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SPENT FUEL TRANSPORTATION RISK ASSESSMENT: TRANSPORTATION ACCIDENT ANALYSIS

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ABSTRACT

The NRC has recently completed an updated Spent Fuel Transportation Risk Assessment, NUREG-2125. This assessment considered four types of accidents that could interfere with routine transportation of spent nuclear fuel; those in which the spent fuel cask is not affected, those in which there is loss of lead gamma shielding, those in which radioactive material is released, and those that could result in a criticality event. The probability of a particular type of accident is the product of the probability that the vehicle carrying the spent fuel cask will be in an accident and the conditional probability that the accident will be of a certain type.

An accident in which the spent fuel cask is not damaged or affected at all is the most probable: 99.95 percent of vehicle accidents are less severe than the regulatory hypothetical accident and most accidents that are more severe than this still do not lead to loss of shielding or release. Loss of lead shielding or release of radioactive material occurs in less than one in a billion accidents. If a lead shielded cask is involved in one of these extremely rare impacts, the lead shield can slump, and a small section of the spent fuel in the cask will be shielded only by the steel shells. The resulting external doses are significant, but would result in neither acute illness nor death. The collective dose risks are vanishingly small. Consequences and risks of an accidental release of radioactive material are similar, since only very small amounts of material would be released, and only through damaged cask seals.

The study also examined the probabilities and risks associated with several “what if?” fire scenarios previously analyzed by the NRC and showed that even these types of events do not result in significant risks. In fact, inclusion of this type of event only increases the estimated risk by a small fraction.

Another accident type that is of potential concern is one that leads to a criticality event. This study has shown that the combination of factors necessary to produce such an event are so unlikely that the event is not credible

INTRODUCTION: TYPES OF ACCIDENTS AND INCIDENTS

The different types of accidents that can interfere with routine transportation of SNF 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 usually are called “incidents.”[1]

[1] In U.S. Department of Transportation terminology, 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 nonroutine transportation are “incidents.” This document uses the term “accident” for both accidents and incidents.

- Accidents that damage the vehicle or trailer enough so 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, or both, but no damage to the spent fuel cask.

- Accidents in which the spent fuel cask is affected.

  - Accidents resulting in the loss of lead gamma shielding or neutron shielding (or both), but no radioactive material is released.

  - Accidents in which radioactive material is released.

Accident risk is expressed as “dose risk,” the product of the radiation dose resulting from the accident and the probability of that accident. The units used for dose risk are Sv. When the consequence to an entire population is considered, the accident risk is expressed as “collective dose risk,” and the units are person-Sv.

When an accident happens at a particular spot along the route, the vehicle carrying the spent fuel cask stops.Therefore, there can only be one accident for a shipment; resumption of the shipment essentially is 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 to 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.

ACCIDENT PROBABILITIES

Quantitatively, 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 specific 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

- The conditional probability that the accident will be a certain type of accident.

The net accident probability is the product of the probability of an accident and the conditional probability of a particular type of accident.

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

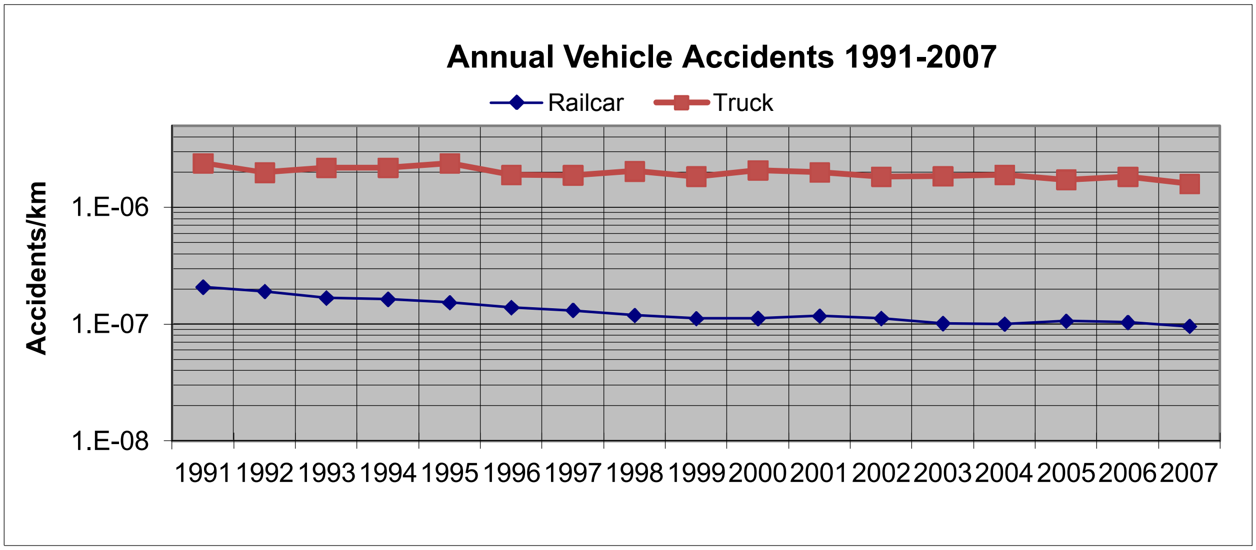


Figure 1 Accident frequencies in the U.S. from 1991 until 2007.

The only accidents in this study that could result in either loss of radiation shielding or release of radioactive material are rail accidents involving the Rail-Lead cask when fuel is directly loaded inside the cask (i.e., the fuel is not contained in a welded canister inside the cask). These accidents are listed below.

- Collisions with hard rock or equivalent at impact speeds greater than 97 kph (60 mph) that result in some loss of lead gamma radiation shielding or damage to the cask seals. Although hard rock is not necessarily an unyielding target, collision of a cask with hard rock is the only type of collision along a transportation route that could damage the cask sufficiently to result in the release of radioactive material or loss of lead shielding.

- Fires of long-enough duration to compromise the lead shielding or that cask seals.

Whether these accidents happen depends on the likelihood (conditional probability) of the accident scenario as well as on accident frequency. The event trees for truck and rail show some elements of accident scenarios in each branch of the respective event tree. The dependence on probability is illustrated in Figure 2, which shows the sequence of events necessary for a pool fire that can burn long enough to compromise the seals and lead shielding.

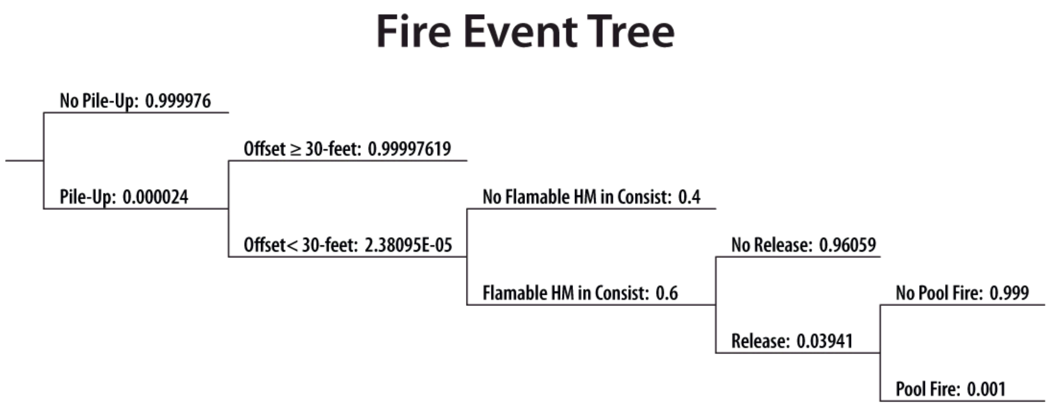


Figure 2 Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16)

Table 1 shows the conditional probabilities of accidents that could result in a radiation dose to a member of the public. The calculation of these probabilities is done using the typical method for risk assessments, but because of the large degree of safety that spent fuel casks provide, only extremely low probability events could lead to a radiation dose to the public. For these extremely low probability events, the results are reported to the precision of the calculation (to aid understanding of derivation of results), but they should be considered accurate only to the order of magnitude.

Table 1 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	8.3×10^{-10}
Loss of lead shielding from fire	10^{-14} to 10^{-10}
Radioactive materials release from impact	5.1×10^{-10}
Radioactive materials release from fire	0

[a] More than 99.999999 percent of potential accidents would result in neither loss of lead shielding nor a release of radioactive material.

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 the type with no release and no lead shielding loss is 99.999999 percent. The only type of cask that could lose gamma shielding is a lead-shielded cask such as 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, it 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.

Doses to emergency responders from an accident in which no material is released and no loss of lead gamma shielding are shown in Table 2, and collective dose risks to the public from this type of accident are shown in Tables 3 and 4. These radiation doses depend on the following:

- The external dose rate from the cask.
- A 10-hour stop (DOE, 2002) at the scene of the accident, until the vehicle and cask, or both, can be moved safely. Ten hours is believed to overstate the stop time for many accidents.
- An average distance of 5 meters (16.4 feet) between the cask and the first responders and others who remain with the cask.
- For collective dose risks, the average rural, urban, and suburban population densities for each route.

The radiation doses in Table 2 and dose risks in Tables 3 and 4 are the consequences of all Truck-DU accidents, all Rail-Steel accidents, and 99.999999 percent of the Rail-Lead accidents.

Table 2 Dose to an Emergency Responder[a] from a Cask in a No-Shielding Loss, No-Release Accident

Cask	Dose in Sv (mrem)	10-hour allowed dose in Sv (mrem) derived from the 1-hour dose in 10 CFR 71.51
Truck-DU	1.0×10^{-3} (100)	0.1 (10,000)
Rail-Lead	9.2×10^{-4} (92)	0.1 (10,000)
Rail-Steel	6.9×10^{-4} (69)	0.1 (10,000)

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

Tables 3 and 4 show collective dose risks in person-Sv for the 10-hour stop following the accident. The routes chosen are for illustrative purposes only. Doses are shown for rural, suburban, and urban segments of each route, but an accident only happens once on any route. Therefore, each listed dose risk is the collective dose residents on that route segment would receive if the accident happened at any spot on that type of route segment.

Table 3 Collective Dose Risks to the Public from a No-Shielding Loss, No-Release Accident Involving Rail Casks (Person-Sv) (1 Sv=10^{5} mrem)

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban [a]	Total	Rural	Suburban	Urban [a]	Total
MAINE YANKEE								
ORNL	3.1x10	5.3x10^{-5}	6.6x10	6.3x10	2.3x10	4.0x10^{-5}	5.0x10	4.8x10
DEAF	2.3x10	5.7x10^{-5}	6.8x10	6.6x10	1.7x10	4.3x10^{-5}	5.2x10	5.0x10
HANFORD	5.7x10	5.2x10^{-5}	6.3x10	6.4x10	4.3x10	3.9x10^{-5}	4.8x10	4.8x10
SKULL	2.8x10	5.1x10^{-5}	5.3x10	6.0x10	2.1x10	3.9x10^{-5}	4.0x10	4.5x10
KEWAUNEE								
ORNL	3.1x10	5.7x10^{-5}	7.2x10	6.8x10	2.3x10	4.3x10^{-5}	5.4x10	5.1x10
DEAF	1.5x10	6.1x10^{-5}	7.2x10	6.9x10	1.2x10	4.6x10^{-5}	5.4x10	5.2x10
HANFORD	1.5x10	5.3x10^{-5}	6.6x10	6.1x10	1.2x10	4.0x10^{-5}	5.0x10	4.6x10
SKULL	2.0x10^{-6}	6.2x10^{-5}	6.0x10^{-6}	7.0x10^{-5}	1.5x10^{-6}	4.7x10^{-5}	4.5x10^{-6}	5.3x10^{-5}
INDIAN POINT								
ORNL	2.6x10	7.2x10^{-5}	8.7x10	8.3x10	2.0x10	5.4x10^{-5}	6.6x10	6.3x10
DEAF	1.9x10	5.9x10^{-5}	7.5x10	6.9x10	1.4x10	4.5x10^{-5}	5.7x10	5.2x10
HANFORD	1.9x10	5.6x10^{-5}	7.2x10	6.5x10	1.4x10	4.3x10^{-5}	5.5x10	5.0x10
SKULL	2.2x10	6.0x10^{-5}	6.6x10	6.9x10	1.7x10	4.6x10^{-5}	5.0x10	5.2x10
IDAHO NATIONAL LAB								
ORNL	1.9x10	6.0x10^{-5}	5.8x10	6.8x10	1.4x10	4.6x10^{-5}	4.4x10	5.2x10
DEAF	8.0x10	6.0x10^{-5}	5.3x10	6.6x10	6.0x10	4.6x10^{-5}	4.0x10	5.0x10
HANFORD	1.0x10	6.0x10^{-5}	6.7x10	6.8x10	7.5x10	4.6x10^{-5}	5.1x10	5.2x10
SKULL	2.0x10	5.9x10^{-5}	7.1x10	6.8x10	1.5x10	4.4x10^{-5}	5.4x10	5.1x10
AVERAGE	2.3x10^{-6}	5.8x10^{-5}	6.7x10^{-6}	6.7x10^{-5}	1.7x10^{-6}	4.4x10^{-5}	5.1x10^{-6}	5.1x10^{-5}

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

Table 4 Collective Dose Risks to the Public from a No-Shielding Loss, No-Release Accident Involving a Truck Cask (Person-Sv) (1 Sv=10^5 mrem)

FROM	TO	Truck-DU			
		Rural	Suburban	Urban[a]	Total
MAINE YANKEE	ORNL	4.2×10^{-6}	7.2×10^{-5}	9.1×10^{-6}	8.5×10^{-5}
	DEAF SMITH	3.9×10^{-6}	6.7×10^{-5}	8.4×10^{-6}	7.9×10^{-5}
	HANFORD	3.2×10^{-6}	5.9×10^{-5}	8.4×10^{-6}	7.1×10^{-5}
	SKULL VALLEY	3.5×10^{-6}	6.1×10^{-5}	8.6×10^{-6}	7.3×10^{-5}
KEWAUNEE	ORNL	4.1×10^{-6}	6.6×10^{-5}	8.3×10^{-6}	7.8×10^{-5}
	DEAF SMITH	2.8×10^{-6}	6.2×10^{-5}	8.4×10^{-6}	7.3×10^{-5}
	HANFORD	2.2×10^{-6}	5.8×10^{-5}	8.4×10^{-6}	6.9×10^{-5}
	SKULL VALLEY	2.6×10^{-6}	5.9×10^{-5}	8.6×10^{-6}	7.0×10^{-5}
INDIAN POINT	ORNL	3.6×10^{-6}	6.7×10^{-5}	8.2×10^{-6}	7.9×10^{-5}
	DEAF SMITH	3.6×10^{-6}	6.7×10^{-5}	8.2×10^{-6}	7.9×10^{-5}
	HANFORD	2.7×10^{-6}	6.2×10^{-5}	8.4×10^{-6}	7.3×10^{-5}
	SKULL VALLEY	3.0×10^{-6}	6.4×10^{-5}	8.5×10^{-6}	7.6×10^{-5}
IDAHO NATIONAL LAB	ORNL	2.6×10^{-6}	5.5×10^{-5}	7.9×10^{-6}	6.6×10^{-5}
	DEAF SMITH	1.6×10^{-6}	6.2×10^{-5}	6.8×10^{-6}	7.0×10^{-5}
	HANFORD	1.4×10^{-6}	3.6×10^{-5}	5.2×10^{-6}	4.3×10^{-5}
	SKULL VALLEY	2.1×10^{-6}	6.2×10^{-5}	8.4×10^{-6}	7.3×10^{-5}
AVERAGE		2.9×10^{-6}	6.1×10^{-5}	8.1×10^{-6}	7.2×10^{-5}

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

The average individual U.S. background dose for 10 hours is 4.1×10^{-6} Sv (0.41mrem). 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 (13.8 person-mrem)
- 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 (382 person-mrem)
- urban: $(4.1\ 10^{-6}\ \text{Sv}) \times (2{,}682\ \text{persons/km}^2) \times \pi \times (0.8\ \text{km})^2 = 0.0221$ person-Sv (2,210 person-mrem)

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 because of the accident) to residents for the 10 hours following the accident would be

- rural: 0.000141 person-Sv (14.1 person-mrem)
- suburban: 0.003881 person-Sv (388.1 person-mrem)
- urban: 0.022108 person-Sv (2,210.8 person-mrem)

The background and accident collective doses would be indistinguishable from the collective background dose. Any dose to an individual is well below the dose that 10 CFR 71.51allows, which is to be expected.

Accidental Loss of Shielding

Type B transportation packages are designed to safely carry radioactive material and require shielding adequate to meet the external dose regulation of 10 CFR Part 71. SNF is extremely radioactive and requires shielding that absorbs gamma radiation and neutrons. The sum of the external radiation doses from gamma radiation and neutrons should not exceed 0.0001 Sv (10 mrem) per hour at 2 meters (6.7 feet) from the cask, as 10 CFR 71.47 stipulates.

Each SNF transportation cask analyzed uses a different material to serve as gamma shielding. They also may use different neutron shielding, but 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 that could have its effectiveness reduced in an accident. Lead is relatively soft as compared to DU or steel and melts at a considerably lower temperature (330 degrees C, 626 degrees F).

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. Figures 3 and 4 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 side 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 that 10 CFR 71.51 allows (0.01 Sv/hour (1 rem/hour) at 1 meter (3.3 feet) from the cask) occur when the lead shielding gap is more than 2 percent of the shield.

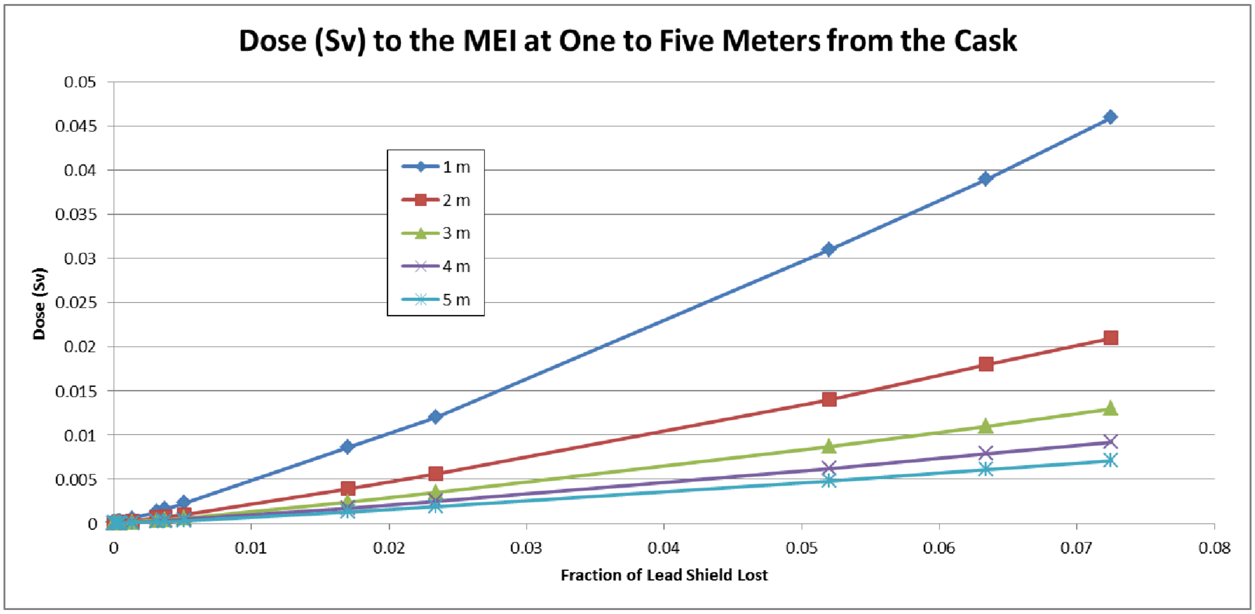


Figure 3 Radiation dose rates to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from 1 to 5 meters from the cask carrying spent fuel. The horizontal axis represents the fraction of shielding lost (the shielding gap). (1 m = 3.3 feet, 1 Sv = 10^5 mrem)

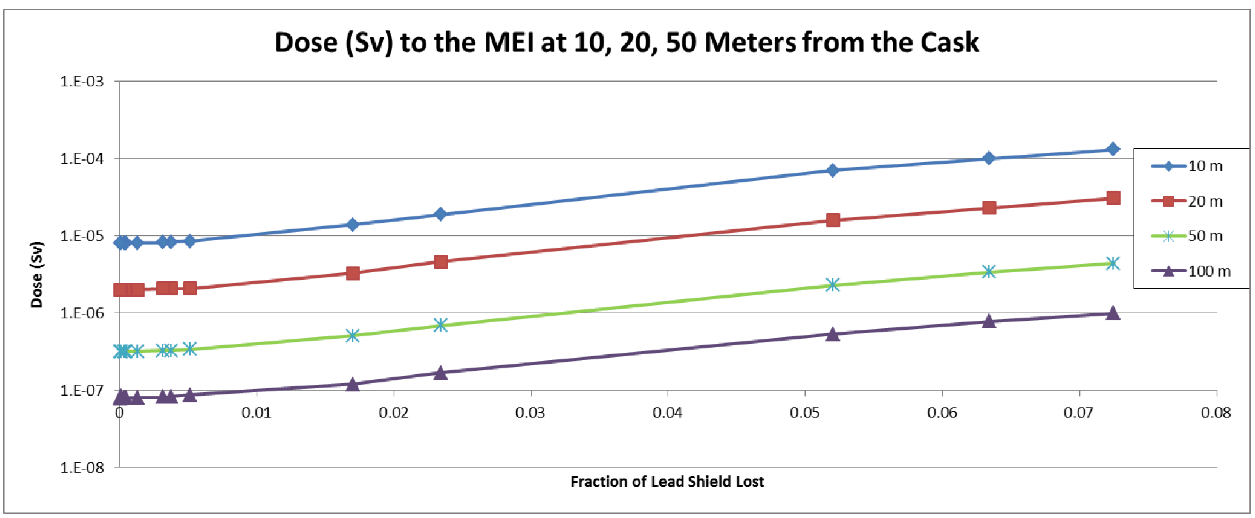


Figure 4 Radiation dose rates to the MEI from loss of lead gamma shielding at distances from 10 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic so that all of the doses can be shown on the same graph. The horizontal axis represents the fraction of shielding lost (the shielding gap) (1 m = 3.3 feet, 1 Sv = 10^5 mrem).

One in a billion accidents could cause loss of lead shielding that results in a dose rate exceeding the regulatory dose rate specified in 10 CFR 71.51. The "one in a billion" is a 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. For example, the probability that an accident resulting in lead shielding loss leading to a dose rate greater than 0.01 Sv/hr (1 rem/hr) will happen on the rail route from Maine Yankee Nuclear Plant site to Hanford is:

$$(8.3\times10^{-10})*(0.00214) = 1.74\times10^{-12}$$

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

This very small probability indicates that severe accidents, which are more traumatic to the cask than the tests shown in Figure 1-1, are unlikely to happen. Conditions that can cause enough lead shielding loss to result in radiation doses to the public above those that 10 CFR 71.51 allows are extreme conditions.

Table 5 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	0.00120
	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

The overall collective dose risks to the resident population from a lead shielding loss accident on the 16 rail routes studied are shown in Table 6. These include accidents in which resulting dose rates would be within regulatory limits. The expected dose to any member of the population along the routes, at least 10 meters (33 feet) 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 higher than along the other routes, and the rail accident rate per kilometer is an order of magnitude larger.

Table 6 Collective Dose Risks per Shipment in Person-Sv for a Loss of Lead Shielding Accident Involving a Lead-Shielded Rail Cask (1 Sv=10^5 mrem)

SHIPMENT ORIGIN	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.5×10^{-13}	2.7×10^{-13}	2.7×10^{-13}	2.6×10^{-13}
KEWAUNEE	1.0×10^{-13}	6.3×10^{-14}	5.4×10^{-14}	1.1×10^{-13}
INDIAN POINT	3.5×10^{-12}	2.4×10^{-13}	2.5×10^{-13}	2.7×10^{-13}
IDAHO NATIONAL LAB	9.9×10^{-14}	4.1×10^{-14}	2.1×10^{-14}	1.5×10^{-14}

The conditional probability that a lead shielding gap will occur after a fire involving the cask is about 10^{-19}. The conditional probability is so small because the following has to occur 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 resulting in a major derailment or 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 are never 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 approximately 1 in 10 billion.

The type of fuel that can be transported in the three casks considered has relatively low neutron emission but does require neutron shielding, usually a hydrocarbon or carbohydrate polymer that often contains a boron compound. All three of the casks studied have polymer neutron shields. Table 7 shows the total radiation dose resulting from a loss of neutron shielding to individuals who are approximately 5 meters from a fire-damaged cask for 10 hours. The dose allowed by 10

CFR 71.51 is provided for comparison. Neutrons are absorbed by air much better than gamma radiation; therefore, external neutron radiation would have an impact on receptors close to the cask but not on the general public.

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

Table 7 Doses to an Emergency Responder or Other Individual 5 Meters (16.4 feet) from the Cask for 10 Hours

Cask	Total Dose in Sv (mrem)	10-hour allowed total dose in Sv (mrem) from 10 CFR 71.51
Truck-DU	0.0073 (730)	0.1(10,000)
Rail-Lead	0.0076 (760)	0.1(10,000)
Rail-Steel	0.0076 (760)	0.1(10,000)

The neutron doses do not exceed the allowable dose cited in the regulation. These doses could result from a regulatory fire accident. 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. These occur, in part, because truck accidents always include a potential source of fuel (the gas tanks of the truck) whereas many railcar accidents do not involve the locomotive. They also occur, in part, because of the way the event trees were constructed. The truck event tree does not distinguish between minor fires and those 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).

The loss of neutron shielding produces a much smaller dose to an emergency responder than would happen if there was a loss of gamma shielding of 7 percent. The 10 hour dose to an emergency responder at 5 meters (16.4 feet) for the rail lead cask after a loss of neutron shielding accident from Table 7 is 0.0076 Sv (760 mrem), while the multiplying the 5-meter (16.4-foot) dose rate in Figure 3, 0.007 Sv/hr (700 mrem/hr) by the assumed ten-hour exposure time results in a dose of 0.07 Sv (7,000 mrem) after a loss of 7% of lead shielding accident. Both of these doses are probably overestimates of what would actually happen in either of these types of accidents because loss of shielding is relatively easy to mitigate, and such actions would likely take place before any extended emergency response activities close to the cask were carried out.

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 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 into the environment.

Spent nuclear fuel contains many different radionuclides. The amount of each fission product nuclide in the SNF depends on the type of reactor fuel, the enrichment when it was loaded into the reactor, burnup, and cooling time. Actinides produced in the reactor undergo radioactive decay, resulting in an increase in concentration of decay progeny. The fuel studied in this analysis is PWR fuel that has "burned" 45,000 MWD/MTU and cooled for 9 years. 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. The resulting inventory is shown in Table 8.

Table 8 Radionuclide Inventory for Accident Analysis of the Rail-Lead Cask

Radionuclide	Name	Form	Terabecquerels (TBq) 26 Assemblies	Curies (Ci) 26 Assemblies
^{241}Am	americium	particle	193	5,210
^{240}Pu	plutonium	particle	184	4,970
^{238}Pu	plutonium	particle	180	4,850
^{241}Pu	plutonium	particle	10,440	282,000
^{90}Y	yttrium	particle	40,400	1,090,000
^{90}Sr	strontium	particle	40,400	1,090,000
^{137}Cs	cesium	volatile	50,400	1,360,000
^{239}Pu	plutonium	particle	71.9	1,940
^{244}Cm	curium	particle	31.5	852
^{134}Cs	cesium	volatile	3030	81,800
^{154}Eu	europium	particle	146	3,950
^{106}Ru	ruthenium	particle	467	12,600
^{243}Cm	curium	particle	1.16	31.3
^{243}Am	americium	particle	0.995	26.9
^{144}Ce	cerium	particle	180	4,850
^{242}Pu	plutonium	particle	0.614	16.6
^{125}Sb	antimony	particle	431	11,600
^{155}Eu	europium	particle	607	16,400
^{242m}Am	americium	particle	0.163	4.40
^{242}Am	americium	particle	0.162	4.38
^{60}Co	cobalt	CRUD	55.6	1,500
^{125m}Te	tellurium	particle	105	2,840
^{234}U	uranium	particle	0.572	15.5
^{85}Kr	krypton	gas	3,340	90,100

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

Seven accident scenarios involving the Rail-Lead cask could result in material releases to the environment. Table 9 provides details of these scenarios pertinent to calculating the resulting doses. Sprung, et al. (2000) and NRC (2013, Appendix E) provide analytical details of the movement of radionuclide particles from fuel rods to the cask interior and from the cask interior to the environment. The last row in Table 9 provides the conditional probabilities of each of these releases. The total conditional probability that an accident will lead to a release for the cask using metal seals is 1.08×10^{-9} (or one in a billion accidents) and for the cask using elastomer seals it is 3.57×10^{-10}.

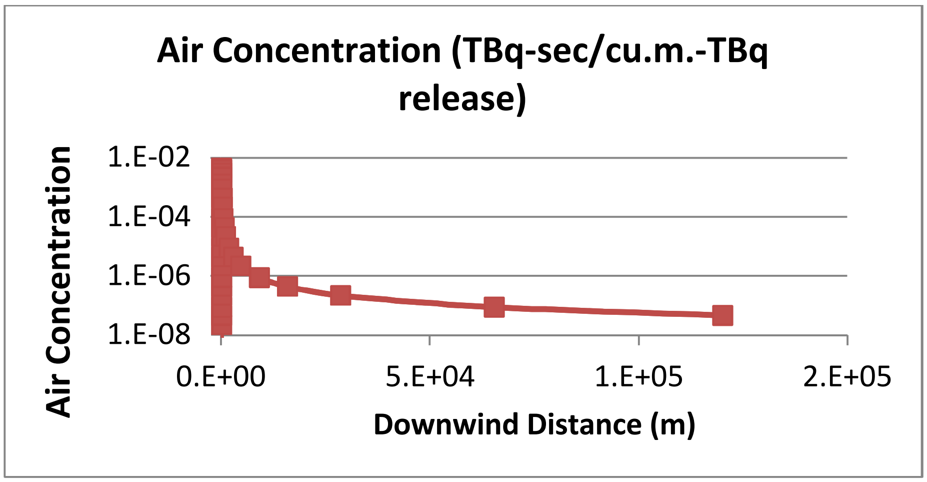
Table 9 Parameters for Determining Release Functions for the Accidents that Would Result in Release of Radioactive Material

	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	4.8×10^{-6}	4.8×10^{-6}	4.8×10^{-6}	4.8×10^{-6}	4.8×10^{-6}	4.8×10^{-6}	2.4×10^{-6}
	Volatiles	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	1.5×10^{-5}
	CRUD	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Conditional Probability	6.0×10^{-12}	3.6×10^{-11}	1.8×10^{-11}	1.8×10^{-11}	3.4×10^{-10}	3.4×10^{-10}	6.8×10^{-10}

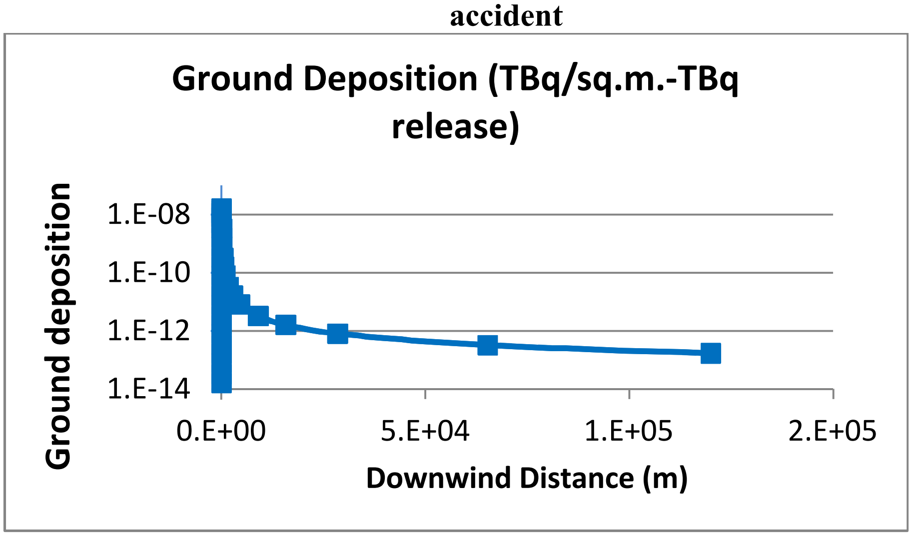
Material swept from the cask and released into the environment is dispersed by wind and weather. The dispersion is modeled using the accident model in RADTRAN 6, which is a Gaussian dispersion model. The release would be at about 1.5 meters above ground level since the cask is sitting on a railcar. The gas sweeping from the cask is warmer than ambient; therefore, the release is elevated. Under these conditions, the maximum ground level air concentration and deposition are 21 meters downwind from the release. The dispersion was modeled using neutral weather conditions (Pasquill: stability D, wind speed 4.7 m/sec (10.5 mph)). It was repeated using very stable meteorology (Pasquill: stability F, wind speed 0.5

m/sec (1.1 mph)), but the difference was negligible because of the relatively low elevation of the release. The MEI would be located directly downwind from the accident, 21 meters (69 feet) from the cask.

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

The dose from accidents that would involve a release is shown in Table 10.

Table 10 Doses (Consequences) in Sv to the Maximally Exposed Individual from Accidents that Involve a Release (1 Sv=10^5 mrem)

Cask Orientation	Impact Speed, kph (mph)	Seal Material	Inhalation	Re-suspension	Cloud-shine	Ground-shine	Total
End	193 (120)	metal	1.6	0.014	8.8×10^{-5}	9.4×10^{-4}	1.6
Corner	193 (120)	metal	1.6	0.014	8.8×10^{-5}	9.4×10^{-4}	1.6
Side	193 (120)	elastomer	1.6	0.014	8.8×10^{-5}	9.4×10^{-4}	1.6
Side	193 (120)	metal	1.6	0.014	8.8×10^{-5}	9.4×10^{-4}	1.6
Side	145 (90)	elastomer	1.6	0.014	4.5×10^{-6}	3.6×10^{-5}	1.6
Side	145 (90)	metal	1.6	0.014	8.8×10^{-5}	9.4×10^{-4}	1.6
Corner	145 (90)	metal	0.73	0.0063	5.1×10^{-5}	9.0×10^{-4}	0.74

The doses listed in Table 10 are consequences, not risks. The dose to the MEI is not the sum of the total doses because only one accident scenario can happen at a time. Each cask orientation is a different accident scenario and results in a set of internal (includes inhalation and resuspension) and external (includes cloudshine and groundshine) doses. The internal and external doses are listed separately because they have different physiological effects. 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.

The inhalation dose, including the dose from inhaled resuspended material, is a "committed" dose because the exposure is for as long as the radionuclide is in the body. The activity of the nuclide decreases exponentially as the nuclide decays. The NRC considers the total effective dose equivalent, which is the sum of the internal and external doses. The doses shown in Table 10 would not result in either acute illness or death (Shleien et al., 1998).

A pool fire co-located with the cask and burning for a long enough time could severely damage the seals. 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 most severe fire scenario analyzed is about 10^{-19}, 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 NRC has conducted several analyses of historic fire accidents making conservative assumptions regarding the placement of a cask within those fires (Adkins et al., 2006; Adkins et al., 2007, and Bajwa et al., 2012). In the case of the railroad tunnel fire similar to the Baltimore Tunnel Fire (Adkins et al., 2006) and based on the rail event tree and the fire branch in Figure 2, the conditional probability that a pool fire would occur in a tunnel is 7×10^{-9}. For this event to be as severe as that analyzed, the car carrying flammable liquid would need to be only one car away from the car carrying the spent fuel cask (DOT regulations require a buffer car between a spent fuel car and other freight). If we assume the train consist is formed randomly, the probability that the closest car to the cask car is carrying flammable hazardous material is 0.055 (from DOT, 2010). Combining these two probabilities gives a net conditional probability of a pool fire in a tunnel, as close as possible to a cask, of 4×10^{-10}. This probability does not include any information about the duration of that pool fire, but if it is assumed that all of these types of fires are as severe as the Baltimore Tunnel Fire, this number can be used to estimate the effect on the transportation risk assessment. Adkins et al. (2006) conservatively estimated that this fire could cause a release of 0.3 A_2 of material from a rail cask without an inner welded canister. This compares to the impact release of 8.4 A_2 with the same probability. Therefore, even with the conservative assumptions about the amount of release and the severity of the fire, including tunnel fires will only increase the accident collective dose risk by about 4%.

The MacArthur Maze highway fire (Bajwa et al., 2012) may lead to a release of radioactive material. The truck event tree in NRC (2013, Appendix E) does not provide sufficient data to determine the probability of this event, so investigation of the historical accident record is required. In the past twenty years there have been two fires similar to this one. There are about 400,000 large truck accidents each year (DOT, 2008, Table 2-23), so the probability that a severe tanker truck fire occurs below a bridge is approximately 3×10^{-7}. Neither of these two accidents involved another truck, which would be necessary for a spent fuel cask to be involved in the accident. From the truck event tree, the conditional probability of a collision with a gasoline tanker is 2.5×10^{-3}. Combining these two probabilities gives the conditional probability that a truck carrying a spent fuel cask is involved in a MacArthur Maze type event is 6×10^{-10}. For this event to cause a release, the spent fuel cask must also be co-located with the fire and not protected by intervening structures (the tractor, the truck bed, or the gasoline tanker). There is no statistical data to provide an estimate for this probability, but it is likely to be less than 0.05. Therefore, the probability of a fire like that analyzed in Bajwa et al. (2012) is less than 3×10^{-11}, a factor of 17 less probable than the impact accident that results in an 8.4 A_2 release. Therefore, this type of accident would not significantly change the results of this study unless it resulted in more than 140 A_2 of release.

Table 11 shows the total collective dose risk from the universe of release accidents. The accident with the most severe consequence could result in a release of 8.4 times the amount of radioactive material that can be transported in a container that is not accident resistant (8.4 A_2). Such an accident would result in a collective dose of 6.8 person-Sv to an exposed population of 58,000, calculated by multiplying RADTRAN output for dose and plume footprint area by a population density of 41.46 persons/km^2 (107.4 persons/mi^2) (the U.S. average minus Alaska). Of the three casks in this study, only the Rail-Lead cask could result in a release in each type of accident considered.

The dose risks in Table 11 are negligible by any standard.

Table 11 Total Collective Dose Risk (Person-Sv) for Release Accidents per Shipment for Each Route (1 Sv=10^5 mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.5×10^{-14}	4.1×10^{-14}	3.2×10^{-14}	3.0×10^{-14}
KEWAUNEE	1.8×10^{-14}	1.2×10^{-14}	5.4×10^{-15}	1.4×10^{-14}
INDIAN POINT	1.5×10^{-11}	5.9×10^{-13}	5.3×10^{-13}	1.9×10^{-13}
IDAHO NATIONAL LAB	9.4×10^{-14}	1.5×10^{-13}	4.1×10^{-14}	2.7×10^{-13}

The dose risks in Table 6, loss of lead shielding, are comparable to the dose risk from an accident involving a release (Table 11). Table shows the total dose risk for release and loss of lead shielding; it shows the sum of Tables 6 and 11 for each route.

Table 12 Total Collective Dose Risk (Person-Sv) from Release and Loss of Lead Shielding Accidents (1 Sv=10^5 mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.8×10^{-13}	3.1×10^{-13}	3.0×10^{-13}	2.9×10^{-13}
KEWAUNEE	1.2×10^{-13}	7.6×10^{-14}	5.9×10^{-14}	1.2×10^{-13}
INDIAN POINT	1.9×10^{-11}	8.3×10^{-13}	7.9×10^{-13}	4.6×10^{-13}
IDAHO NATIONAL LAB	1.9×10^{-13}	1.9×10^{-13}	6.1×10^{-14}	2.9×10^{-13}

Table 13 shows the total collective dose risk for an accident involving the Rail-Lead shielded cask in which there is no loss of lead shielding or release. Since the collective dose risk for this type of accident depends on 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 10 hours.

The dose risks displayed in Table 13 are about eight orders of magnitude larger than the dose risks shown in Table 12, reflecting the difference in the probabilities of the two types of accidents.

Table 13 Total Collective Dose Risk (Person-Sv) from No-Release, No-Loss of Shielding Accidents Involving the Rail-Lead Cask (1 Sv=10^5 mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	$6.3x10^{-5}$	$6.6x10^{-5}$	$6.4x10^{-5}$	$6.0x10^{-5}$
KEWAUNEE	$6.8x10^{-5}$	$6.9x10^{-5}$	$6.1x10^{-5}$	$7.0x10^{-5}$
INDIAN POINT	$8.3x10^{-5}$	$6.9x10^{-5}$	$6.5x10^{-5}$	$6.9x10^{-5}$
IDAHO NATIONAL LAB	$6.8x10^{-5}$	$6.6x10^{-5}$	$6.8x10^{-5}$	$6.8x10^{-5}$

Table 14 shows the collective accident dose risk for the 16 rail routes from loss of neutron shielding for the Rail-Lead cask.

Table 14 Total Collective Dose Risk (Person-Sv) from Loss of Neutron Shielding for Accidents Involving the Rail-Lead Cask (1 Sv=10^5 mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	$8.90x10^{-14}$	$1.16x10^{-13}$	$1.13x10^{-13}$	$1.12x10^{-13}$
KEWAUNEE	$3.48x10^{-14}$	$3.41x10^{-14}$	$3.72x10^{-14}$	$5.46x10^{-14}$
INDIAN POINT	$6.94x10^{-13}$	$1.13x10^{-13}$	$1.14x10^{-13}$	$1.22x10^{-13}$
IDAHO NATIONAL LAB	$5.88x10^{-14}$	$3.48x10^{-14}$	$1.09x10^{-14}$	$7.15x10^{-15}$

Potential Criticality

Spent fuel casks are required to demonstrate that they will remain subcritical following the hypothetical accident sequence of 10CFR71.73. In a transportation risk assessment, it must also be determined if the cask remains subcritical following more severe accidents. Because spent fuel casks are under moderated (Elam et al., 2003) a criticality event requires the addition of moderator (water) into the cask. For water to get into the cask there must be a failure in the seals. In the accidents investigated in this study, only impacts into hard rock surfaces at speeds greater than 93 kph (60 mph) have the potential for failing the seals. Impacts into water at speeds up to the maximum recorded accident speed cannot cause a seal failure due to the lack of shear strength of the water. Therefore, for addition of moderator to be possible the cask would have to first impact a hard rock surface and then fall into a body of water. Even if the cask fell into a body of water after an impact caused the seal to fail, it would have to be in the right configuration for sufficient water to enter the cask that moderation is possible. The starting conditional probability for this is $4x10^{-10}$ accidents that produce a seal failure. The rail event tree does not provide any information about the probability of water, but the truck event tree gives 0.009 as the probability that there is water under a bridge. This is likely an over estimation of the chance that there is water near hard rock surface. Even if water is present, the cask must rebound from the hard rock surface in such a way that it lands in the water. Then, if it lands in the water, the water must be deep enough to submerge the cask. Combined, the conditional probability that the cask gets flooded if there is a seal failure has to be less than 10^{-5}. Even this is not a sufficient condition for there to be a criticality event. The fuel rubble must still be arranged in a manner that supports criticality. Given these extremely low probabilities, it can be deduced that a criticality event is not credible.

SUMMARY

The conclusions that can be drawn from the risk assessment that apply to the three types of casks studied as presented in this chapter are listed below.

- The 16 truck and 16 rail routes selected for study are an adequate representation of U.S. routes for SNF transportation, and there was relatively little variation in the risks per kilometer over these routes.

- The overall collective dose risks are very 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 smaller than those calculated in Sprung, et al, (2000) because of better precision in the FE 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 lead shielding from a fire is negligible.

- The consequences (doses) of some releases and some loss of lead shielding scenarios that occur with extremely low probability are larger than those cited in 10 CFR 71.51; but would not result in an acute lethality. Only one in a billion accidents would result in these doses.

REFERENCES

Adkins, H.E., Cuta, J.M., Koeppel, B.J., Guzman, A.D., and Bajwa, C.S., "Spent Fuel Transportation Package Response to the Tunnel Fire Scenario," NUREG/CR-6886, Revision 2, PNNL-15313, Pacific Northwest National Laboratory, Richland, WA, November 2006.

Adkins, H.E., Koeppel, B.J., Cuta, J.M., Guzman, A.D., and Bajwa, C.S., "Spent Fuel Transportation Package Response to the Caldecott Tunnel Fire Scenario," NUREG/CR-6894, Revision 1, PNNL-15346, Pacific Northwest National Laboratory, Richland, WA, January 2007.

Bajwa, C.S., Easton, E.P., Adkins, H., Cuta, J. Klymyshyn, N., and Suffield, S., "Effects of the MacArthur Maze Fire and Roadway Collapse on a Spent Nuclear Fuel Transportation Package," *Proceedings of the 2011 Waste Management Conference*, Phoenix, AZ, February 27–March 3, 2011.

Shleien, B., Slaback, L.S., and Birky, B.K., *Handbook of Health Physics and Radiological Health*, Third Ed., Williams and Wilkins, Baltimore, MD, 1998.

Sprung, J.L., Ammerman, D.J., Breivik, N.L., Dukart, R.J., Kanipe, F.L., Koski, J.A., Mills, G.S., Neuhaiuser, K.S., Radloff, H.D., Weiner, R.F., and Yoshimura, H.R., "Re-Examination of Spent Fuel Risk Estimates," NUREG/CR-6672, Sandia National Laboratories, Albuquerque, NM, 2000.

U.S. Code of Federal Regulations, "Packaging and Transportation of Radioactive Material," Part 71, Chapter 1, Title 10, "Energy."

U.S. Department of Energy, "Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada," DOE/EIS-0250F, Washington, DC, Chapter 6 and Appendix J, 2002.

U.S. Department of Transportation, "National Transportation Statistics 2008," Bureau of Transportation Statistics, Research, and Innovative Technology Administration, Washington, DC, 2008.

U.S.. Nuclear Regulatory Commission, "Spent Fuel Transportation Risk Assessment" NUREG 2125, Nuclear Regulatory Commission, Rockville, MD, 2013.

Volpe Center, "Spent Nuclear Fuel Transportation Risk," Draft Report, Volpe National Transportation Systems Center, Cambridge, MA, 2006.