based primarily on engineering judgment and was clearly conservative.

NUREG/CR-6672 analyzed the structural and thermal behavior of four generic cask designs—two truck and two rail casks—in great detail, and analyzed the behavior of the five groups that best describe the physical and chemical nature of the radioactive materials potentially released from the spent fuel through the casks. These five groups are particulate matter, semi-volatile substances, ruthenium, gas, and CRUD. The spent fuels considered were high burnup and low burnup PWR and BWR fuel. This analysis resulted in 19 truck accident scenarios and 21 rail accident scenarios, each with an attendant possibility, including a no-release scenario, with better than 99.99 percent probability.

The present study followed the analytical outline of the NUREG/CR 6672 analysis, but analyzed the structural and thermal behavior of a certified lead-shielded cask design loaded with fuel that the cask is certified to transport. Instead of the 19 truck scenarios and 21 rail scenarios that included potential releases of radioactive material, the current study resulted in only seven rail scenarios that included releases, as described in Chapters 3 and 5. The only parts of the cask structure that could be damaged enough to allow a release are the seals. Release could take place through the seals only if the seals fail and if the cask is carrying uncanistered fuel. No potential truck accident scenario resulted in seal failure, nor did any fire scenario. In the present study,

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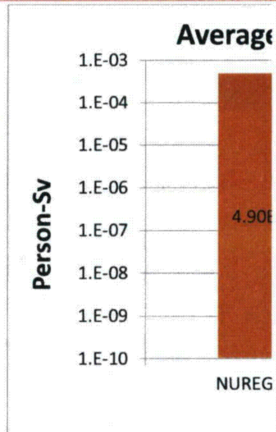

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only the Rail-Lead cask response to extremely severe accident conditions resulted in a release. A comparison of the collective dose risks from potential releases in this study to both NUREG-0170 and NUREG/CR-6672 is appropriate, since the latter two studies considered only potential releases. The collective dose risks decrease with each succeeding study as expected, since the overall conditional probability of release and the quantity of material potentially released decreases with each successive study. The decrease in release is due primarily to the replacement of conservative judgements of cask performance in an accident with finite element analysis of cask performance in an accident. Basically, in succeeding studies, the cask performs better (releases less) than estimated in previously.

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The collective dose risk from a release depends on dispersion of the released material, which then either remains suspended in the air, producing cloudshine, or is deposited on the ground, producing groundshine, or is inhaled. All three studies used the same basic Gaussian dispersion model in RADTRAN, although the RADTRAN 6 model is much more flexible than the previous versions and can model elevated releases. NUREG-0170 calculated only doses from inhaled and resuspended material. NUREG/CR-6672 included groundshine and cloudshine as well as inhaled material, but overestimated the dose from inhaled resuspended material. The combination of improved assessment of cask damage and improved dispersion modeling has resulted in the decrease in collective dose risk from releases shown in Figure 6-4.

Frequently, public interest in the transportation of spent nuclear fuel is focused solely on the consequences of possible accidents (without regard to the likelihood of the accident actually occurring). The maximum estimated consequence, based on average population density, from the accident with the largest release is 2.18 person-Sv. This consequence is orders of magnitude less than the 110 person-Sv in NUREG-0170 and the 9000 person-Sv estimated from Figure 8.27 in NUREG/CR-6672. The maximum dose any person could receive from this accident is 1.6 Sv, about the same dose that is received in a single radiotherapy session by a cancer patient.

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NUREG-0170 did not consider a loss of spent fuel cask lead shielding, which can result in a significant increase the dose from gamma radiation being emitted by the cask contents. NUREG/CR-6672 analyzed 10 accident scenarios in which the lead gamma shield could be compromised and calculated a fractional shield loss for each. An accident dose risk was calculated for each potential fractional shield loss.

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The present study followed the same general calculation scheme, but with a more sophisticated model of gamma radiation from the cask due to the damaged shield and with 18 potential accident scenarios instead of 10. Much of the difference between the NUREG/CR-6672 dose risks from a loss of shielding and this study is the inclusion of accident scenarios that have a higher conditional probability (i.e., accidents that are more likely to happen) than any such scenarios in NUREG/CR-6672. The consequence of a loss of lead shielding estimated in NUREG/CR-6672 Table 8.13 is 41,200 person-Sv, about 100 times the 690 person-Sv estimated in this study. Loss of lead shielding clearly affects only casks that have a lead gamma shield; casks using DU or thicker steel shielding would not be affected.

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More than 99.999 percent of potential accident scenarios do not affect the cask at all and would result in neither a release of radioactive material nor an increased dose from loss of lead shielding. However, these accidents would result in an increased external radiation dose from the

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cask to the population near the accident because the cask would remain at the location of the accident until it could be moved. A nominal ten hour delay in moving the cask was assumed for this study. The resulting collective dose risk from this accident is shown in Figure 6-5 for all three of the cask types studied. Even including this additional consequence type, the accident collective dose risk from this study is less than that reported in either NUREG-0170 or NUREG/CR-6672.

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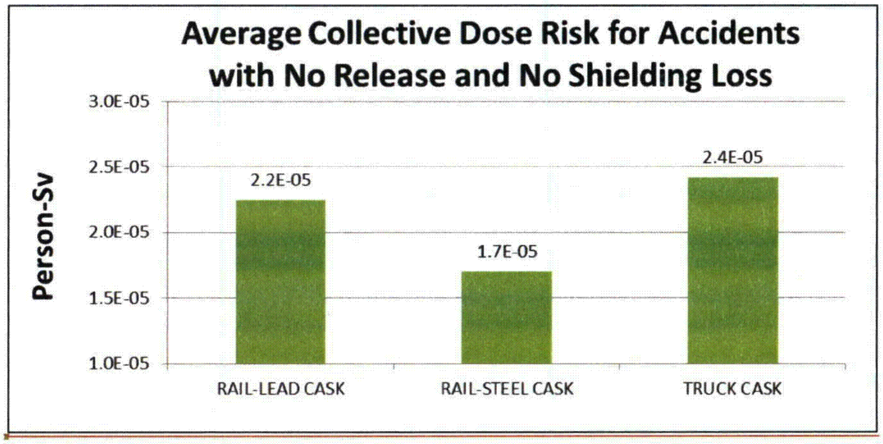

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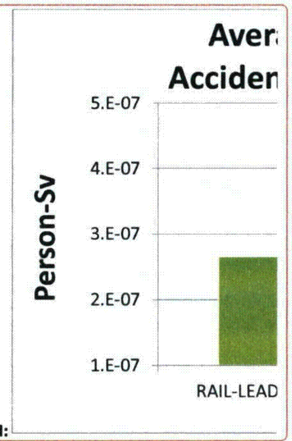

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Figure 6-5. Average collective dose from accidents that have no impact on the cargo.

In conclusion, each of the three transportation risk assessments conducted for the NRC show that the NRC regulation of transportation casks ensures safety and health. The use of data in place of engineering judgment shows that accidents severe enough to cause a loss of shielding or release of radioactive material are improbable and the consequences of such unlikely accidents would require mitigation, but would not result in large radiation doses to even the maximally exposed individual. Moreover, these consequences depend on the size of the population exposed rather than on the radiation or radioactive material released. The consequences (doses) to the maximally exposed individual, 1.6 Sv to a member of the public from a release and 1.1 Sv from loss of lead shielding to a possible first responder, might result in latent, but not immediate, health consequences.

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For accidents that do not involve either loss of shielding or release of material, the most significant consequence of an accident, in addition to any non-radiological consequence of the accident itself, is the external dose from a cask immobilized at the accident location. Average collective doses from this type of accident for the 16 truck routes and 16 rail routes studied are shown in Figure 6-5. The most significant parameters contributing to this dose are the accident frequency and the length of time that the cask sits at the accident location. Even in this case, the significant parameter in the radiological effect of the accident is not the amount or rate of radiation released, but the exposure time.

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6.3 Findings and Conclusion

The following findings are reached from this study:

- The collective dose risks from routine transportation are vanishingly small. Theses doses are about four to five orders of magnitude less than collective background radiation dose.
- The routes selected for this study adequately represent the routes for spent nuclear fuel transport, and there was relatively little variation in the risks per kilometer over these routes.
- Radioactive material would not be released in an accident if the fuel is contained in an inner welded canister inside the cask.
- Only rail casks without inner welded canisters would release radioactive material, and only then in exceptionally severe accidents.
- If there were an accident during a spent fuel shipment, there is only about one in a billion chance the accident would result in a release of radioactive material.
- If there were a release of radioactive material in a spent fuel shipment accident, the dose to the maximum exposed individual would be less than 2 Sv, about the dose given in a single radiotherapy treatment to cancer patients.
- The collective dose risks for the two types of extra-regulatory accidents (accidents involving a release of radioactive material and loss of lead shielding accidents) are negligible compared to the risk from a no-release, no-loss of shielding accident.
- The risk of either a release or loss of shielding from a fire is negligible.

Based on these findings, this study reconfirms that radiological impacts from spent fuel transportation conducted in compliance with NRC regulations are low, in fact generally less than previous, already low, estimates. Accordingly, with respect to spent fuel transportation, the previous NRC conclusion that the regulations for transportation of radioactive material are adequate to protect the public against unreasonable risk is also reconfirmed by this study.

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