

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, which occur in fewer than one accident in a billion. If a lead shielded cask is involved in one of these 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 possible fire scenarios previously analyzed by the NRC, and showed that even such events do not result in significant risks. Inclusion of such events increases the estimated risk by only 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 is 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 Spent Nuclear Fuel (SNF) are:

- Accidents in which the spent fuel cask is not damaged or affected.

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- Minor traffic accidents (“fender-benders,” flat tires) resulting in minor damage to the vehicle. These usually are called “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. Dose units, sieverts (Sv) or rem, are used to express dose risk. When the consequence to an entire population is considered, the accident risk is expressed as “collective dose risk,” and the units are person-Sv or person-rem.

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 U.S. Department of Transportation

[†] 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.

(DOT) and reported by the DOT 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) and show a significant decline 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.

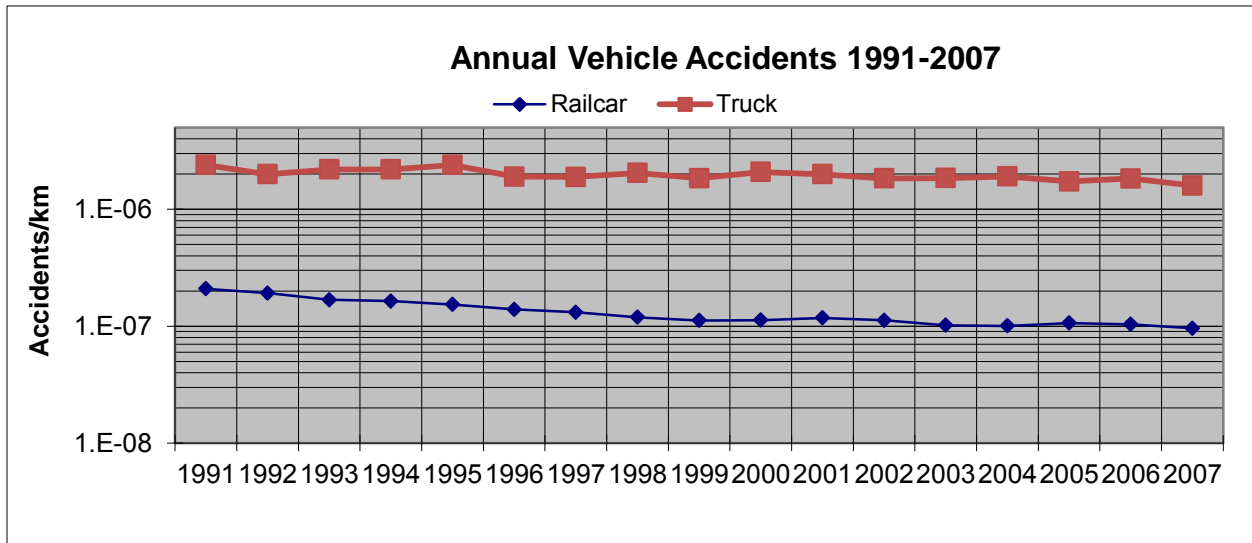


Figure 1. Accident frequencies in the U.S. from 1991 until 2007.

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) (NRC, 2012, Appendix V). 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.

The likelihood of a specific accident, like a fire or collision with hard rock, depends on the probability of an accident and the conditional probability of the specific accident. The event trees for truck and rail (NRC, 2012, Appendix V, Figures V-1 and V-2) 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 lead shielding.

Fire Event Tree

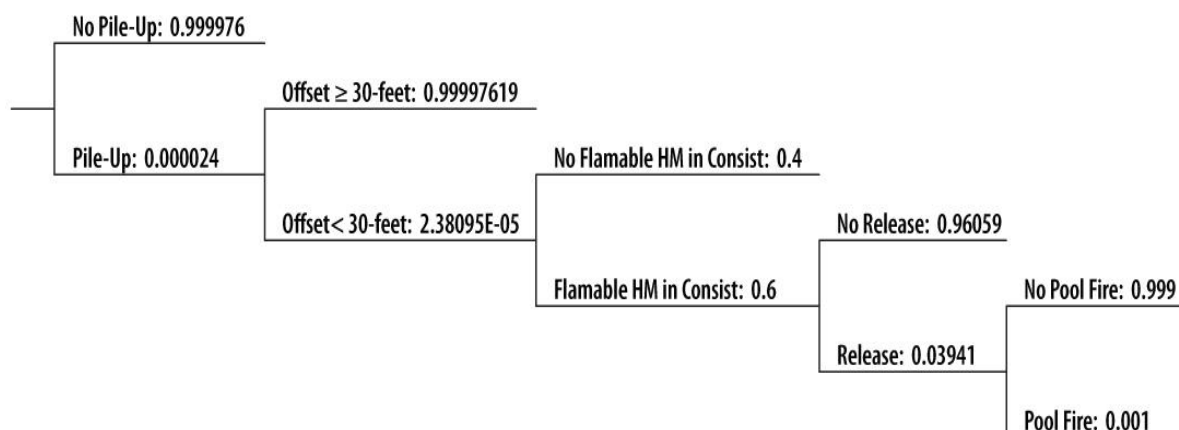


Figure 2. Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16)

Table 1 shows the conditional probabilities of accidents that could result in a radiation dose to a member of the public. Spent fuel casks provide a large degree of safety and only extremely low probability events could result in a radiation dose sustained by members of the public. The results of analyzing the risks of such low probability events are reported to the precision of the calculation, 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 (NRC, 2012, Table 5-2).

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 (NRC, 2012, Table 5-2). 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 NUREG-2125. 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=10⁵ mrem)

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban ^a	Total	Rural	Suburban	Urban ^a	Total
MAINE YANKEE								
ORNL	3.1x10 ⁻⁶	5.3x10 ⁻⁵	6.6x10 ⁻⁶	6.3x10 ⁻⁵	2.3x10 ⁻⁶	4.0x10 ⁻⁵	5.0x10 ⁻⁶	4.8x10 ⁻⁵
DEAF	2.3x10 ⁻⁶	5.7x10 ⁻⁵	6.8x10 ⁻⁶	6.6x10 ⁻⁵	1.7x10 ⁻⁶	4.3x10 ⁻⁵	5.2x10 ⁻⁶	5.0x10 ⁻⁵
HANFORD	5.7x10 ⁻⁶	5.2x10 ⁻⁵	6.3x10 ⁻⁶	6.4x10 ⁻⁵	4.3x10 ⁻⁶	3.9x10 ⁻⁵	4.8x10 ⁻⁶	4.8x10 ⁻⁵
SKULL VALLEY	2.8x10 ⁻⁶	5.1x10 ⁻⁵	5.3x10 ⁻⁶	6.0x10 ⁻⁵	2.1x10 ⁻⁶	3.9x10 ⁻⁵	4.0x10 ⁻⁶	4.5x10 ⁻⁵
KEWAUNEE								
ORNL	3.1x10 ⁻⁶	5.7x10 ⁻⁵	7.2x10 ⁻⁶	6.8x10 ⁻⁵	2.3x10 ⁻⁶	4.3x10 ⁻⁵	5.4x10 ⁻⁶	5.1x10 ⁻⁵
DEAF	1.5x10 ⁻⁶	6.1x10 ⁻⁵	7.2x10 ⁻⁶	6.9x10 ⁻⁵	1.2x10 ⁻⁶	4.6x10 ⁻⁵	5.4x10 ⁻⁶	5.2x10 ⁻⁵
HANFORD	1.5x10 ⁻⁶	5.3x10 ⁻⁵	6.6x10 ⁻⁶	6.1x10 ⁻⁵	1.2x10 ⁻⁶	4.0x10 ⁻⁵	5.0x10 ⁻⁶	4.6x10 ⁻⁵
SKULL VALLEY	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 ⁻⁶	7.2x10 ⁻⁵	8.7x10 ⁻⁶	8.3x10 ⁻⁵	2.0x10 ⁻⁶	5.4x10 ⁻⁵	6.6x10 ⁻⁶	6.3x10 ⁻⁵
DEAF	1.9x10 ⁻⁶	5.9x10 ⁻⁵	7.5x10 ⁻⁶	6.9x10 ⁻⁵	1.4x10 ⁻⁶	4.5x10 ⁻⁵	5.7x10 ⁻⁶	5.2x10 ⁻⁵
HANFORD	1.9x10 ⁻⁶	5.6x10 ⁻⁵	7.2x10 ⁻⁶	6.5x10 ⁻⁵	1.4x10 ⁻⁶	4.3x10 ⁻⁵	5.5x10 ⁻⁶	5.0x10 ⁻⁵
SKULL VALLEY	2.2x10 ⁻⁶	6.0x10 ⁻⁵	6.6x10 ⁻⁶	6.9x10 ⁻⁵	1.7x10 ⁻⁶	4.6x10 ⁻⁵	5.0x10 ⁻⁶	5.2x10 ⁻⁵
IDAHO NATIONAL LAB								
ORNL	1.9x10 ⁻⁶	6.0x10 ⁻⁵	5.8x10 ⁻⁶	6.8x10 ⁻⁵	1.4x10 ⁻⁶	4.6x10 ⁻⁵	4.4x10 ⁻⁶	5.2x10 ⁻⁵
DEAF	8.0x10 ⁻⁷	6.0x10 ⁻⁵	5.3x10 ⁻⁶	6.6x10 ⁻⁵	6.0x10 ⁻⁷	4.6x10 ⁻⁵	4.0x10 ⁻⁶	5.0x10 ⁻⁵
HANFORD	1.0x10 ⁻⁶	6.0x10 ⁻⁵	6.7x10 ⁻⁶	6.8x10 ⁻⁵	7.5x10 ⁻⁷	4.6x10 ⁻⁵	5.1x10 ⁻⁶	5.2x10 ⁻⁵
SKULL VALLEY	2.0x10 ⁻⁶	5.9x10 ⁻⁵	7.1x10 ⁻⁶	6.8x10 ⁻⁵	1.5x10 ⁻⁶	4.4x10 ⁻⁵	5.4x10 ⁻⁶	5.1x10 ⁻⁵
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=10⁵ mrem)

FROM	TO	Truck-DU			
		Rural	Suburban	Urban ^a	Total
MAINE YANKEE	ORNL	4.2x10 ⁻⁶	7.2x10 ⁻⁵	9.1x10 ⁻⁶	8.5x10 ⁻⁵
	DEAF SMITH	3.9x10 ⁻⁶	6.7x10 ⁻⁵	8.4x10 ⁻⁶	7.9x10 ⁻⁵
	HANFORD	3.2x10 ⁻⁶	5.9x10 ⁻⁵	8.4x10 ⁻⁶	7.1x10 ⁻⁵
	SKULL VALLEY	3.5x10 ⁻⁶	6.1x10 ⁻⁵	8.6x10 ⁻⁶	7.3x10 ⁻⁵
KEWAUNEE	ORNL	4.1x10 ⁻⁶	6.6x10 ⁻⁵	8.3x10 ⁻⁶	7.8x10 ⁻⁵
	DEAF SMITH	2.8x10 ⁻⁶	6.2x10 ⁻⁵	8.4x10 ⁻⁶	7.3x10 ⁻⁵
	HANFORD	2.2x10 ⁻⁶	5.8x10 ⁻⁵	8.4x10 ⁻⁶	6.9x10 ⁻⁵
	SKULL VALLEY	2.6x10 ⁻⁶	5.9x10 ⁻⁵	8.6x10 ⁻⁶	7.0x10 ⁻⁵
INDIAN POINT	ORNL	3.6x10 ⁻⁶	6.7x10 ⁻⁵	8.2x10 ⁻⁶	7.9x10 ⁻⁵
	DEAF SMITH	3.6x10 ⁻⁶	6.7x10 ⁻⁵	8.2x10 ⁻⁶	7.9x10 ⁻⁵
	HANFORD	2.7x10 ⁻⁶	6.2x10 ⁻⁵	8.4x10 ⁻⁶	7.3x10 ⁻⁵
	SKULL VALLEY	3.0x10 ⁻⁶	6.4x10 ⁻⁵	8.5x10 ⁻⁶	7.6x10 ⁻⁵
IDAHO NATIONAL LAB	ORNL	2.6x10 ⁻⁶	5.5x10 ⁻⁵	7.9x10 ⁻⁶	6.6x10 ⁻⁵
	DEAF SMITH	1.6x10 ⁻⁶	6.2x10 ⁻⁵	6.8x10 ⁻⁶	7.0x10 ⁻⁵
	HANFORD	1.4x10 ⁻⁶	3.6x10 ⁻⁵	5.2x10 ⁻⁶	4.3x10 ⁻⁵
	SKULL VALLEY	2.1x10 ⁻⁶	6.2x10 ⁻⁵	8.4x10 ⁻⁶	7.3x10 ⁻⁵
AVERAGE		2.9x10 ⁻⁶	6.1x10 ⁻⁵	8.1x10 ⁻⁶	7.2x10 ⁻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 Sv)×(16.8 persons/km²)×π×(0.8 km)² = 0.000138 person-Sv (13.8 person-mrem)
- suburban: (4.1 10⁻⁶ Sv)×(463 persons/km²)×π×(0.8 km)² = 0.00382 person-Sv (382 person-mrem)
- urban: (4.1 10⁻⁶ Sv)×(2,682 persons/km²)×π×(0.8 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 background collective dose. Any dose to an individual is well below the dose that 10 CFR 71.51 allows, which is to be expected.

ACCIDENTAL LOSS OF SHIELDING

Type B transportation packages are designed to carry radioactive material safely and require shielding adequate to meet the external dose regulation of 10 CFR Part 71. The sum of the external radiation doses from gamma radiation and neutrons should not exceed 0.0001 Sv (10 mrem) per hour at two 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, and may use different neutron shielding, which 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 depleted uranium (DU) for gamma shielding. Neither DU nor adequately thick steel would lose their effectiveness in an accident. The effectiveness of the lead gamma shield of the Rail-Lead cask, however, could be reduced in an accident if the accident resulted in thinning or distortion of the lead shield. Lead is soft 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 (Figures 5-2 and 5-3 of NRC, 2012) show the maximum individual radiation dose at various distances from the damaged cask for a range of gaps in the lead shield. Figure 3 shows that doses larger than the external dose that 10 CFR 71.51 allows (0.01 Sv/hour (1 rem/hour) at one meter (3.3 feet) from the cask) occur when the lead shielding gap is more than two percent of the shield.

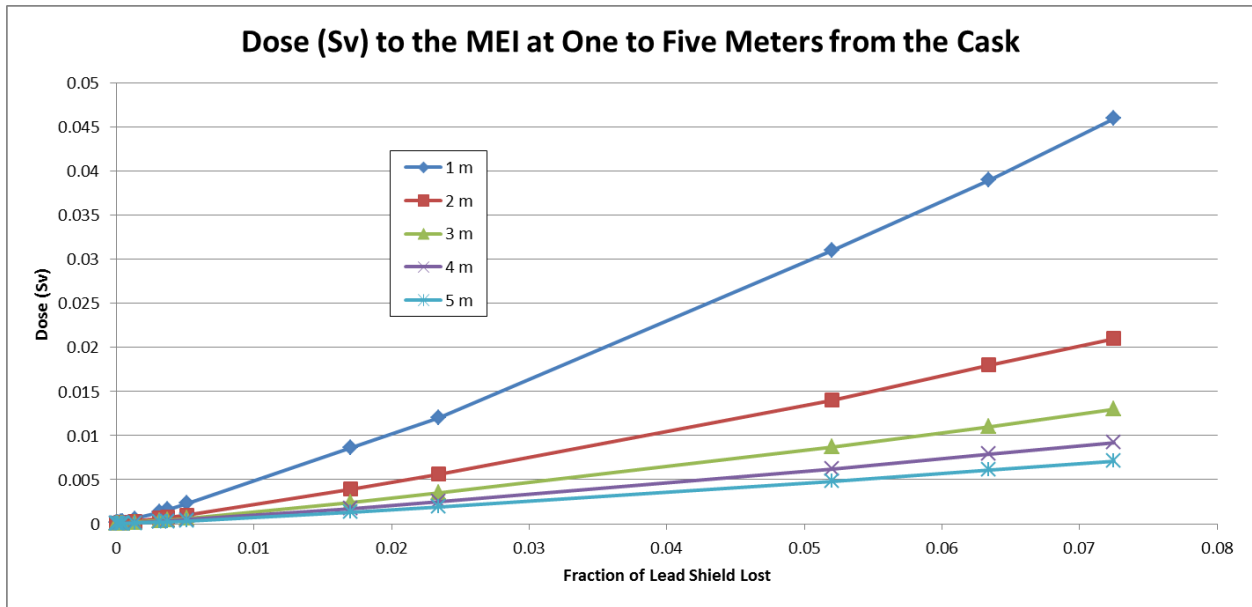


Figure 3. Radiation dose rates to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from 1 to 5 meters from the cask carrying spent fuel. The horizontal axis represents the fraction of shielding lost (the shielding gap). (1 m = 3.3 feet, 1 Sv = 10⁵ mrem)

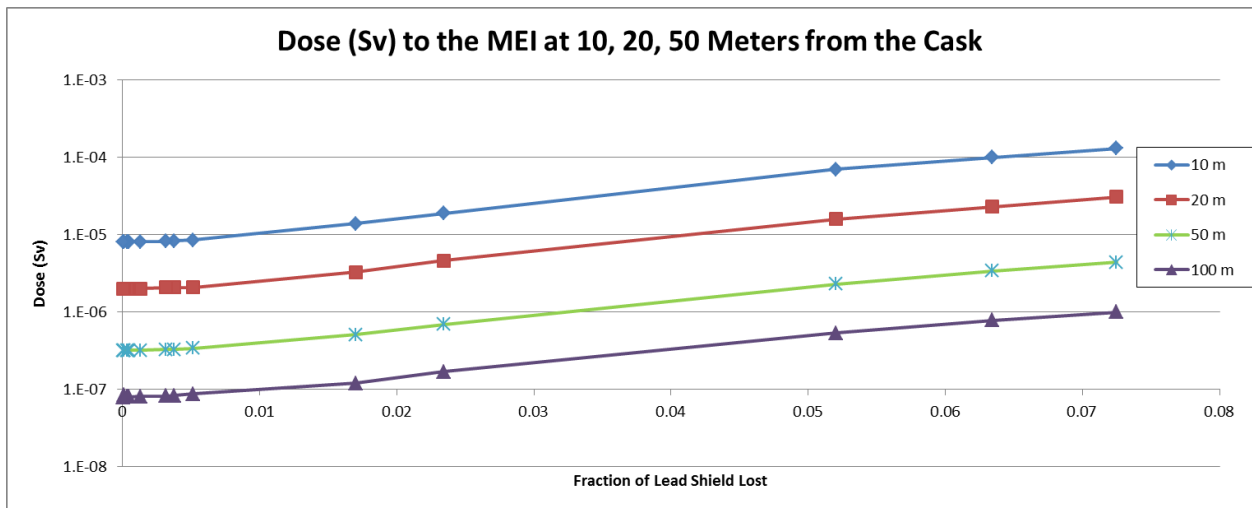


Figure 4. Radiation dose rates to the MEI from loss of lead gamma shielding at distances from 10 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic so that all of the doses can be shown on the same graph. The horizontal axis represents the fraction of shielding lost (the shielding gap) (1 m = 3.3 feet, 1 Sv = 10⁵ mrem).

One accident in a billion 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 probability of an accident is shown in the right-hand column of Table 5. The total probability of an accident resulting in loss of lead shielding, including both the conditional probability and the probability that there will be an accident, is calculated in the example below. On the rail route from Maine Yankee Nuclear Plant site to Hanford, the probability that an accident resulting in lead shielding loss and a dose rate greater than 0.01 Sv/hr (1 rem/hr) will happen is:

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

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

This very small probability indicates that such very severe accidents, are unlikely. Only extreme conditions can cause enough lead shielding loss to result in radiation doses to the public above those that 10 CFR 71.51 allows.

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=10⁵ mrem)

SHIPMENT ORIGIN	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.5x10 ⁻¹³	2.7x10 ⁻¹³	2.7x10 ⁻¹³	2.6x10 ⁻¹³
KEWAUNEE	1.0x10 ⁻¹³	6.3x10 ⁻¹⁴	5.4x10 ⁻¹⁴	1.1x10 ⁻¹³
INDIAN POINT	3.5x10 ⁻¹²	2.4x10 ⁻¹³	2.5x10 ⁻¹³	2.7x10 ⁻¹³
IDAHO NATIONAL LAB	9.9x10 ⁻¹⁴	4.1x10 ⁻¹⁴	2.1x10 ⁻¹⁴	1.5x10 ⁻¹⁴

The conditional probability that a lead shielding gap will occur after a fire involving the cask is about 10⁻¹⁹, because the following series of events has to occur before a fire is close enough to the cask—and burns hot enough and long enough—to 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 five 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, 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 five 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 multiplying the five-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 seven percent of the lead shielding. Both of these doses are probably overestimates of what would actually happen in either of these 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 mass and activity of each nuclide in the SNF depend on the type of reactor fuel, the enrichment when it was loaded into the reactor, burnup, cooling time, and, to some extent, decay of the actinides produced in the fuel. The fuel studied in this analysis is pressurized-water reactor (PWR) fuel that has “burned” 45,000 MWD/MTU[‡] and cooled for nine 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)	Curies (Ci)
			26 Assemblies	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

[‡] MWD/MTU = megawatt-days per metric ton of uranium

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 (2012, Appendix V) 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} and for the cask using elastomer seals it is 3.57×10^{-10} .

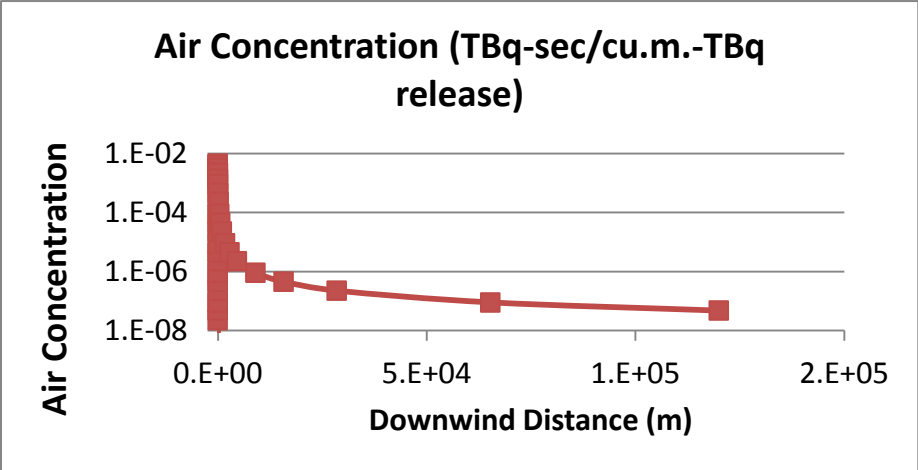
Table 9. Parameters for Determining Release Functions for the Accidents that Would Result in Release of Radioactive Material

	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}

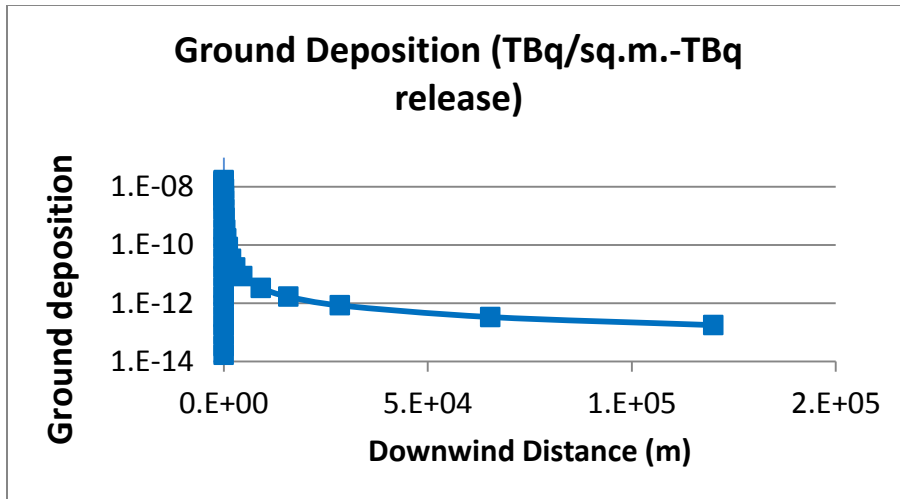
[§] CRUD: Chalk River Unidentified Deposits. These are products of corrosion of metal objects in the fuel pool. CRUD collects on the outside of the fuel rods. The primary radioactive constituents of CRUD are ^{60}Co and ^{63}Fe .

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 maximally exposed individual (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=10⁵ 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	8.8x10 ⁻⁵	9.4x10 ⁻⁴	1.6
Corner	193 (120)	metal	1.6	0.014	8.8x10 ⁻⁵	9.4x10 ⁻⁴	1.6
Side	193 (120)	elastomer	1.6	0.014	8.8x10 ⁻⁵	9.4x10 ⁻⁴	1.6
Side	193 (120)	metal	1.6	0.014	8.8x10 ⁻⁵	9.4x10 ⁻⁴	1.6
Side	145 (90)	elastomer	1.6	0.014	4.5x10 ⁻⁶	3.6x10 ⁻⁵	1.6
Side	145 (90)	metal	1.6	0.014	8.8x10 ⁻⁵	9.4x10 ⁻⁴	1.6
Corner	145 (90)	metal	0.73	0.0063	5.1x10 ⁻⁵	9.0x10 ⁻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 (inhalation and resuspension) and external (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 NRC considers the total effective dose equivalent, which is the sum of the internal and external doses. The inhalation dose, including the dose from inhaled resuspended material, is an internal “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 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 could have 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 2012, Appendix V) 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,

** An A_2 quantity of material is the radioactivity that can be carried in a Type A cask (10 CFR Part 71 Appendix A). A member of the public exposed to an A_2 quantity would sustain a radiation dose that is acceptable (IAEA, 2002, Appendix I).

this type of accident would not significantly change the results of this study unless it resulted in more than 140 A₂ 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 A₂). 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/km² (107.4 persons/mi²) (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=10⁵ mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.5x10 ⁻¹⁴	4.1x10 ⁻¹⁴	3.2x10 ⁻¹⁴	3.0x10 ⁻¹⁴
KEWAUNEE	1.8x10 ⁻¹⁴	1.2x10 ⁻¹⁴	5.4x10 ⁻¹⁵	1.4x10 ⁻¹⁴
INDIAN POINT	1.5x10 ⁻¹¹	5.9x10 ⁻¹³	5.3x10 ⁻¹³	1.9x10 ⁻¹³
IDAHO NATIONAL LAB	9.4x10 ⁻¹⁴	1.5x10 ⁻¹³	4.1x10 ⁻¹⁴	2.7x10 ⁻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 12 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=10⁵ mrem)

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.8x10 ⁻¹³	3.1x10 ⁻¹³	3.0x10 ⁻¹³	2.9x10 ⁻¹³
KEWAUNEE	1.2x10 ⁻¹³	7.6x10 ⁻¹⁴	5.9x10 ⁻¹⁴	1.2x10 ⁻¹³
INDIAN POINT	1.9x10 ⁻¹¹	8.3x10 ⁻¹³	7.9x10 ⁻¹³	4.6x10 ⁻¹³
IDAHO NATIONAL LAB	1.9x10 ⁻¹³	1.9x10 ⁻¹³	6.1x10 ⁻¹⁴	2.9x10 ⁻¹³

Table 13 shows the total collective dose risk for an accident involving the Rail-Lead cask in which there is no loss of lead shielding or release of radioactive material. Since the collective dose risk for this type of accident depends only on the external dose rate of the cask, the collective dose risk from an accident involving the truck cask would be approximately the same. For the Rail-Steel cask carrying canistered fuel, the collective dose risk would be slightly less because the external dose rate is less. 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=10⁵ 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=10⁵ 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, which apply to the three casks studied, are listed below.

- The overall collective dose risks for even the most likely accidents 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 finite element modeling and a more accurate model of the dose from a gap in the lead shield.
- The conditional probability and 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 are larger than those cited in 10 CFR 71.51; but would not result in an acute morbidity or mortality. Only one accident in a billion would result in such doses.

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