CHAPTER 5

TRANSPORTATION ACCIDENTS

5.1 Types of Accidents and Incidents

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

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

Comment [h1]: You also include loss of neutron shielding in Section 5.4.2. Should it be referenced here as well?

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Comment [MF2]: What about loss of both?

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

An accident happens at a particular spot on the route. When the accident happens, the vehicle carrying the spent fuel cask stops. Thus, there can be no more than one accident for a shipment. Accidents can result in damage to spent fuel in the cask even if no radioactive material is released. While this would not result in additional exposure of members of the public, workers unloading or otherwise opening the cask could be affected. Accidents damaging the fuel but not damaging the cask, and potential consequence to workers are not included in this study because it is assumed a cask involved in an accident will be handled as a special case and the workers will be afforded special protection when opening the cask.

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5.2 Accident probabilities

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

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

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

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

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

Table 5-1. Illustrations of net probability

Comment [MF3]: Please fully explain or show an example calculation (with text to explain) of at least one of these examples.

Accident Probability For a 3000-Mile Cross-Country Trip[a]	Accident	Conditional Probability[b]	Net Probability Of Accident
0.0165	Truck collision with a gasoline tank truck	0.82*0.003 = 0.0025	0.82*0.003*0.0165 = 0.000041
0.00138	Rail/truck 80 kph collision at grade crossing	0.7355*0.985*0.0604*0.0113 = 0.00049	0.7355*0.985*0.0604*0.0113*0.00138 = 0.0000067
0.00087	Railcar falling off bridge at 48 kph	0.7355*0.2665* 0.9887 = 0.194	0.7355*0.2665*0.9887*0.00087 = 0.00017

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

Comment [h4]: I think this is a typo, the value should be 6.8e-7 based on the values listed here

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 accident frequency varies somewhat from state to state: the U.S. average for large trucks for the period 1991 to 2007 is 0.0035 large truck accidents per thousand kilometers (km). For rail accidents, the average is 0.00024 per thousand railcar-km (DOT, 2008). The DOT has compiled and validated national accident data for truck and rail from 1971 through 2007, but the accident rates declined so sharply between 1971 and the 1990s that, for this analysis, rates from 1996 through 2007 are used: 0.0019 accidents per thousand large truck-km and 0.00011accidents per thousand railcar-km. Figure 5-1 shows the accidents per truck-km and per railcar-km for this period. The logarithmic scale is used on the vertical axis in order to show the entire range.

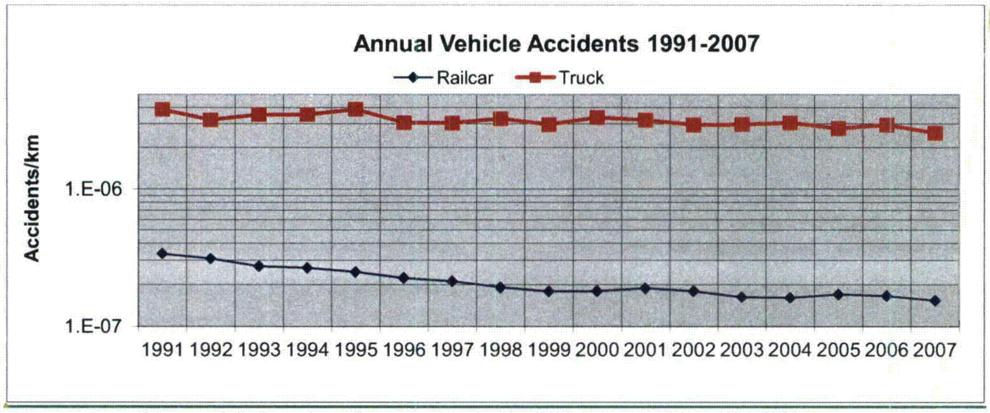

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Figure 5-1. Accident frequencies in the U.S. from 1991 until 2007

As Chapters 3 and 4 show, the only accidents that could result in either the loss of radiation shielding or release of radioactive material are rail accidents involving the Rail-Lead cask. These are:

- Some collisions with hard rock or equivalent at impact speeds greater than 97 km/hour (60 mph) that result in some loss of lead gamma radiation shielding or damage to the cask seals.
- Fires of long enough duration to cause lead melt and subsequent reduction in lead gamma shielding.

Whether or not these accidents happen depends on the likelihood (conditional probability) of the accident scenario as well as on the accident frequency. The event trees for truck and rail, Figures V-1 and V-2 of Appendix V, show some of the elements of accident scenarios in each branch of the respective event tree. The dependence on probability is illustrated by the example of Figure V-5, which shows the sequence of events needed for a pool fire that can burn long enough to compromise the lead shielding.

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

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

Accident Scenario for the Rail-Lead Cask	Conditional probability of gamma shield loss or radioactive material content release exceeding 10 CFR 71.51 quantities
Loss of lead shielding from impact	5.1×10^{-6}
Loss of lead shielding from fire	10^{-14} to 10^{-10}
Radioactive materials release from impact, direct loaded cask	3.6×10^{-6}
No loss of lead shielding and no release of radioactive material, direct loaded cask	0.999991
No loss of lead shielding and no release of radioactive material, canistered fuel	0.999995

Comment [h5]: Where? Figure V-2 in the appendix doesn't show these probabilities. Should either include or reference.

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

The conditional probability that an accident will be this type of accident, with no release and no lead shielding loss is, as Table 5-2 shows, 99.999 percent for the direct loaded Rail-Lead cask and 99.9995 percent for the canistered fuel Rail-Lead cask (and 100 percent for the Rail-Steel and Truck-DU casks). The doses to the public and to emergency responders from an accident in which no material is released and there is no loss of lead gamma shield are shown in Tables 5-3 and 5-4. These doses depend only on the external dose rate from the cask in the accident. The radiation dose depends on:

- The external dose rate from the cask (Table 2-1).
- A ten-hour stop (DOE, 2002) at the scene of the accident, until the vehicle and/or cask can be moved safely.
- An average distance of five meters between the cask and the first responders and others who remain with the cask.
- For collective doses, the average rural, urban, and suburban population densities for each route.

Comment [h6]: More explicit reference

Comment [h7]: reference

The radiation doses in Table 5-3, Table 5-4, and Table 5-5 are the consequences of all Truck-DU accidents, all Rail-Steel accidents, and 99.999% of the Rail-Lead accidents.

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

Cask	Dose in Sv	Ten-hour allowed dose in Sv from 10 CFR 71.51[a]
Truck-DU	1.0 E-03	0.10
Rail-Lead	9.2E-04	0.10
Rail-Steel	6.9E-04	0.10

[a] Calculated by multiplying the allowed dose rate from 10 CFR 71.51 by the 10 hour stop duration.

Comment [s9]: Nothing incorrect here, but to me it is mixing apples and oranges. 1[st] dose column is, according to text on p. 103, based on an average distance of **5 meters**. However, the last column is based on 71.51 which states the external dose at **1 meter** should not exceed 10 mSv/h. The reader who takes some time to look up 71.51 may feel they are being misled since the distances for the dose are not consistent. (CParks)

Comment [h8]: example calculation

Table 5-4 and Table 5-5 show collective dose risks in person-sieverts (person-Sv) for the ten-hour stop that follows the accident. The conditional probability of this type of accident (this accident scenario) is 0.99999 (Table 5-2), so that the results could be called "collective doses" instead of "collective dose risks." Collective dose risks are shown for rural, suburban, and urban segments of each route, but an accident is only going to happen at one place on any route. Each listed collective dose risk is thus the collective dose risk that residents on that route segment could receive if the accident happened at a spot on that particular route segment.

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

Comment [h10]: example calculation

FROM	TO	Rail-Lead			Rail-Steel		
		Rural	Suburban	Urban	Rural	Suburban	Urban
MAINE YANKEE	ORNL	3.1E-06	5.3E-05	6.6E-06	2.3E-06	4.0E-05	5.0E-06
	DEAF SMITH	2.3E-06	5.7E-05	6.8E-06	1.7E-06	4.3E-05	5.2E-06
	HANFORD	3.7E-06	5.3E-05	6.4E-06	2.8E-06	4.0E-05	4.8E-06
	SKULL	2.8E-06	5.1E-05	5.3E-06	2.1E-06	3.9E-05	4.0E-06
KEWAUNEE	ORNL	3.1E-06	5.7E-05	7.2E-06	2.3E-06	4.3E-05	5.4E-06
	DEAF SMITH	1.5E-06	6.1E-05	7.2E-06	1.2E-06	4.6E-05	5.4E-06
	HANFORD	1.5E-06	5.3E-05	6.6E-06	1.2E-06	4.0E-05	5.0E-06
	SKULL	2.0E-06	6.2E-05	6.0E-06	1.5E-06	4.7E-05	4.5E-06
INDIAN POINT	ORNL	2.6E-06	7.2E-05	8.7E-06	2.0E-06	5.4E-05	6.6E-06
	DEAF SMITH	1.9E-06	5.9E-05	7.5E-06	1.4E-06	4.5E-05	5.7E-06
	HANFORD	1.9E-06	5.6E-05	7.2E-06	1.4E-06	4.3E-05	5.5E-06
	SKULL	2.2E-06	6.0E-05	6.6E-06	1.7E-06	4.6E-05	5.0E-06
IDAHO NATIONAL LAB	ORNL	1.9E-06	6.0E-05	5.8E-06	1.4E-06	4.6E-05	4.4E-06
	DEAF SMITH	8.0E-07	6.0E-05	5.3E-06	6.0E-07	4.6E-05	4.0E-06
	HANFORD	1.0E-06	6.0E-05	6.7E-06	7.5E-07	4.6E-05	5.1E-06
	SKULL	2.0E-06	5.9E-05	7.1E-06	1.5E-06	4.4E-05	5.4E-06
AVERAGE		2.1E-06	5.8E-05	6.7E-06	1.6E-06	4.4E-05	5.1E-06

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

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

FROM	TO	Truck-DU		
		Rural	Suburban	Urban
MAINE YANKEE	ORNL	3.8E-06	6.6E-05	8.1E-06
	DEAF SMITH	2.8E-06	7.0E-05	8.4E-06
	HANFORD	4.5E-06	6.5E-05	7.9E-06
	SKULL VALLEY	3.5E-06	6.3E-05	6.6E-06
KEWAUNEE	ORNL	3.8E-06	7.1E-05	8.9E-06
	DEAF SMITH	1.9E-06	7.4E-05	8.9E-06
	HANFORD	1.9E-06	6.5E-05	8.2E-06
	SKULL VALLEY	2.4E-06	7.6E-05	7.4E-06
INDIAN POINT	ORNL	3.2E-06	8.8E-05	1.1E-05
	DEAF SMITH	2.3E-06	7.3E-05	9.2E-06
	HANFORD	2.3E-06	6.9E-05	8.9E-06
	SKULL VALLEY	2.7E-06	7.4E-05	8.2E-06
IDAHO NATIONAL LAB	ORNL	2.4E-06	7.4E-05	7.2E-06
	DEAF SMITH	9.8E-07	7.4E-05	6.6E-06
	HANFORD	1.2E-06	7.4E-05	8.3E-06
	SKULL VALLEY	2.4E-06	7.2E-05	8.8E-06
AVERAGE		2.6E-06	7.2E-05	8.3E-06

Comment [h11]: why is this table different from Table 2-6

These collective dose risks may be compared to the background dose that the exposed population would sustain. The average individual U.S. background dose for ten hours is 4.1×10^{-6} Sv. Average collective background doses for the 16 routes analyzed, for ten hours, are therefore:

- Rural: 6.9×10^{-5} person-Sv
- Suburban: 1.9×10^{-3} person-Sv
- Urban: 0.011 person-Sv

Comment [h12]: Reference population tables (i.e., I assume the average collective background doses would simply be the US background dose for ten hours multiplied by the average RURAL, SUBURBAN and URBAN populations for the 16 routes analyzed.

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

- Rural: 7.2×10^{-5} person-Sv
- Suburban: 2.0×10^{-3} person-Sv
- Urban: 0.011 person-Sv

The urban collective doses from this type of accident would be indistinguishable from the urban collective background dose. The rural and suburban collective doses from the accident add four percent and five percent, respectively, to background dose on this particular route. Any dose to an individual is well below the doses allowed by 10 CFR 71.51.

5.4 Accidental Loss of Shielding

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

5.4.1 Loss of Lead Gamma Shielding

Spent fuel transportation packages are designed to carry highly radioactive material and need shielding in addition to that provided by the package shell. Spent nuclear fuel is extremely radioactive and requires shielding that absorbs both gamma radiation and neutrons. The sum of the external radiation doses from gamma radiation and neutrons cannot exceed 0. 1 mSv per hour at two meters from the cask, by regulation (10 CFR 71.47(b)(3)). The three cask types analyzed in this assessment meet this criterion.

Each spent fuel transportation cask analyzed uses a different gamma shield. The Rail-Steel cask has a steel wall thick enough to attenuate gamma radiation to acceptable levels instead of the relatively thinner walls of the other two casks. The Truck-DU cask uses metallic depleted uranium (DU). Neither of these shields would be damaged, or even affected by, an accident. The Rail-Lead cask has a lead gamma shield which could be damaged in an accident. Lead is relatively soft compared to DU or steel, and melts at a considerably lower temperature (330 °C) than either DU or steel. Thus, the only type of cask that could lose gamma shielding is a lead shielded cask like the Rail-Lead cask.

Comment [h13]: Reference where this is either assumed or shown in this analysis (i.e., *as shown in the analysis documented in Chapters 3 and 4,…….*

In a hard impact, the lead shield could slump, and a small section of the spent fuel in the cask would then be shielded only by the steel shells. Figure 5-2 and Figure 5-3 show the maximum individual radiation dose to a receptor exposed for one hour at various distances from the damaged cask, for a range of gaps. The gaps are equivalent to slumped fractions of the lead shield. Figure 5-2 shows that one-hour doses larger than the external dose rate in 10 CFR 71.51 occur when the lead shielding gap is more than two percent of the shield.

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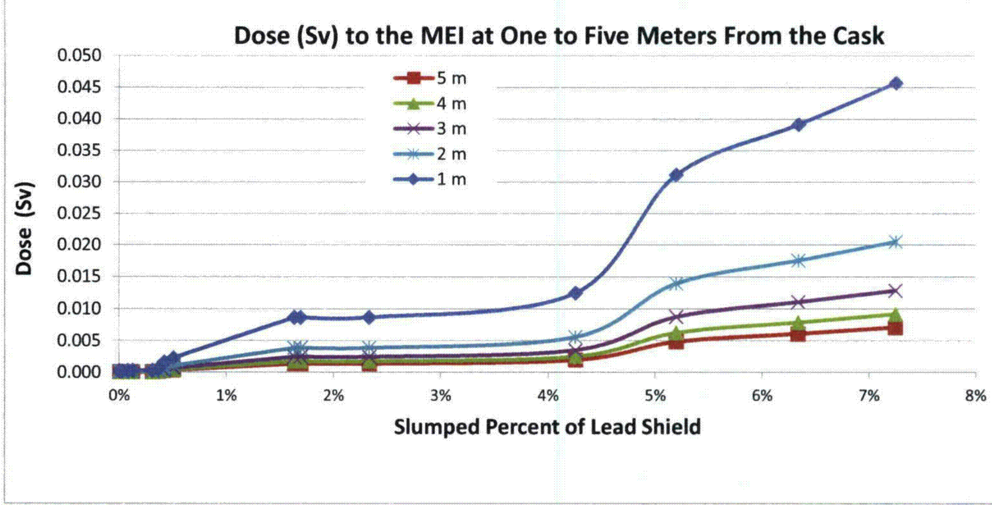

Figure 5-2. Radiation dose for one hour to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from one to five meters from the cask carrying spent fuel.

Comment [h14]: The results for the 1m case look suspicious compare to the other runs. An example calculation using the 1m distance would be useful and serve as a good check on these results.

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Comment [s15]: I am not sure I concur with the accuracy of Fig 5-2 based on the dose trends that are shown and the rather cursory model explanation of Appendix V.3.1? ORNL will do more work to confirm accuracy or illustrate / document inconsistencies based on independent modeling (see comment S8 in Appendix V).

Comment [s16]: It would seem valuable to point the reader to the model used for these analyses as described in Appendix V.3.1? (CParks)

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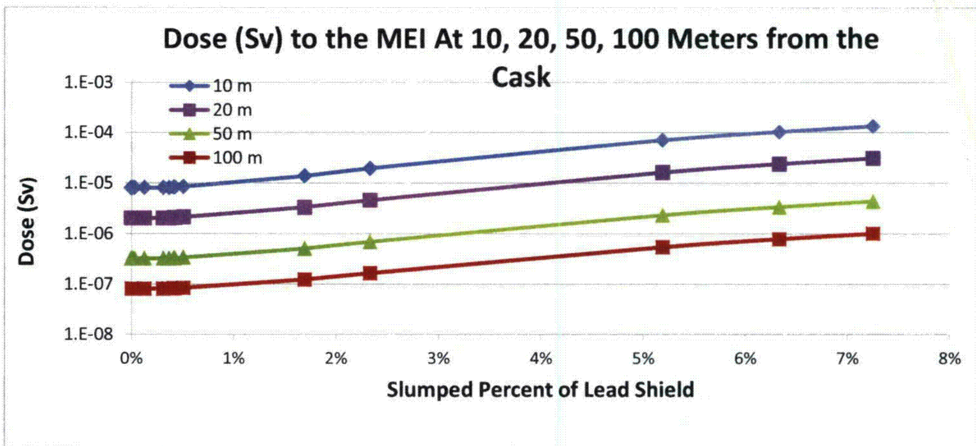

Figure 5-3. Radiation dose to the maximally exposed individual from loss of lead gamma shielding at distances from 20 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic, so that all of the doses can be shown on the same graph.

Table 5-2 shows that the probability of an impact accident causing loss of lead shielding is five per million (5×10^{-6}), or one in 200,000 accidents. "One in 200,000" 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 5-6. For example, the probability that an accident resulting in lead shielding loss will happen on the route from Maine Yankee Nuclear Plant to Hanford is:

$$(5 \times 10^{-6}) \times (0.00178) = 8.9 \times 10^{-9}$$

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or about one in 100 million per Maine Yankee to Hanford shipment. The probability that the lead shielding loss is significant is:

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$$(3 \times 10^{-8}) \times (0.00178) = 5.34 \times 10^{-11}$$

or about one in 10 billion per Maine Yankee to Hanford shipment.

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These very small probabilities indicate that such severe accidents, which are more traumatic to the cask than the tests shown in Figure 1-1, are not likely to happen. The conditions which can cause significant loss of lead shielding are extreme conditions.

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

ORIGIN	DESTINATION	AVERAGE ACCIDENTS PER KM	AVERAGE ACCIDENTS PER SHIPMENT
MAINE YANKEE	ORNL	6.5×10^{-7}	0.00328
	DEAF SMITH	5.8×10^{-7}	0.00195
	HANFORD	4.2×10^{-7}	0.00178
	SKULL VALLEY	5.1×10^{-7}	0.00108
KEWAUNEE	ORNL	4.3×10^{-7}	0.00328
	DEAF SMITH	3.3×10^{-7}	0.00130
	HANFORD	2.4×10^{-7}	0.00062
	SKULL VALLEY	3.7×10^{-7}	0.00066
INDIAN POINT	ORNL	8.8×10^{-6}	0.00052
	DEAF SMITH	6.2×10^{-7}	0.04206
	HANFORD	5.1×10^{-7}	0.00190
	SKULL VALLEY	5.5×10^{-7}	0.00203
INL	ORNL	3.6×10^{-7}	0.00069
	DEAF SMITH	3.5×10^{-7}	0.00038
	HANFORD	3.2×10^{-7}	0.00067
	SKULL VALLEY	2.8×10^{-7}	0.00015

Comment [h17]: ADD Example calculation in Appendix

Comment [s18]: 1.The value of 0.04206 in the last column of Table 5-6 on p. 109 seems too high, please check.

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

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Comment [MF19]: Where is this shown?

Comment [MF20]: Than what? Why would the rail accident rate be so much higher along this route than others since many of the same tracks are used?

Table 5-7. Collective dose risks in person-Sv for a loss of lead shielding accident

SHIPMENT ORIGIN	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	4.4E-10	2.7E-10	2.4E-10	1.4E-10
KEWAUNEE	1.9E-10	9.1E-11	8.6E-11	7.7E-11
INDIAN POINT	7.4E-09	2.8E-10	2.8E-10	1.0E-10
IDAHO NATIONAL LAB	5.6E-11	9.5E-11	2.1E-11	1.3E-10

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

- The train must be in an accident that results in a major derailment
- The train carrying the spent fuel cask must also be carrying at least one tank car of flammable material.
- The derailment must result in a pileup because railcars carrying spent fuel casks are always located between buffer cars and never located next 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 width.

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

5.4.2 Loss of neutron shielding

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

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

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

Cask	Dose in Sv	Ten-hour allowed dose in Sv from 10 CFR 71.51(a)(2)
Truck-DU	0.0073	0.10
Rail-Lead	0.0076	0.10
Rail-Steel	0.0076	0.10

The neutron doses do not exceed the dose cited in the regulation following an accident, so the loss of neutron shield is not included in the overall risk assessment. Essentially, these are not extra-regulatory accidents. The conditional probability of this neutron dose is 0.0063 for a truck fire accident and 0.0000001 for a rail fire accident. The overall probability depends on the accident rate on the particular route segment traveled by the shipment. Details are discussed in Appendix V Section V.3.2.

Comment [s21]: As with Table 5-3, this Table 5-8 is comparing a calculated dose at 5 meters with a regulatory dose limit at 1 meter (71.51) – confusing at best and somewhat misleading (even though the ten-fold difference between the calculated dose and regulatory limit should mitigate real concerns). Plus, the calculated dose column is neutron dose (I think) whereas the regulatory dose column is total dose. So this appears to be an "apples and oranges" comparison. (CParks)

Comment [s22]: The text indicates Table 5-8 is the neutron dose, but the table standalone indicates the value as simply "dose"

Comment [s22]: The text indicates Table 5-8 is the neutron dose, but the table standalone indicates the value as simply "dose"

Comment [h24]: Why is this? Neither do the other doses calculated in this analysis, but they are included.

5.5 Accidental Release of Radioactive Materials

Radioactive materials released into the environment are dispersed in the air, and some deposit on the ground. If a spent fuel cask is in a severe enough accident, spent fuel rods can tear or be otherwise damaged, releasing fission products and very small particles of spent fuel into the cask. If the cask seals are damaged, these radioactive substances can be swept from the interior of the cask pst the seal region into the environment. Release to the environment requires that the accident be severe enough to fail the bolts that hold the cask lid, dislodge the lid, fail the seals, damage the fuel rods, and release the pressure in the rods. There must be positive pressure to sweep material from the cask to the environment. Even if the bolts and seals fail, if the fuel is in a closed canister in the transportation cask, no radioactive material will be released. As discussed earlier, the only cask of the three studied that could release radioactive material in an accident is the direct loaded Rail-Lead cask. The potential releases discussed in this section would be from this cask. The potential accidents that could result in such a release are discussed in Chapter 3. This chapter discusses the probability of such accidents and the consequences of releasing a fraction of the radionuclide inventory.

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5.5.1 Spent fuel inventory

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

The fuel studied in this analysis is PWR fuel that has "burned" 45 GWD/MTU and has been cooled for nine years. The Rail-Lead cask is certified to carry 26 PWR assemblies in its direct loaded configuration.

Comment [s25]: The text notes the fuel is 45 GWD/MTU cooled for 9 years. What is the basis for 9 years – is this the cooling time used in the cask license to obtain the external doses of Table 2-1? If so, why is this not noted in Sect. 2.2 (where Table 2-1 discussed)? And why is there a difference in cooling time here from the 3-5 y cooling time noted in Sect. 1.3? There are "clean" answers here I think that should help reader confidence. (CParks)

Comment [h26]: It would be useful to reference the expected inventory/burnup of BWR fuel relative to the PWR fuel considered here. This would ensure the criticism that BWR fuel was excluded would not be raised.

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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 5-9.

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

Comment [h27]: Reference for these values?

Radionuclide	TBq 26 Assemblies
^{240}Pu	7.82E+03
^{239}Pu	1.84E+02
^{137}Cs	4.38E+04
^{238}Pu	7.18E+01
^{243}Cm	2.50E+01
^{60}Co	4.02E+01
^{154}Eu	9.01E+02
^{134}Cs	4.03E+02
^{85}Kr	2.26E+03
^{241}Am	1.58E-01
^{242}Cm	1.00E+00
^{155}Eu	2.63E+02
^{231}Pa	3.12E-02
^{106}Ru	7.50E+00
^{236}U	1.92E-01
^{233}U	8.99E+02
^{241}Pu	5.75E-01
^{113m}Cd	6.13E-01

The ^{60}Co inventory listed is not part of the nuclear fuel. It is the main constituent of CRUD, a corrosion product that accumulates on the outside of the rods, and is formed by corrosion of hardware in the fuel pool. It is listed here with the inventory because it is released to the environment under the same conditions that spent fuel particles are released. A discussion of CRUD release in a hypothetical accident is in Appendix V, Section V.5.4.1.

Comment [s28]: 2.I have calculated the TBq values in Table 5-9 using the parameters suggested in the text. Some are quite similar (Pu-239 165 vs 184 TBq), others very different (Pu-241 49,000 vs 0.575 TBq, 944 vs. 0.158 for Am-241). My calculations are based on SCALE 6 version of ORIGEN-S. Are your values based on a recent version? I don't see a reference for your results.

5.5.2 Conditional probabilities and release fractions

Seven accident scenarios involving the direct loaded Rail-Lead cask, described in Chapter 3, could result in releases of material to the environment. The details of these scenarios that are important to calculating the resulting doses are shown in Table 5-10. The total probabilities of accidental release of radioactive material, the products of accident probabilities and conditional probabilities of each type of accident, are shown for each route in Table 5-11. A detailed description of the movement of radionuclide particles from fuel rods to the cask interior and from the cask interior to the environment is found in Appendix V Sections V.5.4.1 and V.5.4.2.

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

Comment [h29]: Reference for these values

	Cask Orientation Impact Speed (kph)	End 193	Corner 193	Side 193	Side 193	Side 145	Side 145	Corner 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[a]	Gas	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Particles	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	2.40E-06
	Volatiles	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	1.50E-05
	Crud	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Conditional Probability	2.68E-08	1.61E-07	8.02E-08	8.02E-08	1.52E-06	1.52E-06	5.81E-05

[a] The rod-to-cask release fraction is for the maximum burn-up fuel allowed in the Certificate of Compliance. Appendix VI discusses the effect of high burn-up fuel on this release fraction.

Table 5-11. Total probability of accidental release of radioactive material for each route (for uncanistered fuel in the Rail-Lead cask)

		CONDITIONAL PROBABILITIES							TOTAL PROBABILITY
FROM	TO	2.68E-08	1.61E-07	8.02E-08	8.02E-08	1.52E-06	1.52E-06	5.81E-05	(metal)
MAINE YANKEE	ORNL	8.79E-11	5.28E-10	2.63E-10	2.63E-10	4.99E-09	4.99E-09	1.91E-07	1.96E-07
	DEAF SMITH	5.23E-11	3.14E-10	1.56E-10	1.56E-10	2.96E-09	2.96E-09	1.13E-07	1.17E-07
	HANFORD	4.77E-11	2.87E-10	1.43E-10	1.43E-10	2.71E-09	2.71E-09	1.03E-07	1.07E-07
	SKULL VALLEY	2.89E-11	1.74E-10	8.66E-11	8.66E-11	1.64E-09	1.64E-09	6.27E-08	6.47E-08
KEWAUNEE	ORNL	8.79E-11	5.28E-10	2.63E-10	2.63E-10	4.99E-09	4.99E-09	1.91E-07	1.96E-07
	DEAF SMITH	3.48E-11	2.09E-10	1.04E-10	1.04E-10	1.98E-09	1.98E-09	7.55E-08	7.79E-08
	HANFORD	1.66E-11	9.98E-11	4.97E-11	4.97E-11	9.42E-10	9.42E-10	3.60E-08	3.71E-08
	SKULL VALLEY	1.77E-11	1.06E-10	5.29E-11	5.29E-11	1.00E-09	1.00E-09	3.83E-08	3.95E-08
INDIAN POINT	ORNL	1.39E-11	8.37E-11	4.17E-11	4.17E-11	7.90E-10	7.90E-10	3.02E-08	3.11E-08
	DEAF SMITH	1.13E-09	6.77E-09	3.37E-09	3.37E-09	6.39E-08	6.39E-08	2.44E-06	2.52E-06
	HANFORD	5.09E-11	3.06E-10	1.52E-10	1.52E-10	2.89E-09	2.89E-09	1.10E-07	1.14E-07
	SKULL VALLEY	5.44E-11	3.27E-10	1.63E-10	1.63E-10	3.09E-09	3.09E-09	1.18E-07	1.22E-07
IDAHO NATIONAL LAB	ORNL	1.85E-11	1.11E-10	5.53E-11	5.53E-11	1.05E-09	1.05E-09	4.01E-08	4.13E-08
	DEAF SMITH	1.02E-11	6.12E-11	3.05E-11	3.05E-11	5.78E-10	5.78E-10	2.21E-08	2.28E-08
	HANFORD	1.80E-11	1.08E-10	5.37E-11	5.37E-11	1.02E-09	1.02E-09	3.89E-08	4.01E-08
	SKULL VALLEY	4.02E-12	2.42E-11	1.20E-11	1.20E-11	2.28E-10	2.28E-10	8.72E-09	8.98E-09

Comment [h30]: Are the values at the top of this table supposed to be Sum Totals or Averages ? Example calculation or show where these values come from.

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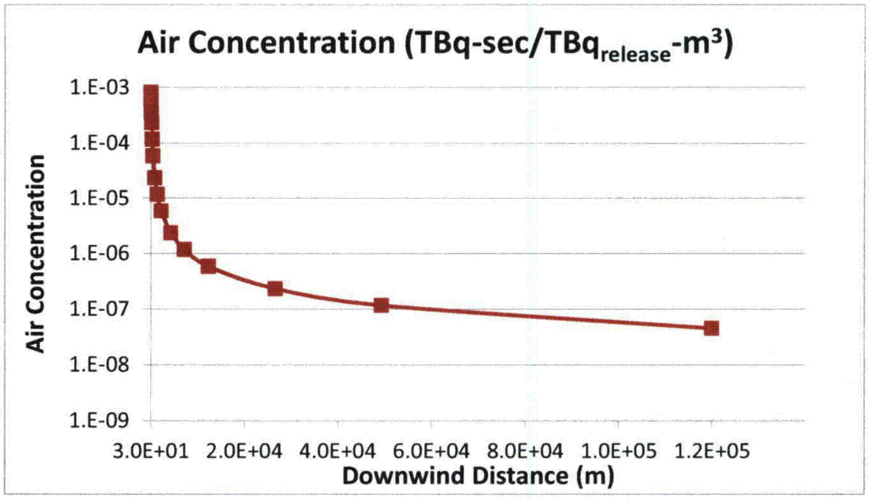
5.5.3 Dispersion

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

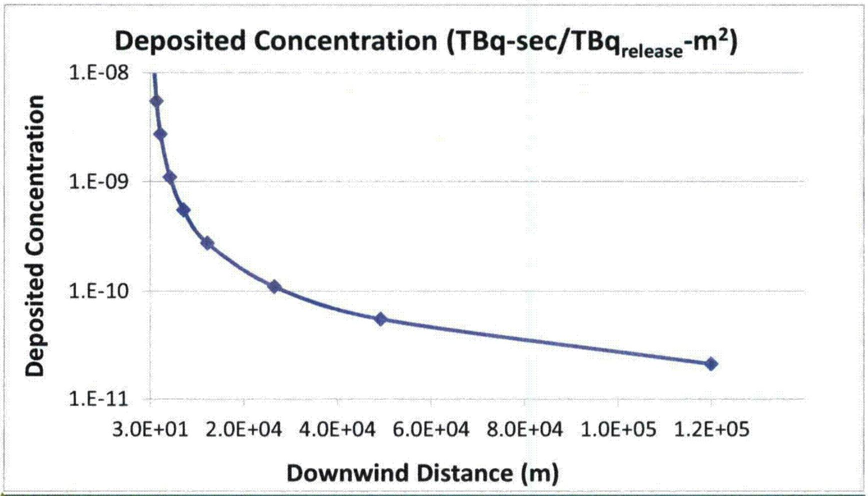
Comment [h31]: How is this distance determined?

Figure 5-4 shows air and ground concentrations of released material as a function of downwind distance. These concentrations 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. The very rapid plume rise, compared to its decay, is responsible for the non-linear scale on the x-axis[3].

[3] Forcing the x-axis to a linear or logarithmic scale distorts the plume.



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



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

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

Comment [h32]: Include example RADTRAN calculation for one of these cases

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Comment [h33]: Include example RADTRAN calculation for one of these cases

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Comment [MF34]: Note that the most of the x-axis is linear, but the first number (on left) appears to be logarithmic. The first number should be 0. This applies to both a and b.

5.5.4. Consequences and Risks from Accidents Involving Release of Radioactive Material

The dose from each of the accidents that would involve a release is shown in Table 5-12.

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Table 5-12. Doses (consequences) in Sv to the maximally exposed individual from accidents that involve a release

Comment [h35]: Does this use the release fractions from Table 5-10? Example calculation.

Cask Orientation	Impact Speed (kph)	Inhalation	Resuspension	Cloud-shine	Ground-shine	Total
End	193	1.6	1.4E-02	8.8E-05	9.4E-04	1.60
Corner	193	1.6	1.4E-02	8.8E-05	9.4E-04	1.60
Side	193	1.6	1.4E-02	8.8E-05	9.4E-04	1.60
Side	193	1.6	1.4E-02	8.8E-05	9.4E-04	1.60
Side	145	1.6	1.4E-02	4.5E-06	3.6E-05	1.59
Side	145	1.6	1.4E-02	8.8E-05	9.4E-04	1.60
Corner	145	0.73	6.3E-02	1.0E-04	1.0E-04	0.73

The doses listed in Table 5-12 are consequences, not risks. The dose to the maximally exposed individual is not the sum of the doses. Each cask orientation is a different accident scenario. These are significant doses, but none would result in either acute illness or death (Shleien et al., 1998, p. 15-3). The inhalation and groundshine doses are listed separately because they have different physiological effects. External doses are exactly that, and the receptor would receive a dose only as long as he or she is exposed to the deposited or airborne material. If people near the accident are evacuated they can only receive an external dose for the duration they are in the vicinity of the accident.

Comment [h36]: Table 5-12?

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Inhaled radioactive particles lodge in the body and are eliminated slowly through physiological processes that depend on the chemical form of the radionuclide. The inhaled dose is called a "committed" dose, because the exposure is for as long as the radionuclide is in the body, though the activity of the nuclide decreases exponentially as it decays. The NRC uses the total effective dose equivalent, the sum of the inhalation and external doses, as a measure of radiological impact.

A pool fire co-located with the cask and burning for a long enough period of time, could damage the seals severely. However, as has already been mentioned, and is discussed in detail in Appendix V Section V.3.1.2, the conditional probability of the series of events required to produce such a fire scenario is about 10^{-19}, which is not a credible accident. Even a fire offset from the cask but close enough to damage lead shielding has a conditional probability of between 10^{-14} and 10^{-10}.

The total dose risk from the universe of release accidents is shown in Table 5-13. Of the three casks in this study, only the Rail-Lead cask could result in a release in each kind of accident considered.

Comment [h37]: Table 5-13?

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Table 5-13. Total collective dose risk (person-Sv) per shipment for release accidents for each route

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.6E-09	2.2E-09	1.9E-09	9.6E-10
KEWAUNEE	1.5E-09	7.4E-10	7.2E-10	5.1E-10
INDIAN POINT	6.1E-08	2.3E-09	2.4E-09	7.7E-10
IDAHO NATIONAL LAB	3.7E-10	6.0E-10	1.6E-10	1.1E-09

These dose risks are negligible by any standard.

The total dose risks from loss-of-lead shielding accidents is shown in Table 5-14, and the sum of the two is shown in Table 5-15.

Comment [h38]: Table 5-14?

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Comment [h39]: Table 5-15?

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Table 5-14. Total collective dose risk (person-Sv) per shipment for each route from a loss of shielding accident

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.6E-10	2. 8E-10	2.5E-10	1.3E-10
KEWAUNEE	1.9E-10	9.1E-11	8.6E-11	7.7E-11
INDIAN POINT	7.4E-09	2.8E-10	3.4E-10	3.2E-10
IDAHO NATIONAL LAB	5.6E-11	9.5E-11	2.1E-11	1.3E-10

Table 5-15. Total collective dose risk (person-Sv) per shipment from release and loss of shielding accidents

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.9E-09	2.5E-09	2.1E-09	1.1E-09
KEWAUNEE	1.7E-09	8.3E-10	8.1E-10	5.9E-10
INDIAN POINT	6.3E-08	2.6E-09	2.7E-09	1.1E-09
IDAHO NATIONAL LAB	4.3E-10	6.9E-10	1.8E-10	1.2E-09

Table 5-16 shows the total collective dose risk for an accident involving the Rail-Lead cask in which there is neither loss of lead shielding nor a release. Since the collective dose risk for this

Comment [h40]: Table 5-16?

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type of accident depends in the TI, the collective dose risk from an accident involving the truck cask would be the same. For the Rail-All Steel cask carrying canistered fuel the collective dose risk would be slightly less because the TI is smaller. For this analysis, the cask was assumed to be immobilized for ten hours.

Table 5-16. Total collective dose risk (person-Sv) per shipment from no-release, no-loss of shielding accidents

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.07E-07	1.29E-07	1.12E-07	6.42E-08
KEWAUNEE	2.22E-07	9.00E-08	3.80E-08	4.62E-08
INDIAN POINT	4.31E-08	2.88E-06	1.24E-07	1.40E-07
IDAHO NATIONAL LAB	4.71E-08	2.52E-08	4.56E-08	1.02E-08

Table 5-17 shows the collective accident risk for the 16 routes from loss of neutron shielding

Table 5-17. Total collective dose risk (person-Sv) per shipment from loss of neutron shielding

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	5.2E-09	3.5E-09	3.6E-09	1.5E-09
KEWAUNEE	3.3E-09	1.9E-09	2.2E-09	1.1E-09
INDIAN POINT	4.5E-09	2.9E-09	3.2E-09	1.1E-09
IDAHO NATIONAL LAB	7.6E-10	1.9E-09	2.4E-10	2.9E-09

5.6 Conclusions

The conclusions that can be drawn from the risk assessment presented in this chapter are:

- The sixteen routes selected for study are an adequate representation of U.S. routes for spent nuclear fuel. There was relatively little variation in the risks per km over these routes.
- The probability of a severe accident for either truck or rail is one in 100,000 (or less).
- The probability of a fire that would damage a cask on a railcar enough to cause loss of gamma shielding is negligible.
- The overall collective dose risks are extremely small.
- The collective dose risks for the two types of extra-regulatory accidents, accidents involving a release of radioactive material and loss of lead shielding accidents, are negligible compared to the risk from a no-release, no-loss of shielding accident. There is no expectation of any release from spent fuel shipped in inner welded canisters from any impact or fire accident analyzed.
- The collective dose risk from loss of lead shielding is comparable to the collective dose risk from a release, though both are very small. The doses and collective dose risks from loss of lead shielding are larger than were calculated in NUREG/CR-6672 as a result of better precision in the finite element modeling and a more accurate model of the dose from a gap in the lead shield.
- The conditional risk of loss of shielding from a fire is negligible.
- The consequences (doses) of some releases and some loss of shielding scenarios are larger than cited in the regulation of 10 CFR 71.51, and are significant, but are neither acute nor lethal.
- These results are expected and are in agreement with previous studies.

Comment [MF41]: Hat about maximally exposed individual?

Comment [MF42]: Indian Point to ORNL is nearly 2 orders of magnitude greater than the other routes, so it is not clear this is a valid statement.

Comment [s43]: It would seem such a conclusion should be a point of discussion in Sect 5.4.1. It would also seem prudent to point the reader to the reference for "acute" and "lethal" doses rather than making a summary judgement with no quantitative data. (CParks)

Comment [s44]: The reader should be referred to Table 3-1 which shows the predicted extent of the lead slumping. And the dose value predicted for 35.55 cm of lead slumping (provided in Appendix V) should be compared with the dose value from 71.51 and the "acute" and "lethal" dose values referred to in the Conclusions. On top of p. 128 of Sect 6.2, it is noted that the max dose from LOS is 1.1 Sv – but I can not figure out how this dose is obtained based on text in Sect 5.4.1 or data of Fig 5-2. A different figure of 1.3 mSv as maximum dose to public is given in App. V.3.1.1 on p. 451 – that one I can figure out by reading the Appendix. (CParks)

Comment [h45]: Rephrase this here you are saying the doses are significant. You need to explain more fully because on the surface this will be perceived as inconsistent with your overall conclusions for the report.

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Comment [h46]: I would delete the double negative…it only confuses.

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