APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

H-18

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APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

V.1 Types of Accidents and Incidents

The different types of accidents 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 lead gamma shielding but no release of radioactive material.
  - Accidents in which there is a release of radioactive material.

Comment [h1]: Also include the loss of neutron shielding listed here?

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 Rail-Lead cask is the only cask studied that uses a lead gamma shield, and is therefore the only cask that could be involved in an accident causing a loss of lead gamma shielding. The shielding could thin or develop a gap in an accident. The Rail-All Steel rail cask is a monolithic steel cask and is loaded with canistered fuel, so that even in an accident there would be no release of radioactive material. Chapter 3 and Appendix III discuss the accident behavior of the Truck-DU cask, which uses a depleted uranium (DU) gamma shield, and conclude that the Truck-DU cask will not release radioactive material in any achievable accident. Accidents that involve the RAIL-All Steel and the Truck-DU are limited to the first two types described above, as discussed in Chapter 5. The NAC-STC could either lose lead shielding or release radioactive material in an accident, and is the only cask of the three whose behavior is discussed in this appendix.

Comment [h2]: This is a definitive statement that should be softened. I suggest something like the following:

" In accordance with the assumed accidents considered in this analysis, there would be no release of radioactive material"

Comment [h3]: Shouldn't this include the Fire scenarios discussed in Chapter 4 as well?

[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:

- 1.87×10^{-6}/km for large trucks on interstates and primary highways.
- $1.08\text{x}10^{-7}$/railcar km for freight rail

Comment [h4]: From the values listed in Table V-1 below, I get an average of 1.98e-6

Comment [h5]: From the values listed in Table V-1 below, I get an average of 1.32E-7

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.

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

YEAR	Truck ACCIDENTS/KM	RAILCAR ACCIDENTS PER RAILCAR KM
1991	$2.39\text{x}10^{-6}$	$2.08\text{x}10^{-7}$
1992	$1.99\text{x}10^{-6}$	$1.91\text{x}10^{-7}$
1993	2.19x10-^{6}	$1.68\text{x}10^{-7}$
1994	2.19x10-^{6}	$1.64\text{x}10^{-7}$
1995	2.39x10-^{6}	$1.53\text{x}10^{-7}$
1996	$1.90\text{x}10^{-6}$	$1.39\text{x}10^{-7}$
1997	$1.89\text{x}10^{-6}$	$1.32\text{x}10^{-7}$
1998	$2.04\text{x}10^{-6}$	$1.19\text{x}10^{-7}$
1999	$1.84\text{x}10^{-6}$	$1.12\text{x}10^{-7}$
2000	$2.08\text{x}10^{-6}$	$1.12\text{x}10^{-7}$
2001	$1.99\text{x}10^{-6}$	$1.18\text{x}10^{-7}$
2002	$1.83\text{x}10^{-6}$	$1.12\text{x}10^{-7}$
2003	$1.85\text{x}10^{-6}$	$1.02\text{x}10^{-7}$
2004	$1.90\text{x}10^{-6}$	$1.00\text{x}10^{-7}$
2005	$1.73\text{x}10^{-6}$	$1.06\text{x}10^{-7}$
2006	$1.83\text{x}10^{-6}$	$1.04\text{x}10^{-7}$
2007	$1.59\text{x}10^{-6}$	$9.60\text{x}10^{-8}$

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.

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.

Figures 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.

$$P_{conditional} = P_{collision} * P_{bridge\ accident} * P_{fall\ off\ bridge} * P_{rocky\ soil}$$

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

Comment [h6]: According to the Truck event tree below, the P(bridgeaccident) value should be 0.04, not 0.064.

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

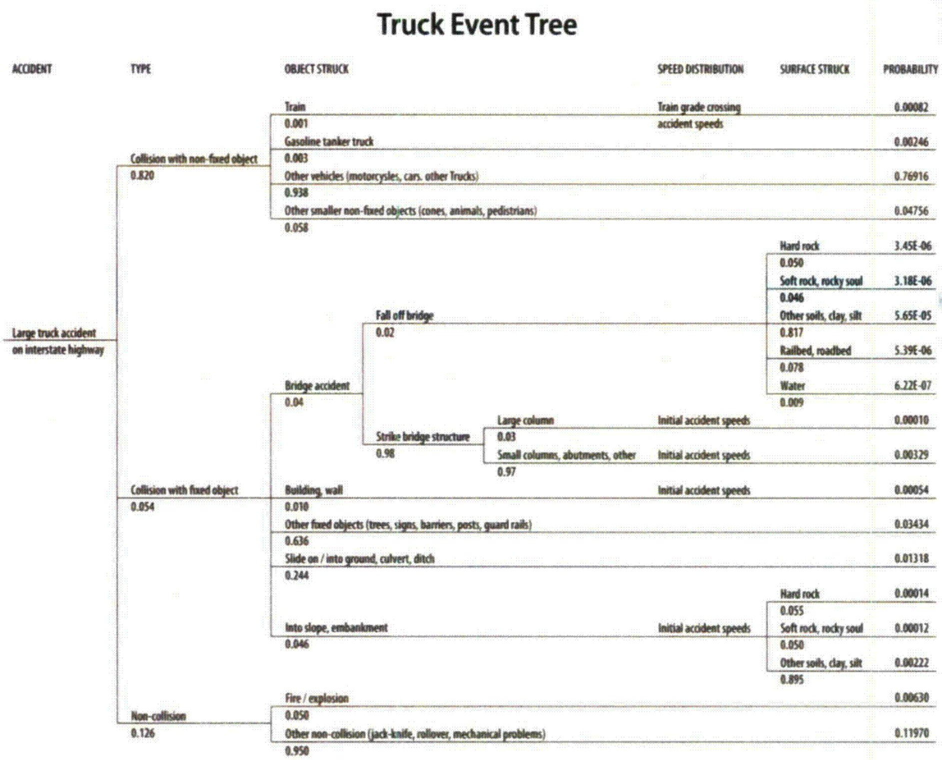

Figure V-1 Event tree for highway accidents (from Mills, et al, 2006)

Comment [h7]: Only 5% of the truck accidents were with fixed objects? This seems awfully low.

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.

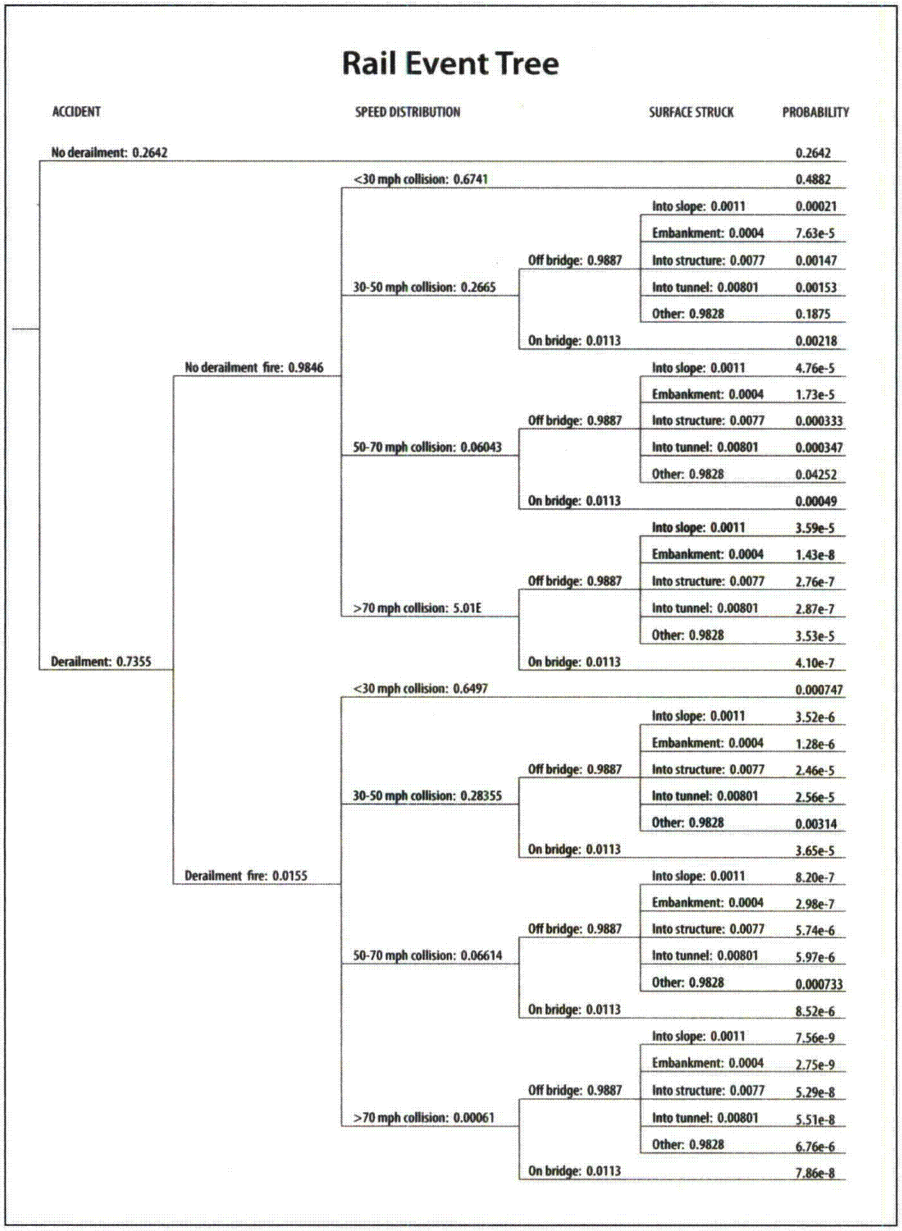

Figure V-2 . Rail accident event tree (after Volpe, 2006)

Comment [MF8]: The mixing of units will make this difficult for end users. Consider Table V-2 and Fig. V-2. Fig. V-2 is in mph but Table V-2, which uses Fig. V-2 for its conditional probabilities is in kph. This isn't the only place however. The fire event tree (Fig. V-4) uses feet.

Comment [h9]: In the event tree how does a "derailment" lead to a "No derailment fire". Aren't these logically inconsistent? Should that be *Derailment no fire*?

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., 2005; 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. Only one side of the model is shown in the figure because the model is symmetric, with the axis of symmetry along the center of the cask. The structural analysis identified 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.

Comment [s10]: reference is incorrect. The bibliography indicates that this is from the INMM Meeting in Fort Lauderdale in 2005. I can find no record of an INMM meeting in Fort Lauderdale in 2005.

Comment [h11]: On the one hand you mention that the model is symmetric, and on the other you identify the cask as having different gaps on opposite sides. This leads to the question, symmetric with respect to what – obviously not in the finest details that would include things like gaps etc. Some additional explanation would be useful.

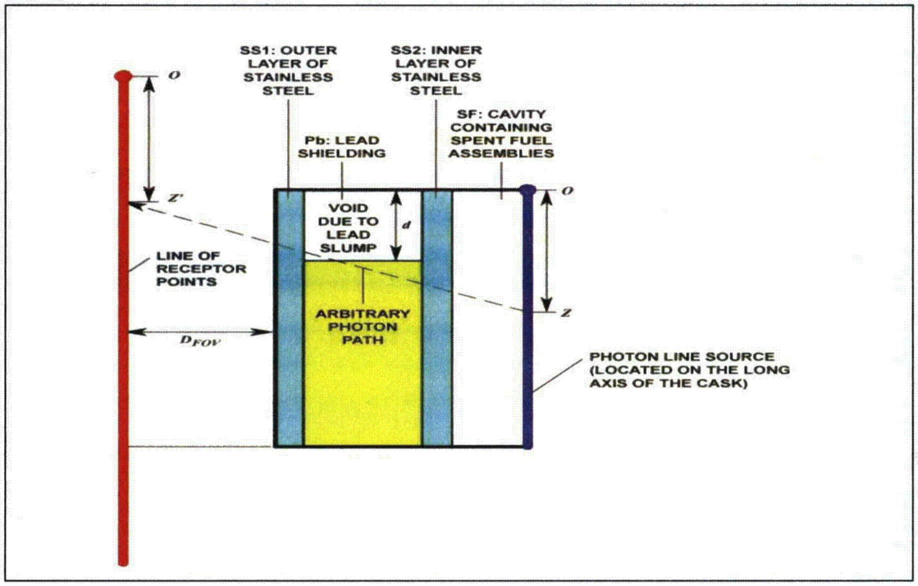

Figure V-3. The RADTRAN Loss-of Shielding 2-D Model (O'Donnell, et al, 2005)

Comment [s12]: The text and corresponding figure V-3 are stated as the model for the loss-of-shielding treatment in RADTRAN. More detail is needed, this is a very difficult shielding problem and a brief description of how the model was solved is needed to give the reader confidence in the results.

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 conditional probabilities shown in Table V-2 are those of a fall from the bridge into a tunnel, a collision on the bridge, and a fall from a bridge onto hard rock (Mills et al, 2006, Table 9), the accident scenarios in which an impact could result in a lead slump. Table V-2 shows the slump as fractions of the longest dimension of the lead shield and combines the conditional probabilities in Table V-2 for each applicable accident scenario in the rail event tree (Figure V-2). Of the two rail casks studied, only the lead-shielded Rail-Lead cask might lose shielding in an accident.

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As Table V-2 shows, the lead slump on one side of the cask may be different from the lead slump on the opposite side following an impact. This is particularly noticeable with the side impact. A radiation dose to any exposed person or population would therefore differ depending on the side of the cask to which the receptor was exposed. Table V-3 shows doses to the maximally exposed individual (MEI) at various distances from the cask. Table V-6 shows the population that could be exposed for each of the sixteen routes modeled.

Comment [b13]: This callout appears to be incorrect.

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.

Comment [h14]: Include Example of how/where the results in here come from (reference/example calculation)

Comment [MF15]: Specific comments to Table V-2:
Why are there 2 impact speeds given if you use the same collision tree top in Fig V-2? How are the conditional probabilities different?
An example should be provided for the conditional probability from rail ET like for the trucks because the probabilities do not match the ET (Fig. V-2).
Also, the probabilities must account for no fire and fire scenarios. This is not explained anywhere.

Orientation	Impact Speed kph	Event Tree Impact Speed	Location (Side 1 or Side 2)	Maximum Slump (mm)	Slumped fraction	Conditional Probability from Rail Event Tree	Conditi Probabi includi Orienta
End (Probability = 0.1)	193	>113	1	355.40	7.25E-02	1.34E-07	1.34E-
			2	355.48	7.25E-02		
	145	>113	1	83.20	1.70E-02	2.54E-06	2.54E-
			2	82.68	1.69E-03		
	97	80 to 113	1	18.28	3.73E-03	8.27E-04	8.27E-05
			2	18.21	3.72E-03		
	48	48 to 80	1	6.43	1.31E-03	2.35E-03	2.35E-04
			2	6.42	1.31E-03		
Corner (Probability= 0.6)	193	>113	1	310.48	6.34E-02	1.34E-07	8.03E-08
			2	254.56	5.20E-02		
	145	>113	1	114.52	2.34E-02	2.54E-06	1.53E-06
			2	80.35	1.64E-02		
	97	80 to 113	1	25.11	5.12E-03	8.27E-04	4.96E-04
			2	20.55	4.26E-03		
	48	48 to 80	1	1.28	2.61E-04	2.35E-03	1.41E-03
			2	1.65	3.37E-04		
Side (Probability= 0.3)	193	>113	1	0.53	1.05E-04	1.34E-07	4.01E-08
			2	15.47	3.16E-03		
	145	>113	1	0.43	8.73E-05	2.54E-06	7.63E-07
			2	20.88	4.26E-03		
	97	80 to 113	1			8.27E-04	2.48E-04
			2	1.37	2.79E-04		
	48	48 to 80	1	0.06	1.31E-05	2.35E-03	7.05E-04
			2	0.09	1.94E-05		

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

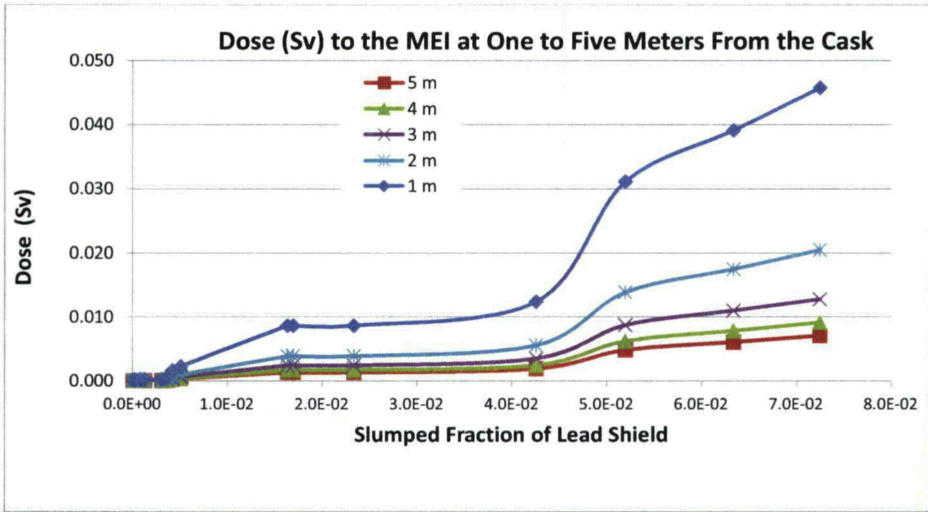

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Figure V-4. Radiation dose for one hour to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from one to five meters from the cask carrying spent fuel.

Comment [h16]: As noted in comments on Chapter 5, Run example case for 1m to test results that seem slightly unusual compared with the other cases.

Comment [s17]: The results shown in Figure V-4 also do not give the reader confidence in the results in that the "bumps" in the curves for 1 m don't really make physical sense.

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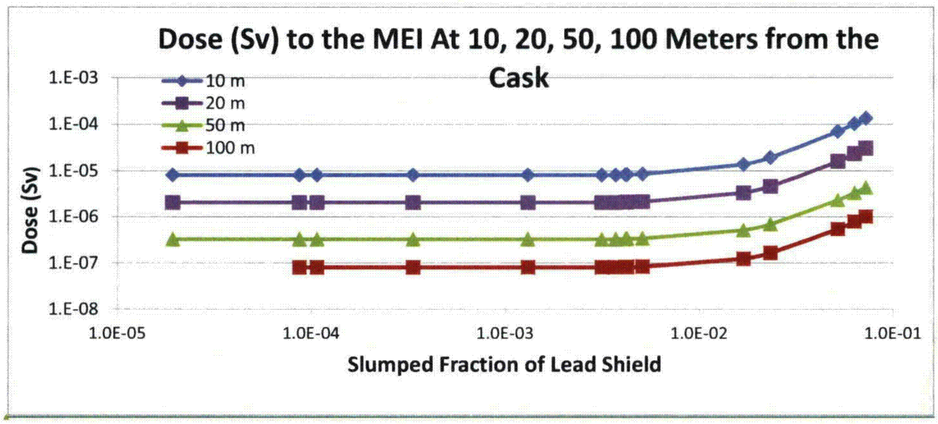

Figure V-5. Radiation dose to the maximally exposed individual from loss of lead gamma shielding at distances from 20 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic, so that all of the doses can be shown on the same graph.

Comment [XXX18]: Data missing from 100 m line.

Table V-3 shows how the dose to the maximally exposed individual (MEI) depends on the fraction of the lead shield lost and distance from the cask, for a ten-hour exposure. The left-hand column of Table V-3 shows lead slump on "side 1" and "side 2" of the cask separately and does not identify the side, since there is an equal probability of exposure to each side. The doses shown in the table are computed by RADTRAN using the model discussed in V.3.1.

The large doses that occur at near the cask (one to five meters from the cask) would be sustained by emergency responders, none of whom would spend all ten hours that close to the cask. The one- to five-meter doses 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 (from the largest gap in the lead shield) would be 0.13 mSv.

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. Tables V-5 a and b show the conditional dose risk, the combination of the conditional probability with the consequence, for each fractional loss of lead shielding. This is the risk of a particular accident scenario if there is an accident, and does not include the probability of an accident. The columns in Tables V-6 are in order of descending risk.

Comment [h19]: Reference for the 10 meters. Where does the 1.33 mSv value come from - estimated from Figure V-5?

Comment [s20]: 0.13 mSv should be the value if the value in Table V-3 is correct and you are using 10 hours as the exposure time. Please clarify.

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Comment [s21]: Please update the current table numbers.

Comment [s22]: 1.The last sentence refers to the order of descending risk in Table V-6, it appears that Tables V-4 and V-5 are intended, but I don't see any ordering of the risk. Perhaps something got messed up, but the numbers seem random and are quite confusing.

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.

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
5.20E-02	***3.1E-02***	***1.4E-02***	8.7E-03	6.2E-03	4.8E-03	7.0E-05	1.6E-05	2.3E-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
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
4.26E-04	2.6E-04	1.2E-04	8.0E-05	5.9E-05	4.6E-05	8.1E-06	2.0E-06	3.2E-07
4.19E-04	2.6E-04	1.2E-04	7.9E-05	5.8E-05	4.6E-05	8.1E-06	2.0E-06	3.2E-07
3.34E-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
1.08E-04	1.6E-04	8.1E-05	5.3E-05	4.0E-05	3.2E-05	8.1E-06	2.0E-06	3.2E-07
8.73E-05	1.6E-04	7.8E-05	5.2E-05	3.9E-05	3.1E-05	8.1E-06	2.0E-06	3.2E-07
1.94E-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

Comment [h23]: Include example calculation for one of these results

Comment [h24]: What does 10 CFR 71.51 say about exceeding regulatory doses? Are these accidents extra-regulatory? Or is there a probabilistic argument for why it is acceptable to exceed these doses with some vanishingly low probability. You should explain in a footnote or in the text.

Comment [s25]: 2.To verify the numbers in TableV-3 I performed a rigorous calculation with a 3D radiation shielding model (see Figure 1). The comparison of my results with those in Table V-3 indicate that your results are likely acceptable, provided some words on the degree of reliability of the values and a correction of some inconsistencies in Table V-3 are included. The comparison is as follows for selected scenarios.

Table 1: Comparison of Table V-3 results with ORNL rigorous calculation results (ORNL values in parentheses) and ratio ORNL/RADTRAN in **bold.**

Fraction of slumped lead

...

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.

Comment [h26]: Example calculation.

Comment [s27]: Table V-4 is not referenced, perhaps another table is numbered incorrectly.

Conditional Probability	Distance from the cask (m)				
	1	2	3	4	5
8.03E-08	3.7E-09	1.6E-09	1.0E-09	7.4E-10	5.7E-10
2.41E-07	9.4E-09	4.2E-09	2.6E-09	1.9E-09	1.5E-09
2.41E-07	7.5E-09	3.3E-09	2.1E-09	1.5E-09	1.2E-09
7.63E-07	9.5E-09	4.2E-09	2.7E-09	1.9E-09	1.5E-09
1.49E-03	1.3E-05	5.7E-06	3.6E-06	2.6E-06	2.0E-06
4.58E-06	3.9E-08	1.8E-08	1.1E-08	7.9E-09	6.1E-09
2.29E-06	5.1E-09	2.3E-09	1.5E-09	1.0E-09	8.1E-10
1.94E-05	3.1E-08	1.4E-08	8.8E-09	6.3E-09	4.9E-09
8.73E-05	1.2E-07	5.3E-08	3.3E-08	2.4E-08	1.9E-08
1.08E-04	6.2E-08	2.8E-08	1.8E-08	1.3E-08	1.0E-08
1.49E-03	3.8E-07	1.8E-07	1.2E-07	8.7E-08	6.9E-08
4.96E-04	1.3E-07	6.1E-08	3.9E-08	2.9E-08	2.3E-08
3.37E-04	7.7E-08	3.7E-08	2.4E-08	1.8E-08	1.4E-08
1.31E-03	2.2E-07	1.1E-07	7.0E-08	5.2E-08	4.2E-08

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.

Comment [h28]: Example calculation – the inclusion of the formula below (V-1) is extremely helpful in determining where these values come from.

Conditional Probability	Distance from the cask (m)			
	10	20	50	100
8.03E-08	1.1E-11	2.4E-12	3.5E-13	8.0E-14
2.41E-07	2.5E-11	5.6E-12	8.1E-13	1.9E-13
2.41E-07	1.7E-11	3.9E-12	5.6E-13	1.3E-13
7.63E-07	1.5E-11	3.5E-12	5.2E-13	1.3E-13
1.49E-03	2.0E-08	4.9E-09	7.5E-10	1.8E-10
4.58E-06	6.3E-11	1.5E-11	2.3E-12	5.6E-13
2.29E-06	1.9E-11	4.9E-12	7.7E-13	1.9E-13
1.94E-05	1.6E-10	4.0E-11	6.4E-12	1.6E-12
8.73E-05	7.2E-10	1.8E-10	2.9E-11	7.1E-12
1.08E-04	8.7E-10	2.2E-10	3.5E-11	8.7E-12
1.49E-03	1.2E-08	3.0E-09	4.8E-10	1.2E-10
4.96E-04	4.0E-09	1.0E-09	1.6E-10	4.0E-11
3.37E-04	2.7E-09	6.8E-10	1.1E-10	2.7E-11
1.31E-03	1.1E-08	2.7E-09	4.2E-10	1.1E-10
3.16E-03	2.5E-08	6.4E-09	1.0E-09	2.5E-10
3.73E-03	3.0E-08	7.5E-09	1.2E-09	3.0E-10

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 on the route segment under consideration
r is the distance from the cask: 20, 50, 100 and 800 meters
$0.5\pi r^2$ is the area of the semicircle of people around the cask
PD is the population density per km^2 in the semicircle
D_{avi} is the average individual dose from the i^{th} fractional loss of shielding
P_{ci} is the conditional probability of the i^{th} fractional loss of shielding.

The index *i* indicates a particular fractional shielding loss; these are summarized above in Table V-3. The population at the shielding loss accident is exposed to only one side of the cask. Thus this analysis assumed that half of this population would be exposed to each side of the cask, so that dose risks were calculated separately for exposure to each side of the cask. The summation in equation (V-1) is the conditional dose risk of all of the accidents considered: the "universe" of accidents. Table V-6 shows collective conditional dose risks for the sixteen routes analyzed.

Comment [h29]: The summation in V-1 is over a single variable (the fractional shielding loss). To some over all sixteen route accidents, shouldn't there be another summation term (a double sum) that includes these variables?

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.[2]

Comment [h30]: Example calculation

		Side 1				Side 2			
		ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFOR D	SKULL VALLEY
MAINE YANKEE	Rural	9.37E-10	6.91E-10	1.10E-09	8.57E-10	5.09E-09	3.75E-09	5.99E-09	4.66E-09
	Suburb	1.78E-08	1.91E-08	1.77E-08	1.72E-08	9.58E-08	1.03E-07	9.49E-08	9.22E-08
	Urban	1.93E-09	1.99E-09	1.86E-09	1.55E-09	1.03E-08	1.07E-08	1.00E-08	8.34E-09
KEWAUNEE	Rural	9.37E-10	4.61E-10	4.62E-10	5.91E-10	5.09E-09	2.50E-09	2.51E-09	3.21E-09
	Suburb	1.92E-08	2.03E-08	1.78E-08	2.08E-08	1.03E-07	1.09E-07	9.54E-08	1.12E-07
	Urban	2.10E-09	2.10E-09	1.94E-09	1.74E-09	1.13E-08	1.13E-08	1.04E-08	9.36E-09
INDIAN POINT	Rural	7.96E-10	5.72E-10	5.66E-10	6.63E-10	4.32E-09	3.11E-09	3.07E-09	3.60E-09
	Suburb	2.40E-08	1.98E-08	1.89E-08	2.02E-08	1.29E-07	1.06E-07	1.01E-07	1.08E-07
	Urban	2.56E-09	2.19E-09	2.12E-09	1.94E-09	1.37E-08	1.18E-08	1.14E-08	1.04E-08
IDAHO NATIONAL LAB	Rural	5.80E-10	2.40E-10	3.01E-10	5.99E-10	3.15E-09	1.30E-09	1.63E-09	3.26E-09
	Suburb	2.02E-08	2.01E-08	2.02E-08	1.97E-08	1.09E-07	1.08E-07	1.08E-07	1.06E-07
	Urban	1.70E-09	1.56E-09	1.97E-09	2.08E-09	9.13E-09	8.37E-09	1.06E-08	1.11E-08

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 routes are shown in Table V-7. These accident frequencies are combined with the average dose risk integrated over the potentially exposed population.

Table V-8 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). Thus the differences in Table V-9 are due to differences in traffic accident frequencies.

Comment [h31]: Table V-9 is for casks in a fire?

[2] 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.

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

Comment [h32]: Why is this table different than Table 5-6?

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}
	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}

Table V-8. Conditional collective dose risks per shipment (person-Sv) from loss of lead shielding, including conditional probabilities

Comment [h33]: Example calculation

ORIGIN	TYPE	Side 1				Side 2			
		ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	Rural	3.09E-12	1.35E-12	1.97E-12	9.31E-13	1.70E-11	7.44E-12	1.09E-11	5.13E-12
	Suburban	5.87E-11	3.74E-11	3.16E-11	1.87E-11	3.19E-10	2.03E-10	1.72E-10	1.02E-10
	Urban	6.34E-12	3.89E-12	3.33E-12	1.69E-12	3.45E-11	2.12E-11	1.81E-11	9.18E-12
KEWAUNEE	Rural	1.22E-12	2.87E-13	3.06E-13	3.06E-13	6.74E-12	1.58E-12	1.69E-12	1.69E-12
	Suburban	2.51E-11	1.26E-11	1.18E-11	1.07E-11	1.36E-10	6.86E-11	6.40E-11	5.85E-11
	Urban	2.74E-12	1.31E-12	1.28E-12	9.01E-13	1.49E-11	7.11E-12	6.98E-12	4.90E-12
INDIAN POINT	Rural	3.36E-11	1.09E-12	1.15E-12	4.62E-13	1.85E-10	6.02E-12	6.34E-12	2.55E-12
	Suburban	1.01E-09	3.78E-11	3.83E-11	1.40E-11	5.49E-09	2.06E-10	2.08E-10	7.64E-11
	Urban	1.08E-10	4.18E-12	4.30E-12	1.35E-12	5.86E-10	2.27E-11	2.34E-11	7.36E-12
IDAHO NATIONAL LAB	Rural	2.22E-13	1.61E-13	4.38E-14	5.56E-13	1.23E-12	8.87E-13	2.41E-13	3.07E-12
	Suburban	7.75E-12	1.35E-11	2.94E-12	1.82E-11	4.22E-11	7.35E-11	1.60E-11	9.93E-11
	Urban	6.52E-13	1.05E-12	2.87E-13	1.92E-12	3.55E-12	5.69E-12	1.56E-12	1.05E-11

V.3.1.2 Loss of lead shielding with fire

Lead melts at 330 °C, so that a prolonged high-temperature fire could result in lead slump, leaving a gap in the gamma shield which results in increased external radiation emission. In calculating doses from a loss of lead shielding, RADTRAN models a gap in the shield as an increase in the dose from a virtual radiation source (O'Donnell et al., 2005; Dennis, et al., 2009). This virtual source is the same as the basis for the incident-free transportation model (Figure II.1, Appendix II).

Comment [s34]: I do not understand what RADTRAN is doing based on this para. The 2nd sentence indicates RADTRAN models a shield gap "as an increase in the dose from a virtual radiation source". Then the next sentence indicates the virtual radiation source is the same used for incident transport, which is stated other places in the document to be the TI. So how is the "increase in dose" due to that gap calculated? I was assuming it was based on description of V.3.1 – so why not just state that rather than use these (to me) confusing sentences? (CParks)

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.

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

Fraction of lead lost	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

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. 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.

Comment [h35]: NOTE: Although probably only a minimal effect, any differential heating of the lead shielding will result in geometry changes that with volume changes would probably impact the effectiveness of the shielding. It is recognized that with the geometry constraints this impact is probably minimal.

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.

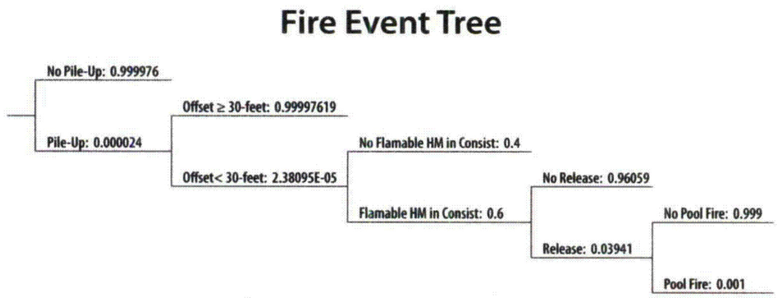

Figure V-4. Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16)

The first of these events is a major derailment, as shown in Table V-11. Volpe estimates that the speed at the time of the accident for such a derailment is at least 80 km/hr. 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 derailment is

$$(0.7355)*(0.0155)*(0.06614+0.00061)*(0.0011+0.0004+0.0077+.0113) = 1.56 \times 10^{-5}$$

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 exceedingly small number.

Thus the conditional probability of Fire Scenario 1, a major derailment that does not involve a pile-up but leads to a three-hour pool fire that surrounds the cask , is

$$(1.56 \times 10^{-5})*(5.6 \times 10^{-10}) = 8.8 \times 10^{-15}$$

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

$$(1.56 \times 10^{-5})*(2.36 \times 10^{-5}) = 3.7 \times 10^{-10}$$

Comment [MF36]: Should this be Figure V-4?

Comment [h37]: The likelihood of a pile-up is 0.000024? This seems awfully low. Similarly the likelihood of an offset fire < 30 feet is 2.38e-5? If these are independent probabilities, they seem awfully low.

Comment [MF38]: Not shown in Table V-11.

Comment [MF39]: While reading the probabilities, it is not explained why "other" is N/A in determining the probability of a major derailment

Comment [MF40]: The example problem should put words in prior to numbers to explain how the numbers are calculated.

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

EVENT	PROBABILITY	ALTERNATIVE EVENT	PROBABILITY
		No major derailment	0.99999
Pileup	2.4 x 10^{-5}	No pileup	0.99998
Offset < 10 m	2.38 x 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

The average accident frequency for the 16 rail routes studied is 3.9 x 10^{-3} (the range is from 1.5 x 10^{-4} to 4.2 x 10^{-2}). Thus, the average probability of an accidental fire that could cause loss of lead shielding in a rail cask is 3.4 x 10^{-19} if the cask is concentric with the fire and 1.4 x 10^{-14} if the cask and fire are offset by 10 meters or more. The largest dose risk would be 4.9 x 10^{-17} Sv.

Comment [h41]: Where is this from (not table V-7)?

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 Figure V-5.

Comment [h42]: Figure V-5 is the radiation dose to MEI @ 10-, 20, 50, and 100 meters from the cask.

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

The neutron TI for the Truck-DU cask is from General Atomics, 1998; the TI for the Rail-Lead cask, from NAC International, 2002; and the TI for the Rail-All Steel cask, from Holtec International, 2004. The RADTRAN external dose rate is 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).

Comment [s43]: "neutron TI" obtained from cask designers; but earlier text (see comment 10) indicated the TI values used in this report were obtained from calculating the 1 m dose based on the 2 m dose reported by the cask vendors. (CParks)

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

Parameter	Truck-DU	Rail-Lead	Rail-All Steel
Conditional probability of a fire	0.0063	8.9 x 10^{-8}	8.9 x 10^{-8}
Dose rate at one meter from the cask in mSv/hour (mrem/hour)	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

Comment [s44]: Is the neutron TI value from Table V-11 used as input to RADTRAN and then the RADTRAN model of Fig 2-2 used to estimate 5 m dose of Table V-12? (CParks)

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

Comment [h46]: Example calculation

Cask	Dose in Sv	Ten-hour 10 CFR 71.51 dose in Sv
Truck-DU	0.00729	0.1
Rail-Lead	0.00761	0.1
Rail-All Steel	0.00763	0.1

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

Comment [h47]: Example calculation

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	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	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	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-14. 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

Comment [h48]: Example calculation

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. 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.[3] 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 [h49]: Is there a reference for where this is defined as the limit (i.e., certificate of compliance?)

[3] 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.

Table V-15. 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

Deleted: ^{63}NI

Deleted: I

Comment [s50]: 3.there is only 1 noble gas nuclide; did you consider the enhanced release of gaseous fission products during an accident?

Comment [s51]: 4.Sections V.5.1 and V.5.2 are missing. The section numbers go from V.4.1 to V.5.3, either missing sections or miss numbered sections.

V.5.3 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. In addition, particles larger than this are filtered by larger particles inside 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).

[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.

(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.

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

Comment [h52]: I believe you have V-3 and V-4 inverted here.

Comment [s53]: Equation appears to be missing something, it doesn't have an H variable in it and is identical to (V-4) without the exponential terms.

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

(V-4) $$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-H^2}{2\sigma_z^2}\right]$$

Comment [h54]: Same as comment above.

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)

Comment [h55]: Is this correct? Most terminal velocity formulations result in some square root term on the right side of the equation (depending upon the formulation). I'm sure it's probably right, but I can't find this one, is there a reference for this? Is this in the RADTRAN users guide.

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)'

[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-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.5.4 Release fractions

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 analysis in Chapter 4 shows 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 [h56]: Chapter 4 is fire, Chapter 3 are the structural calculations. Shouldn't both be referenced if you are claiming that no release would occur?

V.5.4.1 CRUD

Radioactive material available for release comes from both spent fuel and Chalk River Unidentified Deposits (CRUD). CRUD is a corrosion product that forms on the outside of the fuel rods; its source is not the fuel rod inventory but other metallic structures in the reactor. In a PWR reactor its radioactive constituents are ^{60}Co, ^{58}Co, ^{54}Mn, ^{51}Cr, ^{59}Fe, ^{95}Zr, ^{125}Sb, and ^{65}Zn. ^{60}Co is the only CRUD constituent sufficiently long-lived to be part of any accidental release. Although CRUD deposits on the outside of fuel rods, cask seals would have to be breached for CRUD to be released. Sprung, et al (2000, Page 7-49) and Hanson et al (2010) estimate the amount of CRUD per fuel rod for PWR and BWR spent fuel. The estimates include the following assumptions:

- CRUD forms on the outside rods of the assemblies

- Thirteen percent of the rod area is covered with a CRUD layer. The layer is between 33 and 100 microns thick. The total amount of CRUD was thus assumed to be 8.5 microns thick over the entire surface of the outside rods. The density of the CRUD layer was assumed to be one gram per cm^3 for the CRUD that could be airborne in the cask (Einziger and Beyer, 2007)

- CRUD was assumed to be entirely ^{60}Co, and the activity was calculated using Equation (V-7).

(V-7) ________________________

Einziger and Beyer (2007) estimate that, with certain conservative assumptions, about 15 percent of the CRUD formed could remain airborne in the cask and available to be swept from the cask in the event of cask depressurization. Using these estimates, the CRUD activity in the Rail-Lead would be:

- 268 TBq (7075 Ci) in a cask carrying twenty-six 17x17 PWR assemblies

And the airborne fraction in the cask would be 40.2 TBq (1061 Ci).

The fraction of airborne particles that could be swept from the cask depends on the pressure differential between the cask and the environment:

$$F_{CE} = (1 - f_{deposited})(p_{atm}/p_{inp}) \quad \text{(V-6)}$$

Comment [h57]: This formulation seems odd and non-intuitive. The value of a fractional release should never be greater than 1. Mathematically, you can get values greater than 1 based upon this formulation. An example would be if the Fdeposited fraction was 50% and the pressure ratio were greater than 2 you would have a release fraction greater than 1. In addition, it is not intuitive for the numerator in this formulation to be the atmospheric pressure as opposed to the cask internal pressure. You would naturally think the greater the internal pressure (relative to the atmospheric pressure), the more likely any non-fixed contamination would have for being swept from the cask.

Where F_{CE} is the fraction released from the cask to the environment, $f_{deposited}$ is the fraction of airborne material in the cask deposited on its inner surface, p_{atm} is the atmospheric pressure and $p_{inp}$is the cask internal pressure. The only release path that would be available is through the seals at the end of the cask. If the accident involves a collision that fails the seals but there is no fire and no damage to the fuel rods, the cask temperature would probably be close enough to ambient that the pressure differential between the cask and the environment would be insufficient to sweep CRUD from the cask.

If there is a fire but no thermal failure of the seals, there can be no CRUD-only release. The cask seals modeled in this study would not fail thermally, as shown in Chapter 4 and Appendix IV, so these casks would not have a CRUD-only release. For the modeled casks, if the cask seals fail, the fuel rods fail as well, as happens in a severe impact accident(Section V.5.4.3). Thus, an accident in which the seals in this study are breached but the fuel remains undamaged, is a hypothetical situation This hypothetical situation is considered in the following paragraphs of this section. Assuming that the ambient temperature is 300 K and that elastomeric seals fail at 450 K, then from the Ideal Gas Law,

Comment [h58]: Assuming no potential release without seal failure, this is a conservative assumption

$$p_{atm}/p_{inp} = T_{atm}/T_{inp} = 300/450 = 0.667^{6} \quad \text{(V-7)}$$

From Figure 7.5 of Sprung et al (2000), about one percent of the 15 percent of the CRUD that has spalled from the rods, or about 0.15 percent, would be respirable (10 microns or less aerodynamic diameter). From Equation (V-6) the fraction of CRUD that would be released is 0.001.

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[6] The metal seal failure temperature is 477 deg. K, so that in the case of a metal seal $p_{atm}/p_{inp} = 0.628$

This scenario was modeled using RADTRAN, assuming release at ground level, the same dispersion formulation as described in Section V.5.3, and deposition velocity calculated using Equation (V-4). Unit conditional inhalation and external dose risks are shown in Table V-16. These conditional dose risks do not include populations along the route or accident probabilities (frequencies).

Table V-16. Unit conditional inhalation and external dose risks (Sv) for a hypothetical CRUD-only release.

Comment [h59]: Example calculation

ROUTE SEGMENT TYPE	INHALED	RESUSPENDED	CLOUDSHINE	GROUNDSHINE	TOTAL
Rural	1.43E-10	3.85E-12	5.45E-10	1.93E-08	2.00E-08
Suburban	1.43E-10	3.85E-12	5.45E-10	1.93E-08	2.00E-08
Urban	4.15E-10	1.12E-11	1.58E-09	5.62E-08	5.82E-08

Internal doses include doses from direct inhalation and from material resuspended in air. External doses include cloudshine and groundshine. The NRC cites the total effective dose equivalent (TEDE) which includes both internal and external doses.

The average collective dose risks shown in Table V-17 are the averages of the products of the dose risks as shown in Table V-16, and the population and accident frequency along each route. Average accident frequencies for each route are in Table V-8.

Comment [h60]: This is not in Table V-8

Table V-17. Average collective dose risks (person-Sv) for each route for a hypothetical CRUD-only release

Comment [h61]: Example calculation

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE	2.07E-04	1.57E-06	2.13E-04	2.15E-04
KEWAUNEE	8.59E-05	1.66E-06	8.56E-05	8.63E-05
INDIAN	1.05E-04	1.72E-06	8.84E-05	8.91E-05
INL	7.23E-05	1.25E-06	6.66E-05	6.71E-05

The average collective dose risks reported in Table V-17, while very small, are several orders of magnitude larger than the dose risks from an accident involving release as reported in Table V-23, below. However, the values in Table V-17 result from analyzing a purely hypothetical accident, while those in Table V-23 are from a realistic accident.

V.5.4.2 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)[7]. *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*[8]*)..... 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)*

These authors examined the behavior of relatively high burnup fuel. The release fractions from the rods to the cask, under the described conditions, are developed from the data of Hanson, et al for 45 GWD/MTU spent fuel. Einziger (2007) describes the formation of a rim on the fuel pellet that has a higher porosity that the body of the pellet. This porosity results in reduced hardness of the pellet (Hanson et al, Figures 1.6 and 1.7)). However, the pellet rim is toughened by grain refinement, suggesting that release of fine particles from the fuel rods could be smaller than releases from lower burnup fuel. Figure V-6 shows the difference between a rim and the pellet interior.

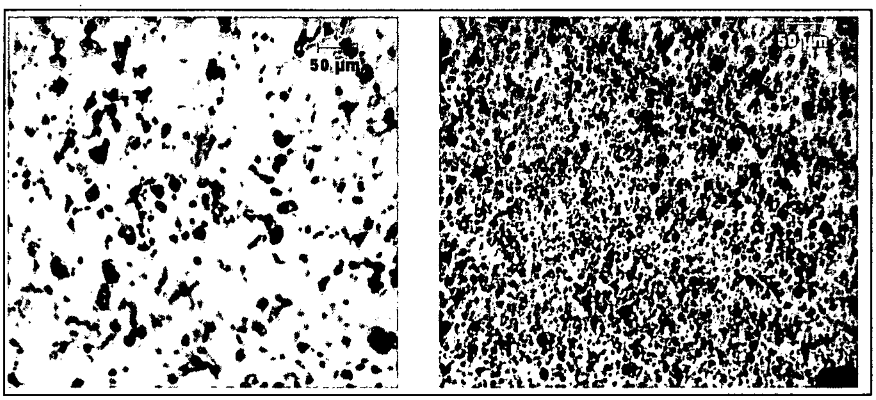

Figure V-6. Electron micrographs of the fuel pellet interior (left-hand picture) and the fuel pellet rim (right-hand picture). (Courtesy of Dr. R. E. Einziger, NRC)

Figure 1.10 of Hanson et al. suggests a release fraction for fission gases (^{85}Kr in the fuel in this analysis) of 0.5 percent. These authors 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.

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

Hanson et al. describe a number of mechanical tests performed on unoxidized fuel of varying burnup. Page 4.12 of Hanson et al. summarizes release fractions from these tests for the fuel that appears to be the most appropriate. A release fraction of 4.8 x 10^{-6}, based on the information in Hansen, et al, 2008, is used in this analysis for release of fine particles from the rod to the cask.

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-18 summarizes the parameters from which release fractions were developed.

Table V-18. Parameters for determining release functions for the accidents that would result in release of radioactive material.

	Cask Orientation	**End**	**Corner**	**Side**	**Side**	**Side**	**Side**	**Corner**
	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**	0.005	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 for combined rod-cask-environment release		2.68E-08	1.61E-07	8.02E-08	8.02E-08	1.52E-06	1.52 e-06	5.81e-05

Table V-19 shows sources of the parameter values in Table V-18. The parameter values are consistent with Sanders, et al, (1992).

Table V-19. Sources of the parameter values in Table V-18.

		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**	0.005	From Hanson, et al, 2008, Figure 1.10 (page 1.10) for 45 GWD/MTU burnup
	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.

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 [9], so that the plume of material will be lofted slightly. Using Equation (V-4), RADTRAN models the maximum air concentration and ground deposition at about 21meters downwind from the cask. The maximally exposed individual would be located at this point. A graph 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-20.

Comment [h62]: This is awkwardly worded. Do you really mean to say…"Models the maximum ground concentration location" or should it alternatively say, …" the results of the model indicate a maximum concentration based upon the neutral and/or conservative met conditions at 21 meters downwind".

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

Table V-20. 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	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Corner	193	metal	1.6	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	193	elastomer	1.6	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	193	metal	1.6	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	145	elastomer	1.6	1.4E-02	4.5E-06	3.6E-05	1.6E+00
Side	145	metal	1.6	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Corner	145	metal	0.73	0.0063	0.0001	0.0009	0.73

Comment [h63]: Example calculation

When the doses in Table V-20 are multiplied by the probabilities in Table V-18, the "conditional dose risks" of Table V-21 result.

Table V-21 Maximally exposed individual conditional dose risks in Sv from accidents that involve a release.

Comment [h64]: Example calculation

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Resuspension	Cloudshine	Groundshine	Total
End	193	metal	4. 3E-08	3. 7E-10	2. 4E-12	2.5E-11	4. 3E
Corner	193	metal	2.6E-07	2.2E-09	1.4E-11	1.5E-10	2. 6E
Side	193	elastomer	1.3E-07	1.1E-09	7.0E-12	7. 6E-11	1. 3E
Side	193	metal	1. 3E-07	1.1E-09	7.0E-12	7. 6E-11	1. 3E
Side	145	elastomer	2.41E-06	2.09E-08	6.90E-12	5.50E-11	2.42E
Side	145	metal	2.42E-06	2.09E-08	1.34E-10	1.44E-09	2.44E
Corner	145	metal	4.23E-05	3.66E-07	2.98E-09	5.37E-08	4.27E

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Comment [XXX65]: Formats changes due to font shift from Times New Roman to Arial

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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 neutral meteorological stability. Collective dose risks are calculated by multiplying each population dose by the appropriate conditional probability. Collective doses are presented in Table V-22 for the end impact, 193 kph impact speed accident, as an example.

Comment [h66]: Wouldn't this be an optimization between the higher doses (to the smaller population) resulting from a small and concentrated plume for stable meteorological conditions and the lower doses (to the larger population) resulting from a larger and more dispersed plume for the neutral stability conditions. How can you quote the population doses as definitively bound as one or the other without a comparison?

Table V-22. Collective conditional inhalation and external dose risks for the end impact, 193 kph impact speed accident, for the 16 routes analyzed.

Comment [h67]: Example calculation

	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	2.6E-14	1.1E-14	1.6E-14	7.7E-15	2.3E-17	1.0E-17	1.5E-17	7.0E-18
SUBURBAN	5.1E-13	3.2E-13	2.7E-13	1.6E-13	4.6E-16	2.9E-16	2.5E-16	1.5E-16
URBAN	8.8E-12	5.4E-12	4.6E-12	2.3E-12	8.0E-15	4.9E-15	4.2E-15	2.1E-15
KEWAUNEE								
RURAL	1.0E-14	2.4E-15	2.5E-15	2.5E-15	9.2E-18	2.2E-18	2.3E-18	2.3E-18
SUBURBAN	2.2E-13	1.1E-13	1.0E-13	9.3E-14	2.0E-16	9.8E-17	9.2E-17	8.4E-17
URBAN	3.8E-12	1.8E-12	1.8E-12	1.3E-12	3.4E-15	1.6E-15	1.6E-15	1.1E-15
INDIAN POINT								
RURAL	2.8E-13	9.1E-15	9.6E-15	3.8E-15	2.5E-16	8.2E-18	8.7E-18	3.5E-18
SUBURBAN	8.7E-12	3.3E-13	3.3E-13	1.2E-13	7.9E-15	3.0E-16	3.0E-16	1.1E-16
URBAN	1.5E-10	5.8E-12	6.0E-12	1.9E-12	1.4E-13	5.3E-15	5.4E-15	1.7E-15
IDAHO NATIONAL LAB								
RURAL	1.1E-12	1.7E-12	3.5E-13	2.1E-12	3.6E-15	5.4E-15	1.1E-15	6.6E-15
SUBURBAN	1.5E-15	1.1E-15	2.9E-16	3.7E-15	4.8E-18	3.4E-18	9.4E-19	1.2E-17
URBAN	5.3E-14	9.3E-14	2.0E-14	1.3E-13	1.7E-16	3.0E-16	6.5E-17	4.0E-16

Comment [s68]: Columns 3 and 6 are missing the exponents. Note that the exponents show up here, but they did not show up in the original sent to ORNL for review. For some reason they have been truncated since when the columns are expanded, the exponents show up (but other column's exponents are then truncated). It appears that the quickest solution is to use the *Distribute Columns* button under *Layout Tab* that appears when the portions of the table are selected.

Internal doses include doses from direct inhalation and from 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 product of the collective dose risk as shown in Table V-23 and the accident frequency along the route. Average accident frequencies for each route are in Table V-7.

Table V-23 shows the total dose risk for each route.

Table V-23. Total collective dose risks (person-Sv) for each route

Comment [h69]: Example calculation

	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
INL	3.7E-10	6.0E-10	1.6E-10	1.1E-09

V.6. Summary

The more important technical observations for the analysis of accidents are:

- 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.

- 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.

- The external dose from loss of lead shielding is negligible unless more than two percent of the lead shield is lost and unless the receptor is within four meters of the cask, as shown in Table V-3.

- 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 [h70]: Some additional discussion should be provided. You quote in Table V-3 how the doses at less than 4m for certain cases are greater than 10 CFR 71.51. How do you go from negligible to greater than regulatory requirements with no additional discussion of how this is acceptable? (either due to the low probability of the event or some other mitigating factor)