APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

TABLE OF CONTENTS

V.1 TYPES OF ACCIDENTS AND INCIDENTS 6
V.2 ACCIDENT PROBABILITIES 7
V.2.1 Historic Accident Frequencies 7
V.2.2 Development of Conditional Accident Probabilities 8
V.3. ACCIDENT RISKS AND CONSEQUENCES 11
V.3.1 Loss of Lead Gamma Shielding 11
V.3.2 Loss of Neutron Shielding 23
V.4 RELEASE OF RADIOACTIVE MATERIALS IN ACCIDENTS 26
V.4.1 Spent Fuel Inventory 26
V.4.2 Dispersion of Released Radionuclides 27
V.4.3 Release Fractions 29
V.6. SUMMARY 34

LIST OF FIGURES

Figure V-1. Event tree for highway accidents (Mills, et al., 2006). 9
Figure V-2. Rail accident event tree (Volpe, 2006). 10
Figure V-3. The RADTRAN Loss-of Shielding 2-D Model (O'Donnell, et al., 2005). 11
Figure V-4. 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. The difference in the slopes of doses at one and three meters from doses at larger distances reflect the transition in RADTRAN from a linear (1/r) to a quadratic (1/r2) dose dependence. 14
Figure V-5. 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. 14
Figure V-6. Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16). 21

LIST OF TABLES

Table V-1. Truck and railcar accidents per km, 1991 through 2007. 7
Table V-2. Parameters of lead shield slumping from impact. Opposite sides of the cask are labeled "side 1" and "side 2" only to distinguish one side from the other. These are input parameters to the RADTRAN calculation 13
Table V-3. Radiation dose (Sv) to the MEI at various distances for the cask for 10 hours. The numbers in bold italics exceed the external dose rate of 10 CFR 71.51. The doses are the direct output of the RADTRAN loss-of-shielding model. 16

Table V-4. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances from the cask from one to five meters for 10 hours. 17

Table V-5. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances 10 to 100 meters from the cask for 10 hours. 17

Table V-6. Collective conditional dose risks due to loss of lead shielding in person-Sv in a semicircular area of radius 800 meters around the cask. These are not the total dose risks. ..... **Error! Bookmark not defined.**

Table V-7. Average railcar accident frequencies on the routes studied. 19

Table V-8. Conditional collective dose risks per shipment (person-Sv) from loss of lead shielding, including conditional probabilities. These are not the total dose risks. 20

Table V-9. Radiation dose (Sv) to the maximally exposed individual at various distances from a cask that has been in a fire. 21

Table V-10. Events leading to a train fire that could involve a spent fuel cask 22

Table V-11. Some parameters used in calculating loss of neutron shielding. 24

Table V-12. Doses to an emergency responder five meters from the cask. 24

Table V-13. Collective doses (consequences) to an emergency responder in person-Sv from loss of neutron shielding 25

Table V-14. Collective dose risks in person-Sv from loss of neutron shielding 25

Table V-15. TBq inventory for the Rail-Lead cask. 26

Table V-16. Parameters for determining release functions for the accidents that would result in release of radioactive material. 30

Table V-17. Sources of the parameter values in Table V-16. 31

Table V-18. Maximally exposed individual doses (consequences) in Sv from accidents that involve a release. 32

Table V-19. Maximally exposed individual conditional dose risks in Sv from accidents that involve a release. 32

Table V-20. Collective conditional inhalation and external dose risks for the end impact, 193 kph impact speed accident, for the 16 routes analyzed. 33

Table V-21. Total dose risks (person-Sv) for each route from an accident involving release, per shipment. 34

APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

V.1 Types of Accidents and Incidents

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

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

Formatted: Highlight

Comment [JRC1]: Is this a different accident type? Not found on page 5?

In this analysis the first three types of accidents are considered together. Chapter 5, Section 5.3, discusses the radiation doses and risks from these types of accidents. The last three types of accidents are evaluated in detail in this Appendix. Only very severe accidents (those resulting in conditions much more severe than the regulatory accident) have the possibility of causing a loss of lead gamma shielding or release of radioactive material.

The analyses from Chapters 3 and 4 and Appendices III and IV indicate that none of the accidents studied for this report lead to loss of radioactive material or gamma shielding effectiveness for the Rail-Steel or Truck-DU casks, so these casks can only suffer a loss of neutron shielding. Some of the accident environments studied did lead to a loss of effectiveness of the gamma shielding for the Rail-Lead cask. When spent fuel is transported in this cask without an inner welded canister, some of the accident environments studied could also result in a release of radioactive material. In this appendix, the probability and consequence of accidents that lead to a loss or shielding or release of radioactive material are evaluated.

---

[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.

V.2 Accident probabilities

V.2.1 Historic Accident Frequencies

The probability that a traffic accident happens is based on historic accident frequencies. These have been developed and the statistics validated by the Department of Transportation (DOT). Table V-1 shows truck and railcar accidents from 1991 through 1997 (DOT, 2008). Average accident frequencies for this period are:

- 1.98×10^{-6}/km for large trucks on interstates and primary highways.
- 1.32×10^{-7}/railcar km for freight rail.

Accident frequencies decreased 33.5 percent for trucks and 53.8 percent for railcars between 1991 and 2007. The average is used in this document because there are annual fluctuations. The accident frequency trends are shown in Figure 5.2 in Chapter 5.

Comment [JRC2]: occurs

Comment [JRC3]: Don't understand overlap with 1991-1997 data?

Comment [JRC4]: So which average are you referring to 1991-1997 or 1991-2007?

Table V-1. Truck and railcar accidents per km, 1991 through 2007.

YEAR	TRUCK ACCIDENTS/KM	RAILCAR ACCIDENTS PER RAILCAR KM
1991	2.39×10^{-6}	2.08×10^{-7}
1992	1.99×10^{-6}	1.91×10^{-7}
1993	$2.19\times10\text{-}^{6}$	1.68×10^{-7}
1994	$2.19\times10\text{-}^{6}$	1.64×10^{-7}
1995	$2.39\times10\text{-}^{6}$	1.53×10^{-7}
1996	1.90×10^{-6}	1.39×10^{-7}
1997	1.89×10^{-6}	1.32×10^{-7}
1998	2.04×10^{-6}	1.19×10^{-7}
1999	1.84×10^{-6}	1.12×10^{-7}
2000	2.08×10^{-6}	1.12×10^{-7}
2001	1.99×10^{-6}	1.18×10^{-7}
2002	1.83×10^{-6}	1.12×10^{-7}
2003	1.85×10^{-6}	1.02×10^{-7}
2004	1.90×10^{-6}	1.00×10^{-7}
2005	1.73×10^{-6}	1.06×10^{-7}
2006	1.83×10^{-6}	1.04×10^{-7}
2007	1.59×10^{-6}	9.60×10^{-8}

Deleted: ruck

Comment [JRC5]: Are these rates, or those in V-6 used in the results?

V.2.2 Development of Conditional Accident Probabilities

Each specific accident scenario is described by a conditional probability ("conditional" on an accident happening). Conditional probabilities are derived from event trees, as described below.

Comment [JRC6]: occurring. The total probability of a specific accident scenario is the product of the average accident frequency and the conditional probability for that scenario.

V.2.2.1 Conditional Probabilities of Truck Accidents

A transportation accident scenario can be disaggregated into a series of events. The conditional probability of a particular event in the scenario is best illustrated with an event tree: a diagram that includes all possible accident scenarios. Each branch of the tree is the series of events that comprise a particular accident scenario. The conditional probability is the product of the probabilities along a particular branch.

Figure V-1 is an event tree for truck accidents (Mills, et al., 2006). Calculation of the conditional probability of a truck in a collision with another vehicle on a bridge, then falling from the bridge onto a rocky embankment, is illustrative.

Comment [JRC7]: Why use soft rock instead of hard rock?

$$P_{conditional} = P_{collision} * P_{bridge\ accident} * P_{fall\ off\ bridge} * P_{soft\ rock}$$

Deleted:

Deleted: rocky soil

$$P_{conditional} = (0.054)*(0.064)*(0.02)*(0.046) = 3.18 \times 10^{-6}$$

Deleted: 1.99

The conditional probabilities are listed in the right-hand column of Figure V-1.

The construction of the event tree of Figure V-1 is described in detail in Mills, et al. (2006). Details of collision accidents are discussed in Appendix III and of fire accidents, in Appendix IV.

V.2.2.2 Conditional Probabilities of Rail Accidents

Figure V-2 is an event tree for rail.

Comment [JRC8]: the

Comment [JRC9]: used in this study

V.2.2.3 Uncertainty in Event Trees

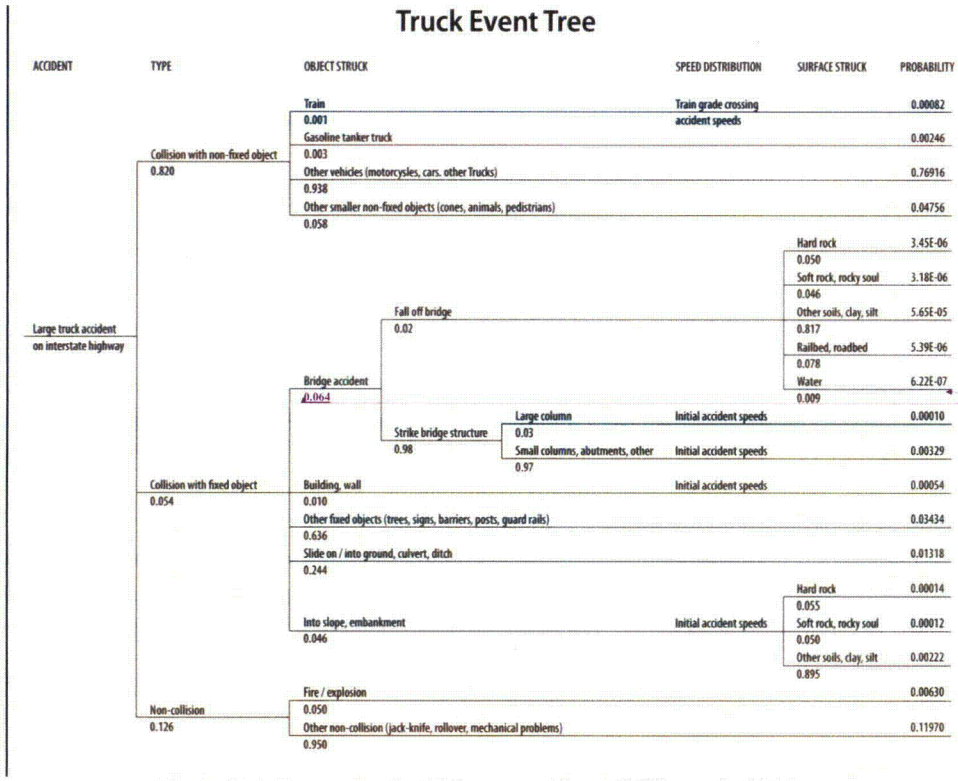
Event trees are excellent tools for dividing the universe of accidents into categories. The resultant probabilities are only as precise as the data that was available to develop the event tree. This becomes especially problematic for events that occur very rarely, such as the most severe accidents. For these events, the branch point distributions are assumed to be the same as those distributions for events that occur more frequently. In this study, no attempt was made to quantify the uncertainty associated with the event trees, but NUREG/CR-6672 did investigate uncertainties and found the total effect of all uncertainties to be approximately an order of magnitude.

Comment [JRC10]: delete

Comment [JRC11]: not sure what is meant here

Formatted: Font: 12 pt, Highlight

Comment [JRC12]: Replace with: NUREG/CR-6672 investigated uncertainties associated with event trees and found the total effect of all uncertainties to be approximately an order of magnitude. No further attempt was made to quantify the uncertainty associated with event trees in this study.



Formatted: Font: 6 pt, Bold, Font color: Text 1

Formatted: Left, Space After: 0 pt

Figure V-1. Event tree for highway accidents (Mills, et al., 2006).

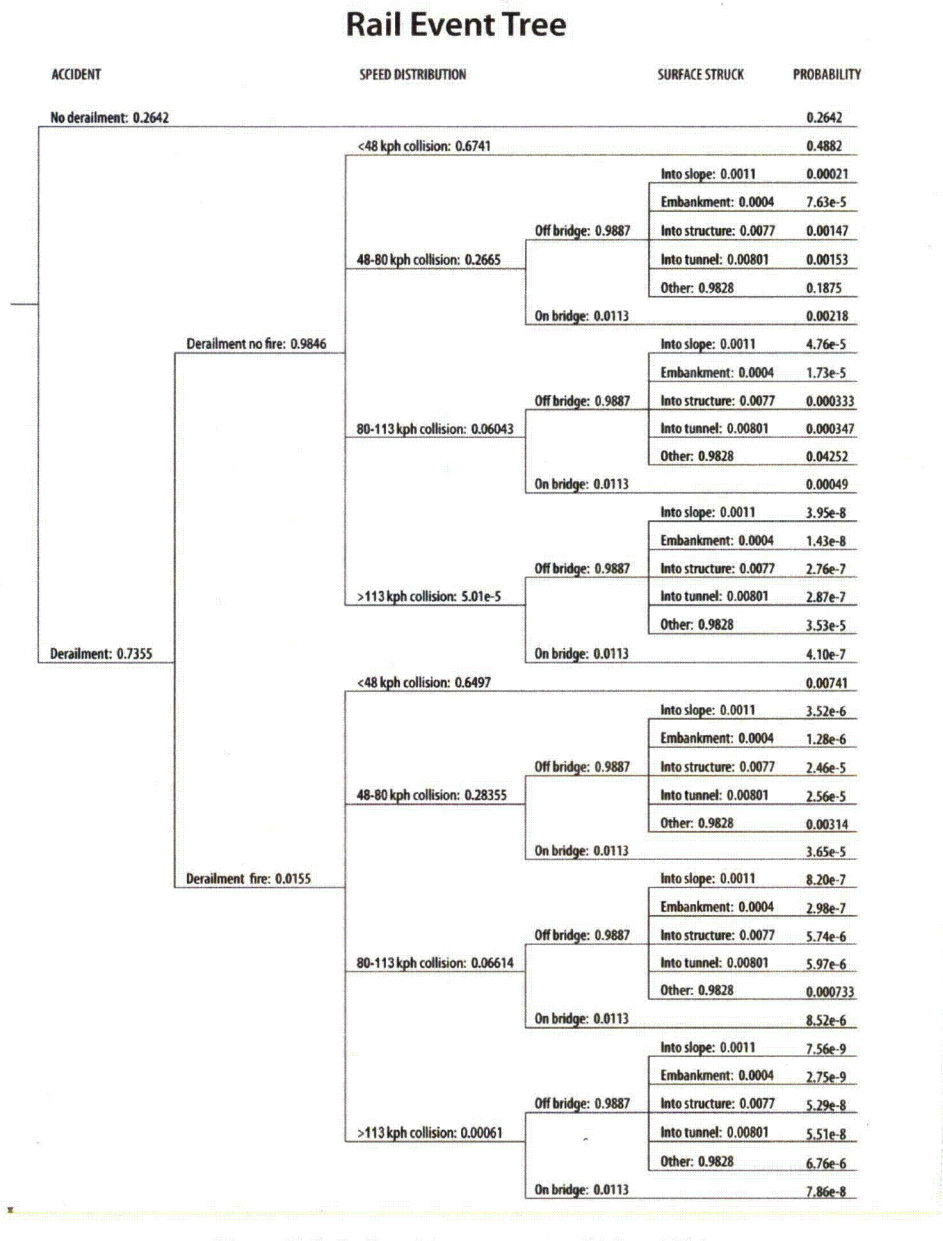


Figure V-2. Rail accident event tree (Volpe, 2006).

Deleted: +.9887¶ .0664¶

Formatted: Font: Times New Roman, 12 pt

V.3. Accident Risks and Consequences

V.3.1 Loss of Lead Gamma Shielding

The cask studied that uses lead as gamma shield is the Rail-Lead cask, so loss would occur only in rail accidents. The Rail-Lead gamma shield is a lead cylinder about 0.127 m. thick. The lead shell can slump in a sufficiently severe impact, leaving a gap in the lead shield which results in increased external gamma radiation. RADTRAN models a gap in the shield from an impact and translates this to an increase in the dose from the virtual radiation source (O'Donnell, et al., 2004; Dennis, et al., 2009) that is the basis for the incident-free transportation model (Figure II-1, Appendix II). Figure V-3 is a diagram of the loss-of-shielding model, which recognizes the two-dimensional symmetry of the lead-shielded cask.

Comment [JRC13]: sleve?

The Monte Carlo N-Particle (MCNP) transport code was used to calculate the photon density along the line of receptor points (Figure V-3) both with and without a void (gap) in the lead shield. The difference in photon density, which is a function of the gap size, was expressed as a multiplier of the external dose rate at one meter (TI) from the fully shielded cask. Different gap sizes are modeled using different values of this multiplier.

Comment [JRC14]: The void is also labeled as Pb: Lead Shielding. That label should point to yellow area.

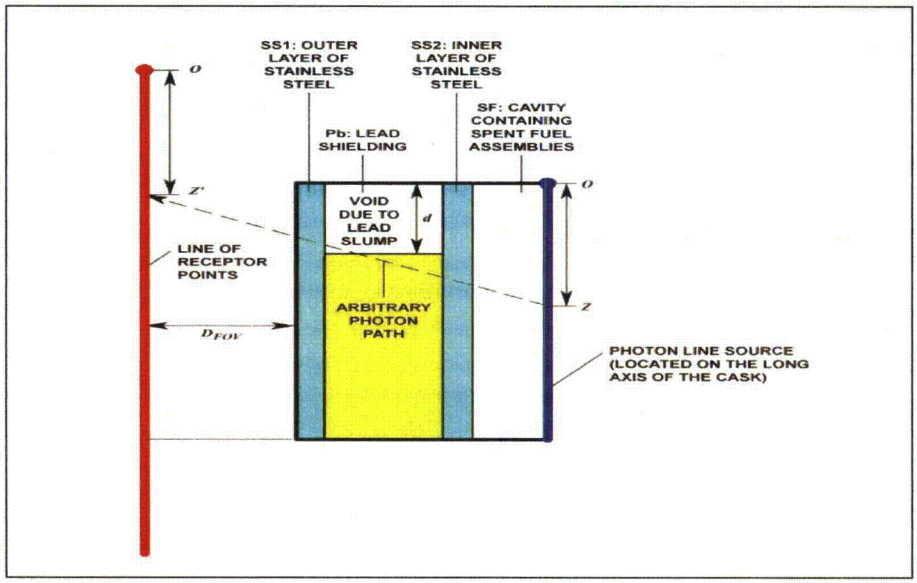


Figure V-3. The RADTRAN Loss-of Shielding 2-D Model (O'Donnell, et al., 2004).

Comment [JRC15]: V-3. Check all Figure numbers in App V and Table of Contents.

Deleted: 5

The product of the multiplier and the TI of the fully shielded cask then provides a new value of the TI, which is then used in RADTRAN to calculate doses to receptors. Thus the results of MCNP calculations provide a RADTRAN source for various gap sizes. The RADTRAN model overestimates the dose to a receptor because it models all loss of lead shielding as a gap in the

lead shield, rather than, e.g., thinning of the lead shield. Therefore, the doses calculated using RADTRAN are larger than what would be calculated using MCNP.

Only one side of the model is shown in the figure because the model is symmetric and can apply to either side of the cask. The post-impact structural analysis (Chapter 3) did identify different gaps on opposite sides of the cask, and identified "side 1" and "side 2" only to distinguish the two sides from each other. The model of Figure V-3 is generic and applies equally to either side of the cask. Any receptor receiving a radiation does from loss of lead shielding would be on one side of the cask.

Comment [JRC16]: Insert?

V.3.1.1 Loss of Lead Shielding from Impact

Appendix III (Section 3.2.2) described the various amounts of lead slump resulting from impact speed and aspect. Table V-2 shows the conditional probabilities of each combination of impact speed and orientation. The rail event tree does not include information on the hardness of the surfaces struck for any of its branches and only impacts into hard rock surfaces are severe enough to cause lead slump (see Section 3.3 for a discussion on impacts into yielding targets). To account for this, the impact surface distributions from the truck event tree (Figure V-1) were used. This event tree indicated that only 5.5% of impacts are into hard rock surfaces. Only impacts that are at angles greater than 45 degrees are severe enough to cause lead slump (see Section 3.4). Using the triangular distribution of impact angles, 33.3% of accidents have an impact angle greater than 45 degrees. The rail event tree also does not include any information about what happens after an accident that occurs on a bridge. Again, the detail for this is taken from the truck event tree, which indicates that 2% of the accidents that occur on a bridge result in the vehicle falling off the bridge and that 5% of those cases result in an impact onto hard rock. For falling off a bridge the impact angle distribution is uniform rather than triangular, so the probability that the angle is greater than 45 degrees is 50%. Using this information, the conditional probabilities for accident scenarios in which an impact could result in lead slump are calculated by adding the probabilities at a particular impact speed for impacts into a slope and impact into an embankment multiplied by 0.055 for hard rock and multiplied by 0.333 for impact angle. To this is added the probability that the impact occurs on a bridge multiplied by 0.02 for falling off the bridge, multiplied by 0.05 for hard rock and multiplied by 0.5 for impact angle. An example calculation for calculating the conditional probability for a 193 kph impact is shown below:

Comment [JRC17]: orientation

Rail event tree impact onto slope > 113 kph = 3.95×10^{-8} (from the derailment no fire branch)
Rail event tree impact onto embankment > 113 kph = 1.43×10^{-8}
Rail event tree accident on bridge > 113 kph = 4.10×10^{-7}
Fraction of accidents >113 kph that are > 145 kph = 0.05

Conditional probability = $\{[(3.95 \times 10^{-8} + 1.43 \times 10^{-8}) \times 0.055 \times 0.333] + [(4.10 \times 10^{-7}) \times 0.02 \times 0.05 \times 0.5]\} \times 0.05 = 5.96 \times 10^{-11}$

Table V-2 also shows the amount of lead slump, both as an absolute amount and as a fraction of the longest dimension of the lead shield. Of the two rail casks studied, only the lead-shielded Rail-Lead cask might lose shielding in an accident.

Comment [JRC18]: 3rd repeat of this?

Table V-3 shows dose rates to the maximally exposed individual (MEI) at various distances from the cask. The populations within 800 meters of the rail routes, as shown in Table 2-5, are the populations that could be exposed for each of the sixteen rail routes modeled.

Deleted:

Table V-2. Parameters of lead shield slumping from impact. These are input parameters to the RADTRAN calculation

Orientation	Impact Speed kph	Event Tree Impact Speed (kph)[a]	Maximum Slump (mm)[b]	Slumped fraction	Conditional Probability from Rail Event Tree[c]	Conditional Probability including Orientation
End (Probability = 0.1)	193	>113 (5%)[d]	355.48	0.0725	5.96E-11	5.96E-12
	145	>113 (95%)	83.2	0.0170	1.13E-09	1.13E-10
	97	80 to 113	18.28	0.00373	1.44E-06	1.44E-07
	48	48 to 80	6.43	0.00131	6.34E-06	6.34E-07
Corner (Probability = 0.6)	193	>113 (5%)[d]	310.48	0.0634	5.96E-11	3.57E-11
	145	>113 (95%)	114.52	0.0234	1.13E-09	6.79E-10
	97	80 to 113	25.11	0.00512	1.44E-06	8.62E-07
	48	48 to 80	1.65	0.000337	6.34E-06	3.80E-06
Side (Probability = 0.3)	193	>113 (5%)[d]	15.47	0.00316	5.96E-11	1.79E-11
	145	>113 (95%)	20.88	0.00426	1.13E-09	3.40E-10
	97	80 to 113	1.37	0.000280	1.44E-06	4.31E-07
	48	48 to 80	0.09	0.0000184	6.34E-06	1.90E-06

[a]Event tree impact speeds are binned. This column relates the binned speeds to the modeled impact speed.

[b]From the finite element analysis (Chapter 3 and Appendix III)

[c]The sum of probabilities of collision scenarios at a particular impact speed into slope and embankment multiplied by 0.055 because only impacts onto hard surfaces can cause lead slump multiplied by 0.333 because only impacts that are at angles greater than 45 degrees can cause lead slump plus the probability the accident occurs on a bridge multiplied by 0.02 for accidents that fall off the bridge multiplied by 0.055 for hard targets multiplied by 0.5 for impact angles greater than 45 degrees.

[d]The event tree did not distinguish between impacts from 113 kph to 145 kph and from 145 kph to 193 kph. It is assumed that 5% of the impacts are >145 kph and 95% are between 113 kph and 145 kph.

Formatted: Font: 12 pt, Not Bold

Deleted:

Formatted: Font: 12 pt, Not Bold

Formatted: Not Superscript/ Subscript

Deleted: [a]

Deleted: [b]

Deleted: ; i.e., the total probability of a collision at that impact speed

Formatted: Font: 12 pt, Superscript

Figures V-4 and V-5 show dose rates to the MEI as a function of the fraction of shielding lost and as a function of distance from the cask.

Comment [JRC19]: Dose at 1 m for 1 h = Head CT scan

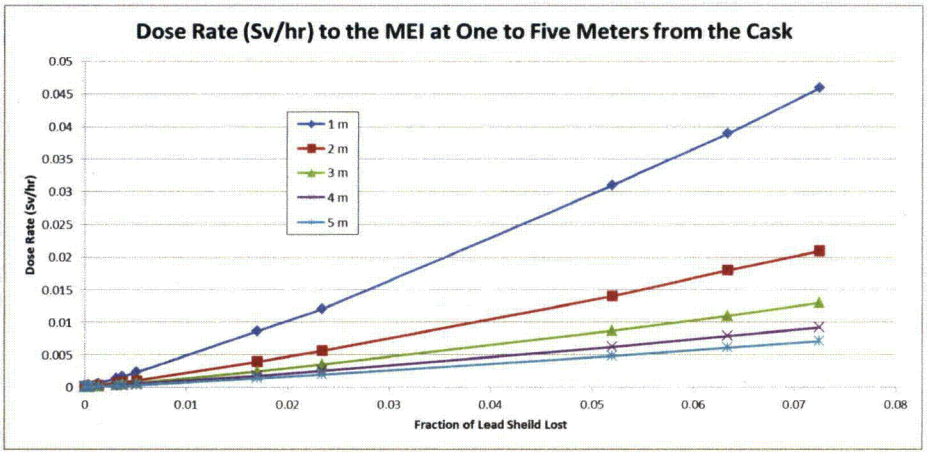


Figure V-4. Radiation dose rates to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from one to five meters from the cask carrying spent fuel.

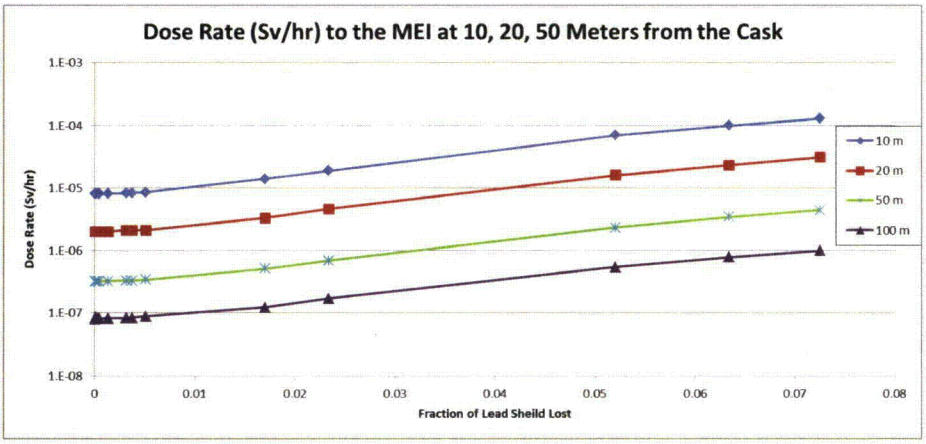


Figure V-5. Radiation dose rates to the maximally exposed individual from loss of lead gamma shielding at distances from 10 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic, so that all of the dose rates can be shown on the same graph.

Table V-3 shows how the dose rate to the maximally exposed individual (MEI) depends on the fraction of the lead shield lost and distance from the cask. The left-hand column of Table V-3 shows lead slump of the cask as computed from the finite element analyses in Chapter 3 and Appendix III. The dose rates shown in the table are computed by RADTRAN using the model discussed in section V.3.1. Only a few of the dose rates in the table exceed the regulatory dose rate of 0.01 Sv/hr from 10CFR71.51 (shown in bold italics in the table). These dose rates are the result of accidents that are much more severe than the regulatory accident and occur with a very small probability (less than one in a billion accidents would produce the amount of lead slump required to result in these dose rates).

The large dose rates that occur near the cask (one to five meters from the cask) would be sustained by emergency responders. The one- to five-meter dose rates can be considered occupational rather than public doses. If a loss-of-shielding accident occurred on a public right of way – a railroad track in this case – no member of the public would be closer than ten meters. The public MEI dose rate (from the largest gap in the lead shield) would be 0.13 mSv/hr (the 10-meter curve in Figure V-5).

Comment [JRC20]: Exposure at the maximum dose rate (maximum slump at one meter) for one hour would approximate the annual occupational dose limit.

The "dose risk" combines the probability of a particular accident with the consequence (the dose). It is a risk, not a dose, and is much smaller than the dose due to the very low probability of an accident that produces loss of shielding. Tables V-4 and V-5 show the conditional dose risk, the combination of the conditional probability with the consequence, for each fractional loss of lead shielding. For distances less than 10 meters from the cask, these doses are for a one hour exposure and represent an occupational dose to emergency responders. For distances of 10 meters and greater, these doses are for a 10 hour exposure and represent the dose to the public. These dose risks are the risk of a particular accident scenario if there is an accident, and does not include the probability of an accident.

Comment [JRC21]: Table V-3 estimates accident consequences (dose rates) only; it does not consider the probability of an accident severe enough to produce those consequences.

Comment [JRC22]: The dose-risk

Table V-3. Radiation dose rates (Sv/hr) to the MEI at various distances for the cask. The numbers in bold italics exceed the external dose rate of 10 CFR 71.51. The dose rates are the direct output of the RADTRAN loss-of-shielding model.[2]

Fraction of slumped lead	1 m	2 m	3 m	4 m	5 m	10 m	20 m	50 m
7.25E-02	***4.6E-02***	***2.1E-02***	***1.3E-02***	9.2E-03	7.1E-03	1.3E-04	3.1E-05	4.4E-06
6.34E-02	***3.9E-02***	***1.8E-02***	***1.1E-02***	7.9E-03	6.1E-03	1.0E-04	2.3E-05	3.4E-06
2.34E-02	***1.2E-02***	5.6E-03	3.5E-03	2.5E-03	1.9E-03	1.9E-05	4.6E-06	6.9E-07
1.70E-02	8.6E-03	3.9E-03	2.4E-03	1.7E-03	1.3E-03	1.4E-05	3.3E-06	5.1E-07
5.12E-03	2.3E-03	1.0E-03	6.4E-04	4.6E-04	3.5E-04	8.5E-06	2.1E-06	3.4E-07
4.26E-03	1.9E-03	8.3E-04	5.2E-04	3.8E-04	2.9E-04	8.4E-06	2.1E-06	3.3E-07
3.73E-03	1.6E-03	7.2E-04	4.5E-04	3.3E-04	2.5E-04	8.3E-06	2.1E-06	3.3E-07
3.16E-03	1.3E-03	6.1E-04	3.8E-04	2.8E-04	2.1E-04	8.2E-06	2.1E-06	3.3E-07
1.31E-03	5.7E-04	2.6E-04	1.7E-04	1.2E-04	9.5E-05	8.1E-06	2.0E-06	3.2E-07
3.37E-04	2.3E-04	1.1E-04	7.2E-05	5.3E-05	4.2E-05	8.1E-06	2.0E-06	3.2E-07
2.80E-04	2.1E-04	1.0E-04	6.7E-05	5.0E-05	4.0E-05	8.1E-06	2.0E-06	3.2E-07
1.84E-05	1.4E-04	7.2E-05	4.8E-05	3.6E-05	2.9E-05	8.1E-06	2.0E-06	3.2E-07

[2] A rigorous calculation was performed at Oak Ridge National Laboratory using a 3D radiation shielding model. The comparison of results with those in Table V-3 indicate that the results are acceptable. Results of the more rigorous calculation show generally good agreement; however, the ORNL 1 m values are 33-67% higher than the Table V-3 values. The differences may be the result of the manner in which the loss-of-shielding model was incorporated into RADTRAN: the additional dose due to the shielding gap was expressed by a multiplier to the external dose rate.

Formatted: Font: Bold
Formatted Table
Formatted: Not All caps
Formatted: Font: Bold
Formatted: Centered, None, Space After: 0 pt, No bullets or numbering, No page break before, Don't keep with next, Tab stops: Not at 0.5"
Formatted: Not All caps
Formatted: Font: Bold
Formatted: Not All caps
Formatted: Centered, Space After: 0 pt
Formatted: Font: Bold
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Font: Bold
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Space After: 0 pt
Formatted: Centered, Indent: Left: 0", First line: 0", Space After: 0 pt
Deleted:
Deleted: your
Deleted: likely
Deleted: provided some words on the degree of reliability of the values are included
Deleted: .
Deleted: dl
Deleted:

Table V-4. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances from the cask from one to five meters for one hour. The "conditional dose risk" is the product of conditional probabilities from Table V-2 and the 1 to 5 meter doses from Table V-3.

Fraction of slumped lead	Conditional Probability	Distance from the cask (m)				
		1	2	3	4	5
7.25E-02	5.96E-12	2.74E-13	1.25E-13	7.74E-14	5.48E-14	4.23E-14
6.34E-02	3.57E-11	1.39E-12	6.43E-13	3.93E-13	2.82E-13	2.18E-13
2.34E-02	6.79E-10	8.15E-12	3.80E-12	2.38E-12	1.70E-12	1.29E-12
1.70E-02	1.13E-10	9.73E-13	4.41E-13	2.72E-13	1.92E-13	1.47E-13
5.12E-03	8.62E-07	1.98E-09	8.62E-10	5.52E-10	3.97E-10	3.02E-10
4.26E-03	3.40E-10	6.34E-13	2.81E-13	1.77E-13	1.29E-13	9.78E-14
3.73E-03	1.44E-07	2.30E-10	1.03E-10	6.47E-11	4.74E-11	3.59E-11
3.16E-03	1.79E-11	2.32E-14	1.09E-14	6.79E-15	5.00E-15	3.75E-15
1.31E-03	6.34E-07	3.61E-10	1.65E-10	1.08E-10	7.61E-11	6.02E-11
3.37E-04	3.80E-06	8.75E-10	4.18E-10	2.74E-10	2.02E-10	1.60E-10
2.80E-04	4.31E-07	9.19E-11	4.44E-11	2.91E-11	2.15E-11	1.71E-11
1.84E-05	1.90E-06	2.66E-10	1.37E-10	9.13E-11	6.84E-11	5.51E-11

Formatted: None, Space After: 0 pt, No bullets or numbering, No page break before, Don't keep with next, Tab stops: Not at 0.5"

Table V-5. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances 10 to 100 meters from the cask for 10 hours. The "conditional dose risk" is the product of conditional probabilities from Table V-2 and the 10, 20, and 50 meter doses from Table V-3 and the 100-meter dose from Figure V-5.

Fraction of slumped lead	Conditional Probability	Distance from the cask (m)			
		10	20	50	100
7.25E-02	5.96E-12	7.74E-15	1.85E-15	2.62E-16	5.93E-17
6.34E-02	3.57E-11	3.57E-14	8.22E-15	1.22E-15	2.82E-16
2.34E-02	6.79E-10	1.29E-13	3.12E-14	4.69E-15	1.16E-15
1.70E-02	1.13E-10	1.58E-14	3.74E-15	5.77E-16	1.37E-16
5.12E-03	8.62E-07	7.33E-11	1.81E-11	2.93E-12	7.53E-13
4.26E-03	3.40E-10	2.84E-14	7.13E-15	1.13E-15	2.87E-16
3.73E-03	1.44E-07	1.19E-11	3.02E-12	4.74E-13	1.19E-13
3.16E-03	1.79E-11	1.47E-15	3.75E-16	5.90E-17	1.47E-17
1.31E-03	6.34E-07	5.13E-11	1.27E-11	2.03E-12	5.15E-13
3.37E-04	3.80E-06	3.08E-10	7.61E-11	1.22E-11	3.07E-12
2.80E-04	4.31E-07	3.49E-11	8.62E-12	1.38E-12	3.47E-13
1.84E-05	1.90E-06	1.54E-10	3.80E-11	6.08E-12	1.50E-12

Formatted: None, Space After: 0 pt, No bullets or numbering, No page break before, Don't keep with next, Tab stops: Not at 0.5"

Formatted: Highlight

Formatted: Font: 12 pt, Highlight

Formatted: Highlight

Formatted: Font: 12 pt, Highlight

Formatted: Highlight

Comment [JRC23]: 10 meter doses exceed 5 meter doses??

Formatted: Font: 12 pt, Highlight

The collective dose risk to an exposed population within a radius *r* of the cask may be calculated by equation (V-1)

(V-1)

Where:

A is the accident frequency per km on the route segment under consideration
L is the length of the route segment in km
PD is the population density per km^2
S is the shielding factor due to residence type from Table II-3
P_{ci} is the conditional probability of the ith fractional loss of shielding
10^{-6} is used to convert the integrated area from m^2 to km^2
r is the distance from the cask: 20 to 800 meters
D_{ir} is the dose from the ith fractional loss of shielding at a distance r from the cask (these are tabulated in Table V-3)
$2\pi rdr$ is the incremental area of the band at distance r from the cask (in m^2) .

The index *i* indicates a particular fractional shielding loss; these are summarized above in Table V-3. The summation in equation (V-1) is the conditional dose risk of all of the accident considered: the "universe" of accidents. Only one accident is modeled, which is assumed to occur on any route segment, but not on more than one route segment. The summation is Equation V-1 is independent of accident location.

Population dose risk ultimately depends on the accident frequency as well as on the population along the route where the accident happens. The accident frequency, accidents per km, is equated to the accident probability. The rail accident frequencies used in this analysis are from DOT, 2008. Average railcar accident frequencies for each of the 16 rail routes are shown in Table V-6. These accident frequencies are combined with the average dose risk integrated over the potentially exposed population.

Table V-7 shows the collective dose risks to populations on each side of the rail cask that has lost lead shielding on impact. These estimates include both the conditional probabilities and the accident frequencies on each route, as in Equation (V-1).

Comment [JRC24]: delete

Deleted: [8] For a particular population density, the collective dose is the same for a semicircle (or any segment of a circle) of 20 m radius, 100 m. radius, or 800 m. radius, because the population in a semicircle is proportional to r^2 and the average dose is proportional to $1/r^2$. The average dose decreases as the total population increases.¶

Formatted: Font: 12 pt, Highlight

Table V-6. Average railcar accident frequencies on the routes studied.

Origin	Destination	Average Accidents per km
MAINE YANKEE	ORNL	6.5×10^{-7}
	DEAF SMITH	5.8×10^{-7}
	HANFORD	4.2×10^{-7}
	SKULL VALLEY	5.1×10^{-7}
KEWAUNEE	ORNL	4.3×10^{-7}
	DEAF SMITH	3.3×10^{-7}
	HANFORD	2.4×10^{-7}
	SKULL VALLEY	3.7×10^{-7}
INDIAN POINT	ORNL	8.8×10^{-6}
	DEAF SMITH	6.2×10^{-7}
	HANFORD	5.1×10^{-7}
	SKULL VALLEY	5.5×10^{-7}
INL	ORNL	3.6×10^{-7}
	DEAF SMITH	3.5×10^{-7}
	HANFORD	3.2×10^{-7}
	SKULL VALLEY	2.8×10^{-7}

Deleted: 5.1

Deleted: ¶
¶

Deleted: - - - - - - Page Break- - - - - - -

Formatted: Tab stops: Not at 0.06"

Table V-7. Conditional collective dose risks per shipment (person-Sv) from loss of lead shielding, including conditional probabilities. These are not the total dose risks.

Comment [JRC25]: but not including accident frequency from table v-6?

ORIGIN	TYPE	Destination			
		ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	Rural	2.11E-14	2.65E-14	4.74E-14	3.59E-14
	Suburban	2.23E-13	2.34E-13	**2.16E-13**	2.19E-13
	Urban	5.95E-15	7.17E-15	8.19E-15	4.83E-15
KEWAUNEE	Rural	9.64E-15	6.29E-15	8.06E-15	1.34E-14
	Suburban	9.07E-14	5.49E-14	4.50E-14	9.41E-14
	Urban	3.35E-15	2.25E-15	8.24E-16	2.38E-15
INDIAN POINT	Rural	1.12E-13	2.25E-14	3.02E-14	3.04E-14
	Suburban	3.04E-12	2.07E-13	2.16E-13	2.33E-13
	Urban	3.72E-13	8.15E-15	7.27E-15	7.21E-15
IDAHO NATIONAL LAB	Rural	1.66E-14	4.00E-15	2.56E-15	1.62E-15
	Suburban	8.09E-14	3.60E-14	1.76E-14	1.26E-14
	Urban	1.34E-15	6.49E-16	3.71E-16	4.38E-16

Formatted: Left

Example: For the suburban route segment of the Maine Yankee-to-Hanford route:

Deleted:

Accident rate: 4.2E-7/km
Segment Length: 1135 km.
Population density: 357 persons/km^2
Suburban shielding factor: 0.87
Dose risk = 4.2E-7 accident/km*1135 km*357persons/km^2*0.87*1.46E-12 Sv-km^2/accident
= 2.16E-13 person-Sv

V.3.1.2 Loss of Lead Shielding with Fire

Deleted: - - -Section Break (Next Page)- - -

The loss of lead shielding does not occur during a fire. Lead expands as it melts and can buckle the innermost cask shell. When the melted lead cools and solidifies, it occupies the same volume as before expansion but the volume available between the steel cask shells is larger because of the buckling of the inner shell, leaving a gap. Melting of lead and the formation of a gap in the lead are described fully in Appendix IV. Briefly, if the cask is offset from the fire, the gap would be in the section of lead shield facing the fire. In an engulfing fire, the gap would be at the upper surface of the cask. However, if the cask is turned after the melted lead has solidified; the gap in the lead would be on the side of the cask rather than at the top. Thus, in both cases, anyone facing the side of the cask with the shielding gap could sustain an increased radiation dose.

Comment [JRC26]: Occurs following

Comment [JRC27]: explain

Two accidental fire scenarios can result in a loss of lead shielding:

- Fire Scenario 1: a sufficiently hot pool fire engulfing a cask on the ground can melt enough lead in three hours to create an 8.14 percent fractional shield loss.
- Fire Scenario 2: a sufficiently hot pool fire offset from the cask, burning for more than three hours, can create a 2.01 percent fractional shield loss.

These scenarios are described fully in Appendix IV. The doses sustained by the maximally exposed individual at various distances from the cask, exposed for an hour, are shown in Table V-9.

Table V-8. Radiation dose (Sv) to the maximally exposed individual at various distances from a cask that has been in a fire (direct RADTRAN output)

Fraction of lead lost[a]	1 m	2 m	5 m	10 m	20 m	50 m	100 m
0.0201	7.0E-03	3.1E-03	1.1E-03	1.1E-05	2.6E-06	3.9E-07	9.4E-08
0.0814	3.5E-02	1.6E-02	5.4E-03	1.1E-04	2.6E-05	3.7E-06	8.5E-07

[a] From the thermal analyses in Chapter 4 and Appendix IV.

No lead shielding would be lost until after the fire was out and the cask had cooled enough for the lead to solidify, since only then would there be a gap in the lead shield. Differential heating of the lead shield could result in geometry and associated volume changes that could impact the shielding effectiveness locally. Such effects would have minimal impact on the dose. Thus no one would be exposed for many hours after the accident, and with a fire this severe, nearby residents and the public would probably have been evacuated. The maximally exposed individual in this case would be an emergency responder. Under these circumstances, measures could be taken to mitigate emergency responder exposures.

Volpe (2006, Figure 16) postulates a chain of events leading to a fire, from which the probability of these scenarios can be calculated. The relevant portion of the Volpe figure is shown in Figure V-6 below.

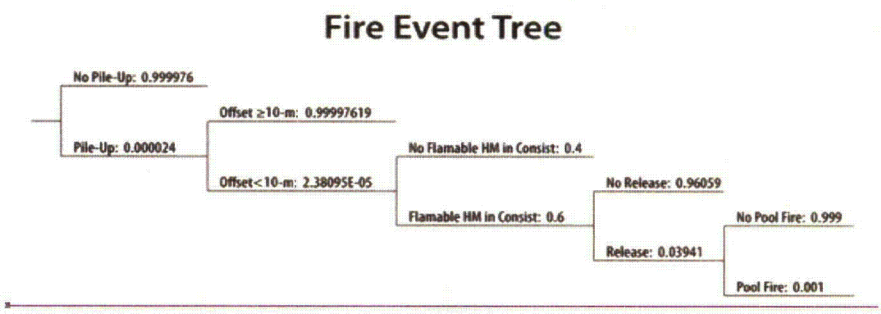


Figure V-6. Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16).

Deleted: Angie
Deleted:
Comment [JRC28]: slump?
Formatted: Font: 12 pt, Not Italic, Superscript
Formatted: Font: 12 pt, Not Bold, Not Italic, Superscript
Deleted:
Formatted: Font: Times New Roman, 12 pt, Not Bold, Not Italic
Field Code Changed

The first of these events is a major derailment, as shown in Table V-10. Volpe estimates that the speed at the time of the accident for such a derailment is at least 50 mph (80kph). If a pileup could occur in any kind of derailment other than in a tunnel, from Figure V-2, the probability of such a major collision/derailment/fire is

$$P_{derailment} * P_{fire} * (P_{80\text{-}113kph\ collision} + P_{>113kph\ collision})) * [P_{offbridge} * (P_{slope} + P_{embankment} + P_{structure}) + P_{onbridge}] = P$$

$$(0.7355)*(0.0155)*(0.06614+0.00061)*[.9887*(0.0011+0.0004+0.0077) +.0113] = 1.55 \times 10^{-5}$$

The summation of surfaces struck does not include the "other" branch of the event tree because this branch represents the most common case for derailments—where the derailed cars remain upright on the side of the track. Table V-10 lists the other events in the scenario, together with the probability of each event. These events are a pileup, a flammable hazardous cargo within 10 meters (about half a rail-car length), leaking of that hazardous substance, and ignition of a pool fire. The net probability of the sequence of events shown in Table V-10 following a major pileup is 1.35×10^{-14}. The net probability depends on the very small pileup probability of 2.4×10^{-5}. Thus it is instructive to estimate the probability without the assumption of a pileup. Using the "no pileup" branch, the net probability for the events of Table V-10 is 5.6×10^{-10}, still an exceptionally small number. The uncertainties in this analysis are exceedingly large compared to the probabilities. Essentially, the sequence of events in Figure V-6, with or without the pileup, is unlikely to happen.

The conditional probability of Fire Scenario 1, a major derailment with or without a pile-up that leads to a three-hour pool fire that surrounds the cask, is

$$(1.55 \times 10^{-5})*(5.6 \times 10^{-10}) = 8.7 \times 10^{-15}$$

The conditional probability of Fire Scenario 2, a major derailment that does not involve a pile-up but leads to a three-hour fire offset from the cask by more than 10 meters, is then

$$(1.55 \times 10^{-5})*(2.36 \times 10^{-5}) = 3.7 \times 10^{-10}$$

Table V-9. Events leading to a train fire that could involve a spent fuel cask

Event	Probability	Alternative event	Probability
Major derailment (>48 kph)	8×10^{-5}	No major derailment	0.99992
Pileup	2.4×10^{-5}	No pileup	0.99998
Offset < 10 m	2.38×10^{-5}	Offset >10 m	0.99998
Flammable hazardous material in another railcar	0.6	No flammable material available	0.4
Release of flammable material	0.0394	No release of flammable material	0.9606
Pool fire	0.001	No pool fire	0.999

Comment [JRC29]: Not in Figure V-7

Comment [rw30]: Mona has fixed the rail event tree so it is all kph.

Deleted: 5

Deleted: 70

Deleted: m

Deleted: 70m

Deleted: (

Formatted: Font: Not Bold, Not Italic, Subscript

Deleted:

Deleted: i

Formatted: Font: Not Bold, Not Italic, Not Superscript/ Subscript

Deleted:)

Deleted: (

Deleted:)

Deleted: 56

Comment [JRC31]: Suggests we know what they are?

Deleted:

Deleted:

Deleted:

Comment [JRC32]: Does not match 1.35x10-14 in text? V-10 Net probability does not fire scenario 1 conditional probability? Text says net probability dependent on pileup, but conditional probability same with or without plie-up?

Deleted: 6

Deleted: 8

Deleted: .56

Deleted: ------ Page Break------

Formatted Table

Deleted: Major high speed derailment

Deleted: 30

Deleted: m

Formatted: Superscript

Deleted: 9

The average accident frequency for the 16 rail routes studied is 1.9×10^{-3} (the range is from 1.3×10^{-4} to 1.1×10^{-2}).[3] Thus, the average probability of an accidental fire that could cause loss of lead shielding in a rail cask is $1.9 \times 10^{-3} * 8.7 \times 10^{-15} = 1.7 \times 10^{-17}$ if the cask is concentric with the fire and $1.9 \times 10^{-3} * 3.7 \times 10^{-10} = 7.0 \times 10^{-13}$ if the cask and fire are offset by 10 meters or more. The largest dose risk to a person 1-meter away from the cask with 2% lead loss for an hour would be $7.0 \times 10^{-13} * 7.0 \times 10^{-3} = 4.9 \times 10^{-15}$ Sv (this dose risk is larger than that from the cask in the engulfing fire).

Deleted: 3

Deleted: 5

Deleted: 4.2

Formatted: Font: 12 pt, Not Highlight

Formatted: Font: 12 pt, Not Highlight

Deleted: 19

Formatted: Font: 12 pt, Not Superscript/ Subscript

Deleted: 3.4

Formatted: Font: 12 pt, Not Superscript/ Subscript

Deleted: 1.4

Deleted: 14

Formatted: Font: 12 pt, Not Superscript/ Subscript

Deleted: 4.9

Deleted: 17

Comment [JRC33]: How possible if engulfing fire has 8% shield loss?

V.3.2 Loss of Neutron Shielding

The neutron shield is usually a hydrocarbon or carbohydrate polymer, sometimes borated, since boron and organic polymers are good neutron absorbers. Neutron shielding burns, and could be destroyed in a fire. The neutron dose from loss of shielding in a fire is estimated using the parameters listed in Table V-11. The conditional probability of a truck fire is from Figure V-1. The conditional probability of a rail fire is a combination of the fire probability in Figure V-2 and the following steps from Table V-10.

- A pileup
- Flammable cargo on the train
- Release of the flammable cargo

The neutron dose at two meters from the Truck-DU cask is from General Atomics, 1998; for the Rail-Lead cask, from NAC International, 2002; and for the Rail- Steel cask, from Holtec International, 2004. The respective TI values were calculated from these numbers using RADTRAN, which slightly overestimates results (Steinman, et al., 2002). The RADTRAN external dose rate is then modeled as entirely neutron emission. The other parameters are the same as those used in calculating doses from an accident in which there is no release of radioactive material and no loss of lead shielding (Chapter 5, Section 5.4).

[3] This is obtained by multiplying the appropriate accident frequency per km from Table V-7 by the appropriate route length in km from Table 2-5.

Table V-10. Some parameters used in calculating loss of neutron shielding.

Parameter	Truck-DU	Rail-Lead	Rail-All Steel
Conditional probability of a fire[a]	0.0063	8.9×10^{-8}	8.9×10^{-8}
Neutron dose rate at one meter from the cask in mSv/hour (mrem/hour)[b]	1.78 (178)	1.81 (181)	1.82 (182)
Shielding of residents.	none	none	none
Time until the cask is removed (hours)	10	10	10

[a] The truck fire probability comes from Figure V-1 and the rail fire probability comes from Volpe (Volpe-Center, 2006).

[b] The neutron dose at two meters from the Truck-DU cask is from General Atomics, 1998; for the Rail-Lead cask, from NAC International, 2002; and for the Rail- Steel cask, from Holtec International, 2004. The respective TI values were calculated from these numbers using RADTRAN, which slightly overestimates results (Steinman, et al., 2002). The RADTRAN external dose rate is then modeled as entirely neutron emission.

The neutron doses to emergency responders (five meters from the cask) are shown in Table V-12, the collective doses on the 16 routes are shown in Table V-13, and the total collective dose risks, including accident frequency, are shown in Table V-14. For the Rail-Lead cask, the neutron doses would add to the gamma dose from the loss of lead shielding.

Table V-11. Doses to an emergency responder five meters from the cask.

Cask	Ten-hour 10 CFR 71.51 dose in Sv
Truck-DU	0.0073
Rail-Lead	0.0076
Rail-All Steel	0.0077

```
RADTRAN STOP INPUT FILE

STOP RESPONDERT GA_4 1.0 5.0 5.0 1.0 10.0
STOP RESPONDERNAC NAC-STC 1.0 5.0 5.0 1.0 10.0
STOP RESPONDERHI HISTAR 1.0 5.0 5.0 1.0 10.0

RADTRAN OUTPUT FILE

STOP EXPOSURE IN PERSON-REM

LINE-SOURCE    RESPONDERT    7.29E-01
LINE-SOURCE    RESPONDERNAC  7.61E-01
LINE-SOURCE    RESPONDERHI   7.73E-01
```

Figure V-7. RADTRAN input and output for Table V-12.

Comment [JRC34]: 5 orders of magnitude greater than rail?

Formatted: Font: 12 pt, Superscript

Deleted: D

Formatted: None, Indent: Left: 0", First line: 0", Line spacing: At least 12 pt, Don't keep with next, Don't adjust space between Latin and Asian text

Deleted:

Deleted: a

Formatted: Font: 12 pt, Not Bold, Superscript

Formatted: Font: 10 pt

Formatted: Font: 10 pt, Superscript

Formatted: Font: 10 pt

Formatted: Font: Times New Roman, 10 pt

Deleted: a

Formatted: Font: 10 pt, Not Bold, Not Italic

Comment [JRC35]: This footnote repeats text on page v-23.

Comment [JRC36]: 16 truck and 16 rail

Deleted: =

Deleted: ¶

Deleted: ¶

Deleted:

Deleted:

Deleted:

Table V-12. Collective doses (consequences) to an emergency responder in person-Sv from loss of neutron shielding

FROM	TO	Truck-DU	Rail-Lead	Rail-All Steel
MAINE YANKEE	ORNL	7.49E-04	7.17E-04	7.40E-04
	DEAF SMITH	7.01E-04	6.71E-04	6.93E-04
	HANFORD	6.23E-04	5.96E-04	6.15E-04
	SKULL VALLEY	6.38E-04	6.11E-04	6.31E-04
KEWAUNEE	ORNL	6.87E-04	6.57E-04	6.78E-04
	DEAF SMITH	6.41E-04	6.13E-04	6.33E-04
	HANFORD	5.98E-04	5.72E-04	5.91E-04
	SKULL VALLEY	6.17E-04	5.91E-04	6.10E-04
INDIAN POINT	ORNL	7.28E-04	6.97E-04	7.20E-04
	DEAF SMITH	6.95E-04	6.65E-04	6.87E-04
	HANFORD	6.38E-04	6.11E-04	6.31E-04
	SKULL VALLEY	6.63E-04	6.34E-04	6.55E-04
INL	ORNL	5.78E-04	5.53E-04	5.71E-04
	DEAF SMITH	6.16E-04	5.89E-04	6.08E-04
	HANFORD	3.78E-04	3.62E-04	3.73E-04
	SKULL VALLEY	6.41E-04	6.13E-04	6.33E-04

Table V-13. Collective dose risks in person-Sv from loss of neutron shielding

FROM	TO	Truck-DU	Rail-Lead	Rail-All Steel
MAINE YANKEE	ORNL	4.7E-06	6.4E-11	6.6E-11
	DEAF SMITH	4.4E-06	6.0E-11	6.2E-11
	HANFORD	3.9E-06	5.3E-11	5.5E-11
	SKULL	4.0E-06	5.4E-11	5.6E-11
KEWAUNEE	ORNL	4.3E-06	5.8E-11	6.0E-11
	DEAF SMITH	4.0E-06	5.5E-11	5.6E-11
	HANFORD	3.8E-06	5.1E-11	5.3E-11
	SKULL	3.9E-06	5.3E-11	5.4E-11
INDIAN POINT	ORNL	4.6E-06	6.2E-11	6.4E-11
	DEAF SMITH	4.4E-06	5.9E-11	6.1E-11
	HANFORD	4.0E-06	5.4E-11	5.6E-11
	SKULL	4.2E-06	5.6E-11	5.8E-11
INL	ORNL	3.6E-06	4.9E-11	5.1E-11
	DEAF SMITH	3.9E-06	5.2E-11	5.4E-11
	HANFORD	2.4E-06	3.2E-11	3.3E-11
	SKULL	4.0E-06	5.5E-11	5.6E-11

V.4 Release of Radioactive Materials in Accidents

V.4.1 Spent Fuel Inventory

A Rail Lead -cask is the only cask studied that would release any radioactive material in an accident. Since there is no traffic accident that would result in a release from the Truck-DU or Rail-All Steel cask, the inventory of those casks is not relevant to this analysis. The fuel used in this analysis is PWR fuel, 45,000 MWD/MTU burnup, the maximum burnup that a Rail-Lead cask would transport, and has cooled for nine years before transport (Appendix I). The radionuclide inventory of this fuel was determined using ORIGEN (Croff, 1980). The radionuclide activities in the inventory were "normalized" by dividing each activity by the A_2 value for that radionuclide. The A_2 value, the amount of the radionuclide that could be transported in a Type A container, is an indication of the radiotoxicity; the larger the A_2 value, the smaller the radiotoxicity of that nuclide. The normalized radioactivities were then sorted and added until 99.99 percent of the total normalized radioactivity was reached. The "total normalized activity" referred to here is not the total A_2 value as calculated by the formula in 10 CFR Part 71 Appendix A. The radionuclides selected this way are listed in Table V-15, together with their actual radioactivities (not the normalized radioactivities). Normalized radioactivities are used only to identify 99.9 percent of the radiotoxicity. The actual activity is the basis for the release fraction of each radionuclide.

Comment [JRC37]: Rail-Lead cask

Table V-14. TBq inventory for the Rail-Lead cask.

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
^{154}Eu	9.01E+02
^{134}Cs	4.03E+02
^{85}Kr	2.26E+03
^{241}Am	1.58E-01
^{242}Cm	1.00E+00
^{155}Eu	2.63E+02
^{231}Pa	3.12E-02
^{106}Ru	7.50E+00
^{236}U	1.92E-01
^{63}Ni	8.99E+02
^{233}U	5.75E-01
^{241}Pu	6.13E-01
^{113m}Cd	5.24E+00

V.4.2 Dispersion of Released Radionuclides

If a spent fuel cask transportation accident did result in the release of radioactive material, the public could be exposed if the material was dispersed through the air. Experimental work reviewed by Sprung et al. (2000, pp.7-30 et seq.) indicates that only very small particles with analytic mean aerodynamic diameter (AMAD)[4] ten microns or less would be released from a cask in an accident, because the only release path is through the seals at the ends of the cask. Ten microns is generally considered the upper limit of respirability. Thus particles accidentally released from a cask will be released as a respirable aerosol.

The discussion below is an abbreviated discussion of air dispersion, a subject that is treated extensively and in detail in textbooks like Wark and Warner (1981).

The basic equation for atmospheric dispersion of an aerosol is the Gaussian dispersion equation: Equation (V-2) (Turner, 1994, Chapter 2).

(V-2)
$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-z^2}{2\sigma_z^2}\right]$$

where CHI[5] = the concentration of particles in the air
Q = the radioactivity or mass of airborne particles
u = the wind speed
σ_y, σ_z are meteorological constants and are functions of the downwind distance x and the meteorological conditions.

Deleted:

The wind direction is traditionally along the x axis of a Cartesian coordinate system, the crosswind direction is y, and z represents the altitude above ground. When the plume of released material rises buoyantly to a height H, the Gaussian equation becomes

(V-3)
$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right]\left[\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right]$$

where H is the height to which the plume rises before being blown downwind. For a ground-level release along the plume centerline, Equations (V-2) and (V-3) reduce to

$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z}$$

[4] The AMAD is the diameter of a sphere of density 1 gm/cm^3 that has the same inertial properties as the actual particle.

[5] The Greek letter X is traditionally used to represent air concentration, but is so easily confused in typescript with the 24th letter of the alphabet that it is often written phonetically ("chi").

(V-4)

Radioactive gases released in accident will disperse in the air according to Equations (V-1) and (V-3). Particles, however, have mass and will settle on the ground. The settling velocity V_t—the terminal velocity of a particle in the indicated size range—is given by Equation (V-5)

(V-5)

where g = gravitational acceleration
d = particle aerodynamic diameter
ρ = particle density
μ = air viscosity at ambient temperature

Ground deposition rate is then described by Equation (V-6) (Wark and Warner, 1981, Chapter 5)

(V-6)

$$\frac{w_p}{Q} = \frac{V_t}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-\left(H - \frac{xV_t}{u}\right)^2}{2\sigma_z^2}\right]$$

where w_p is the particle deposition rate. These equations are programmed in RADTRAN.

Both wind and air temperature profiles affect the dispersion of airborne material. The predominant motion of airborne material is downwind, while crosswind motion is diffusive. Light winds, stable air, and temperature inversions result in less dispersion and higher airborne and ground concentrations of radionuclides. Strong winds and turbulent air are good conditions for dispersion and result in lower airborne and deposited radionuclides concentration and consequently result in lower radiation doses to the public, even though the plume of radioactive material may spread over a large area.

RADTRAN calculates external doses from deposited material ("groundshine") and from material that remains suspended in the air ("cloudshine"). The code also calculates internal committed doses from airborne material that is inhaled, and from material that becomes resuspended in the air. The doses reported are the sums of the groundshine, cloudshine, inhaled, and resuspended inhaled doses, unless otherwise indicated. Adding these doses to sum to a "total effective dose equivalent" is NRC practice in determining public exposure, as discussed in 10 CFR 20.1301. RADTRAN accommodates a number of atmospheric dispersion conditions.

V.4.3 Release Fractions

Comment [JRC38]: Why are thermal results discussed first when structural precedes it in Chapter order?

Release of radionuclides into the environment from a cask depends on releases from the fuel rods into the cask and from the cask to the environment. If the cask contains canistered fuel, the cask structural and thermal analyses in Chapters 3 and show that the canister does not rupture even under the most severe accidents analyzed, so no radioactive material can exit the cask. In the present study, therefore, only the Rail-Lead transporting uncanistered could release any radioactive material or CRUD as a consequence of a traffic accident. Only PWR spent fuel is considered in this section.

Comment [JRC39]: Appendix III

V.4.3.2 Spent Fuel Radionuclides

When fuel rods are fractured in an impact, they depressurize, and the consequent overpressure sweeps fuel particles out of the cask if there is a breach in the seal. The depressurization and release of material from the rod is described very clearly in Hanson, et al., 2008,

> *When commercial spent nuclear fuel (CSNF) is handled in a dry environment, whether as fuel assemblies, canned, or within a container, one possible mechanism for radionuclide release is a drop accident scenario, [in which] it is possible that the cladding could fracture, and cans or containers could breach..., (Sprung et al. 2000)[6]. Upon clad breach, it is expected that the rod would rapidly depressurize, releasing its fill gas (e.g., He) and fission gases (e.g., Kr, Xe) that have been released from the fuel matrix, depending on the size of the cladding defect and fuel burnup characteristics (Einziger and Beyer 2007[7])..... It is also possible for fuel fines to be ejected as the high-pressure fill and fission gases rapidly escape through the defect.... (Hanson, et al., 2008, Section 1)*

The release fractions from the rods to the cask, under the described conditions, are developed from the data of Hanson et al. (2008) for 45 GWD/MTU spent fuel.

Hanson et al. suggest that volatile fission products like the cesium isotopes exhibit release behavior like fission gases. However, any cesium isotope would be released as the oxide or chloride, and would therefore behave more like volatile compounds than like gases. Because the volatile compounds tend to migrate to the fuel rim and Einziger (2007) recommends 3×10^{-5} as an appropriate release fraction for rim material, this release fraction is used for volatiles, including ruthenium, in the present analysis.

Hanson et al. describe a number of mechanical tests performed on unoxidized fuel of varying burnup. Page 4.12 of Hanson et al. (2008) summarizes release fractions from these tests for the fuel that appears to be the most appropriate. A release fraction of 4.8×10^{-6}, based on the information in Hanson et al. (2008), is used in this analysis for release of fine particles from the rod to the cask. An analysis that recognizes and accommodates the uncertainty in estimating release fractions would be appropriate but is beyond the scope of this study.

---

[6] This citation is made by Hanson, et al.
[7] See Footnote 7.

Figure 7.11 of Sprung et al. (2000) presents release fractions of several compounds as functions of the available leak area. The compounds studied represent the physical/chemical groups present in spent nuclear fuel: gas, volatiles, and particulate matter. This figure served as the basis for estimating the cask-to-environment release fractions of the physical/chemical groups studied.

Table V-16 summarizes the parameters from which release fractions were developed.

Table V-15. Parameters for determining release functions for the accidents that would result in release of radioactive material.

Comment [rw40]: Same as Table 5-10

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

Table V-17 shows sources of the parameter values in Table V-18. The parameter values are consistent with Sanders, et al. (1992).

Table V-16. Sources of the parameter values in Table V-16

		Release fraction	Comment
Cask to Environment Release Fraction	**Gas**	0.800	The basis of each release fraction is the size of the gap in the seal – the leak area --, provided for each combination of impact speed and orientation by Table III-1of Appendix III. Release fractions were obtained from the graph of Figure 7.11(p. 7-53) of Sprung et al. (2000).
	Particles	0.70	
	Particles – Corner Impact	0.64	
	Volatiles	0.50	
	Volatiles - Corner Impact	0.45	
	CRUD	0.001	This release fraction is based on Einziger and Beyer (2007) and discussed in Section V.5.4.1.
Rod to Cask Release Fraction	**Gas**	0.12	From Einziger, personal communication.
	Particles	4.80E-06	From the release fraction in Hanson et al., 2008, Table 4.10.
	Particles – Corner Impact	2.4E-06	
	Volatiles	3.00E-05	Average of values in Hanson et al. (2008), Section 4.3, p. 4.12.
	Volatiles - Corner Impact	1.5E-05	
	CRUD	1.00	CRUD is on the outside of the rod.

Formatted Table

The release from these potential accidents is not at ground level but at about two meters above ground, taking into account the height of the flatcar and the diameter of the horizontally mounted cask. The factor *H* in Equation (V-4) is the release height, two meters in this case. The gas flowing from the cask is warmer than ambient and the heat rate is about 660 watts per assembly[8], so that the plume of material will be lofted slightly. Results of the RADTRAN model of Equation (V-4) indicate a maximum air concentration and ground deposition at about 21meters downwind from the cask. Since the release is slightly elevated above ground level, the maximum air concentration at the ground and the maximum deposition are downwind from the release point.[9], based on the postulated meteorological conditions, the maximally exposed individual would be located at this point. A graph of the plume is presented in Figures 5-4a and 5-4b in Chapter 5. Results of the RADTRAN calculation, the radiation dose (consequence) that could result if radioactive material was released in a spent fuel cask accident, are shown in Table V-18.

Deleted:

Deleted:

When the doses in Table V-18 are multiplied by the probabilities in Table V-16, the "conditional dose risks" of Table V-19 result.

Formatted: text

Deleted: ¶
¶
Page Break

[8] For nine-year-cooled PWR fuel from the ORIGEN analysis. 660 watts per assembly = 17160 watts per cask = 4.1 Kcal/sec.

[9] Earlier versions of RADTRAN (before RADTRAN 5.6) could not model elevated releases.

Table V-17. Maximally exposed individual doses (consequences) in Sv from accidents that involve a release.

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Resuspension	Cloudshine	Groundshine	Total
End	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Corner	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	193	elastomer	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	193	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Side	145	elastomer	1.6	0.014	4.5E-06	3.6E-05	1.6
Side	145	metal	1.6	0.014	8.8E-05	9.4E-04	1.6
Corner	145	metal	0.73	0.0063	5.1E-05	9.0E-04	0.73

Table V-18. Maximally exposed individual conditional dose risks in Sv from accidents that involve a release.

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Resuspension	Cloudshine	Groundshine	Total
End	193	metal	9.5E-12	8.2E-14	5.2E-16	5.6E-15	9.5E-12
Corner	193	metal	5.7E-11	4.9E-13	3.1E-15	3.4E-14	5.7E-11
Side	193	elastomer	2.8E-11	2.4E-13	1.6E-15	1.7E-14	2.9E-11
Side	193	metal	2.8E-11	2.4E-13	1.6E-15	1.7E-14	2.9E-11
Side	145	elastomer	5.4E-10	4.7E-12	1.5E-15	1.2E-14	5.4E-10
Side	145	metal	3.4E-07	2.9E-09	1.9E-11	2.0E-10	3.4E-07
Corner	145	metal	3.1E-07	2.7E-09	2.2E-11	4.0E-10	3.1E-07

Comment [rw41]: Same as Table 5-11

Deleted: 1.4E-02
Deleted: 1.6E+00
Formatted: Indent: Left: 0", Hanging: 0.02"
Deleted: 1.6E+00
Formatted Table
Deleted: 1.4E-02
Formatted: Indent: Left: 0", Hanging: 0.02"
Deleted: 1.4E-02
Formatted: Indent: Left: 0", Hanging: 0.02"
Deleted: 1.6E+00
Deleted: 1.4E-02
Formatted: Indent: Left: 0", Hanging: 0.02"
Deleted: 1.6E+00
Deleted: 1.4E-02
Deleted: 1.6E+00
Deleted: 1.4E-02
Deleted: 1.6E+00
Deleted: 0.0001
Deleted: 0.000
Formatted Table

Population doses are calculated by integrating the rural, suburban, and urban population densities, respectively, over the largest plume footprint in the dispersion calculation: 1420 km^2 for average meteorological stability (Pasquill Class 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. Collective dose risks are calculated by multiplying each population dose by the appropriate conditional probability. Collective doses are presented in Table V-20 for the end impact, 193 kph impact speed accident, as an example.

Table V-19. Collective conditional inhalation and external dose risks for the end impact, 193 kph impact speed accident, for the 16 routes analyzed.

	Collective Internal Dose Risk (person –Sv)				Collective External Dose Risk (person –Sv)			
	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE								
Rural	5.2E-15	2.3E-15	3.3E-15	1.6E-15	4.7E-18	2.1E-18	3.0E-18	1.4E-18
Suburban	1.0E-13	6.5E-14	5.5E-14	3.2E-14	9.3E-17	5.9E-17	5.0E-17	2.9E-17
Urban	1.8E-12	1.1E-12	9.3E-13	4.7E-13	1.6E-15	9.9E-16	8.5E-16	4.3E-16
KEWAUNEE								
Rural	2.1E-15	4.8E-16	5.1E-16	5.1E-16	1.9E-18	4.4E-19	4.7E-19	4.7E-19
Suburban	4.4E-14	2.2E-14	2.1E-14	1.9E-14	4.0E-17	2.0E-17	1.9E-17	1.7E-17
Urban	7.7E-13	3.7E-13	3.6E-13	2.5E-13	7.0E-16	3.3E-16	3.3E-16	2.3E-16
INDIAN POINT								
Rural	5.6E-14	1.8E-15	1.9E-15	7.8E-16	5.1E-17	1.7E-18	1.8E-18	7.0E-19
Suburban	1.8E-12	6.6E-14	6.7E-14	2.4E-14	1.6E-15	6.0 E-17	6.0E-17	2.2E-17
Urban	3.0E-11	1.2E-12	1.2E-12	3.8E-13	2.7E-14	1.1E-15	1.1E-15	3.4E-16
IDAHO NATIONAL LAB								
Rural	3.7E-16	2.7E-16	7.4E-17	9.3E-16	3.4E-19	2.5E-19	6.7E-20	8.5E-19
Suburban	1.4E-14	2.4E-14	5.1E-15	3.2E-14	1.2E-17	2.1E-17	4.6E-18	2.9E-17
Urban	1.8E-13	2.9E-13	8.0E-14	5.4E-13	1.7E-16	2.7E-16	7.3E-17	4.9E-16

The values in Table V-20 are calculated as in the following example. This example is for one accident scenario *i*: end impact, 193 kph impact speed accident.

Collective internal dose risk = (accident rate)*(route segment length)*$P_{cond\ i}$*($dose_{inhalation\ i}$ + $dose_{resuspension\ i}$) *] Internal dose includes the doses from both direct inhalation and inhaled material resuspended in air. External doses include cloudshine and groundshine. The NRC cites the total effective dose equivalent (TEDE) which includes both inhalation (internal) doses and external doses. The complete collective dose risk is the sum of the collective dose risks shown in Table V-21 over all accident scenarios , summed over the entire route:.

Comment [JRC43]: So for per shipment risks, would need to multiplied by state accident frequency? Example suggests this is not conditional, but net.

Comment [JRC44]: rail

Deleted:

Formatted Table

Formatted Table

Formatted Table

Formatted Table

Comment [JRC45]: see comment 42

Deleted: 22

Total dose risks (person-Sv) for each route =

Table V-21 shows the total dose risk for each route.

Table V-20. Total dose risks (person-Sv) for each route from an accident involving release, per shipment

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

Comment [JRC46]: collective

Formatted Table

V.5. Summary

Deleted: 6

The technical observations for the analysis of accidents are:

Comment [JRC47]: seem to use findings, conclusions, and observations interchangeably.

- Event trees based on current accident statistics show that 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 or release of radioactive material is negligible.

Comment [JRC48]: Conditional or net?

Comment [JRC49]: delete

- The analyses in Appendices III and IV demonstrate that there would be no releases of radioactive material from a cask carrying canistered fuel, and the only cask that would suffer a loss of lead shielding or release of radioactive material is the Rail-Lead cask. Most accidents involving spent fuel casks – 99.991 percent – do not lead to either a release of radioactive material or a loss of lead gamma shielding.

Comment [JRC50]: could

- A dose larger than the 10 CFR 71.51 limit would be sustained only if more than two percent of the lead shielding is lost and if the receptor is within four meters of the cask.

- If the fuel rods are not breached in an accident, even if the seals are compromised, there would be no net flow of gas out of the cask, and nothing would be released.

Comment [JRC51]: Is this scenario worth consideration?