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United States Nuclear Regulatory Commission

Spent Fuel Transportation Risk Assessment

Draft Report for Comment

U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety
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COMMENTS ON DRAFT REPORT

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ABSTRACT

The U. S. Nuclear Regulatory Commission (NRC) is responsible for issuing regulations for the packaging of spent fuel (and other large quantities of radioactive material) for transport that provide for public health and safety during transport (Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71, "Packaging and Transportation of Radioactive Waste," dated January 26, 2004). In September 1977, the NRC published NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," which assessed the adequacy of those regulations to provide safety assurance. In that assessment, the measure of safety was the risk of radiation doses to the public under routine and accident transport conditions, and the risk was found to be acceptable. Since that time there have been two affirmations of this conclusion for spent nuclear fuel (SNF) transportation, each using improved tools and information that supported the earlier studies. This report presents the results of a fourth investigation into the safety of SNF transportation. The risks associated with SNF transportation come from the radiation that the spent fuel gives off, which is attenuated—but not eliminated—by the transportation casks shielding and the possibility of the release of some quantity of radioactive material during a severe accident. This investigation shows that the risk from the radiation emitted from the casks is a small fraction of naturally occurring background radiation and the risk from accidental release of radioactive material is several orders of magnitude less. Because there have been only minor changes to the radioactive material transportation regulations between NUREG-0170 and this risk assessment, the calculated dose due to the external radiation from the cask under routine transport conditions is similar to what was found in earlier studies. The improved analysis tools and techniques, improved data availability, and a reduction in the number of conservative assumptions has made the estimate of accident risk from the release of radioactive material in this study approximately five orders of magnitude less than what was estimated in NUREG-0170. The results demonstrate that NRC regulations continue to provide adequate protection of public health and safety during the transportation of SNF.

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EXECUTIVE SUMMARY

The U. S. Nuclear Regulatory Commission (NRC) has conducted several risk assessments and other analyses to evaluate the safety of transportation of spent power reactor nuclear fuel during the past 35 years. Regulations, shipping practices, and cask designs for transporting radioactive material have remained essentially unchanged during this time. Therefore, the *actual* per shipment risk over this time period also would have remained essentially the same. What *has* changed during this period is the *calculated* risks. This change was brought about by the improved ability to evaluate cask responses and their spent fuel contents to accident environments. The improvements include advancements in tools available to determine those responses and to calculate the consequences and risks that result from their response. This has resulted in a decrease in the calculated per shipment risk. The consequences and risks resulting from accidents calculated in this study are several orders of magnitude less than those calculated in previous risk assessments.

In this study the risk associated with the transportation of spent nuclear fuel (SNF) was estimated by examining the behavior of three NRC-certified casks during routine transportation and in transportation accidents. Two casks are designed for transport by railroad: 1) a cask with steel gamma shielding and an inner welded canister for the spent fuel and 2) a cask with lead gamma shielding that can transport spent fuel within an inner welded canister (referred to in this report as canistered fuel) or without an inner canister (referred to as directly loaded fuel). A third cask with depleted uranium (DU) gamma shielding is designed to transport directly loaded spent fuel by highway. The response of these casks is typical of other cask designs. The use of certified cask designs means this risk assessment includes the factors of safety typically included in cask designs but not specifically considered in previous risk assessments.

The risks associated with routine shipments (incident-free) and shipments where an accident occurs are calculated separately. During routine transportation, the risk and the consequence are the same. In this case, the dose to residents living along a transportation route, to people sharing the highway or railway, people at stops, and transportation workers are all calculated. Regulations allow limited external radiation from the cask. The dose of radiation to members of the public during routine transportation is a small fraction of the naturally occurring background radiation that individuals experience.

If an accident occurs during shipment, most likely there is no damage to the cask, but the vehicle is stopped for a period of time, which exposes people in the vicinity of this stop (nearby residents, emergency response workers, etc.) to the allowed external radiation from the cask. If the accident is more severe, the shielding effectiveness of the cask could be reduced. If the cask is involved in a fire, the plastic neutron shielding material could melt, resulting in a slightly elevated amount of radiation emanating from the cask. If the lead shielded cask was involved in an exceptionally severe long-lasting fire, there could be a reduction in the effectiveness of the gamma shielding. The response of the cask to fire accidents was determined using detailed computer analyses. Even in the worst-case fires analyzed, no cask experienced a seal failure that could have led to a release of radioactive material from the spent fuel cask.

For impact accidents, the steel shielded cask with inner welded canister and the DU-shielded cask have no release and no loss of gamma shielding effectiveness even under the most severe impacts studied, which encompass all historic or even realistic accidents. The lead shielded cask experiences some loss of gamma shielding effectiveness during severe impacts. Also, when spent fuel is transported without an inner welded canister some release of radioactive material could occur during exceptionally severe impacts.

If material were to be released, weather conditions at the accident location would affect the dispersal of that material. The risk assessment uses national average weather conditions because the time and location of an accident are unknown. The number of people exposed to the dispersed material is a function of the population density at the site of the accident, which is determined from census data. The amount of material released, the dispersion, and the population density are combined to determine the consequence (potential effects) of a release. The estimated dose from the most severe accident scenarios evaluated in this study is less than that required to produce an immediate injury and is similar to a single dose from a cancer therapy regimen.

Accident risk is the product of the consequence of the accident and its probability. The probability of an accident that has an effect on the cask is the product of the probability that the cask is involved in an accident and the conditional probability that the accident is severe enough to reduce the shielding or containment effectiveness of the cask. The conditional probability is based on State accident statistics for all types of heavy trucks and railcars. The accident probability is determined by multiplying these State-by-State accident rates by the distance traveled within each State. This was done for 16 representative truck routes and 16 representative rail routes.

The study reached the findings listed below.

- The collective dose risks from routine transportation are vanishingly small. Theses doses are approximately four to five orders of magnitude less than the collective background radiation dose.
- The routes selected for this study adequately represent the routes for SNF transport, and there was relatively little variation in the risks per kilometer (km) over these routes.
- Radioactive material would not be released in an accident if the fuel is contained in an inner welded canister inside the cask.
- Only rail casks without inner welded canisters would release radioactive material, and only then in exceptionally severe accidents.
- If there were an accident during a spent fuel shipment, there is only about one in a billion chance that the accident would result in a release of radioactive material.
- If there were a release of radioactive material in a spent fuel shipment accident, the dose to the maximally exposed individual (MEI) would be less than 2 sieverts (Sv) (200 rem), and would be neither acute nor lethal.

- The collective dose risks for the two types of extremely severe accidents (accidents involving a release of radioactive material and loss of lead shielding (LOS) accidents) are negligible compared to the risk from a no-release, no-loss of shielding accident.
- The risk of gamma shielding loss from a fire is negligible.
- None of the fire accidents investigated in this study resulted in a release of radioactive material.

Based on these findings, this study reconfirms that radiological impacts from spent fuel transportation conducted in compliance with NRC regulations are low. In fact, they are generally less than previous, already low, estimates. Accordingly, this study also reconfirms the NRC's previous conclusion that regulations for transportation of radioactive material are adequate to protect the public against unreasonable risk.

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as is reasonably achievable
AMAD	activity median aerodynamic diameter
Btu	British thermal unit
BWR	boiling-water (nuclear) reactor
C	Celsius
CAFE	container analysis fire environment
CFD	computational fluid dynamics
CFR	*Code of Federal Regulations*
CG	center of gravity
Ci	curie
cm	centimeter(s)
COC	certificate of compliance
CRUD	Chalk River unidentified deposit
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DU	depleted uranium
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EQPS	equivalent plastic strain
F	Fahrenheit
FDR	final design report
FE	finite element
FEM	finite element method
FSS	fuel support structure
g	acceleration due to gravity
gal	gallon
GWD	gigawatt days
HAC	hypothetical accident condition
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
ILSS	impact limiter support structure
in	inch
INL	Idaho National Laboratory
KE	kinetic energy
km	kilometer(s)
kph	kilometers per hours
ksi	1000 pounds per square inch
lb	pound(s)
lbm	pound(s) mass
LOS	loss of (lead) shielding
MCNP	Monte Carlo N-Particle
MEI	maximally exposed individual
MJ	million Joules
MLEP	multi-linear elastic/plastic
mm	millimeter(s)
MN	million Newtons
MPC	multi-purpose canister
MPa	million Pascals

mph	miles per hour
mrem	millirem
MTU	metric ton of uranium
MWd	megawatt-days
NP	nuclear plant
NRC	U.S. Nuclear Regulatory Commission
OFA	Optimized Fuel Assembly
ORNL	Oak Ridge National Laboratory
psi	pounds per square inch
PWR	pressurized-water reactor
rem	roentgen equivalent man
SAR	safety analysis report
SNF	spent nuclear fuel
Sv	sievert
TBq	terabecquerels = 10^{12} becquerels
TC	thermocouple
TEDE	total effective dose equivalent
TI	transport index
W	watt

CHEMICAL SYMBOLS

Am	americium
Cm	curium
Co	cobalt
Cs	cesium
Eu	europium
I	iodine
Kr	krypton
O	oxygen
Pb	lead
Pu	plutonium
Ru	ruthenium
Sb	antimony
Sr	strontium
Te	tellurium
U	uranium
Y	yttrium
Zr	zirconium

1. INTRODUCTION

1.1 Organization of this Report

The body of the report consists of an executive summary and six chapters. The chapters describe the risk analysis qualitatively. Each chapter in this study has an associated appendix that describes the analytical methods and calculations used to arrive at the results discussed in the chapters. Descriptions of programs, calculations, and codes used are located in the relevant appendices.

1.1.1 Chapter 1 and Appendix I

Chapter 1 gives an introduction to the study, a brief background, a discussion of risk as applied to the transportation of radioactive materials, a discussion of cask selection, and a review of the organization of the report. Appendix I contains a glossary of special terms used in this study.

1.1.2 Chapter 2 and Appendix II

Chapter 2 and Appendix II discuss RADTRAN[1] analysis of incident-free transportation. During routine (incident-free) transportation, spent fuel transportation casks deliver an external dose to anyone in proximity to the shipment. This chapter describes the consequence of the external dose. In most previous transportation risk studies, the regulatory maximum dose rate of 0.1 millisieverts (mSv)/hour at 2 meters from the cask was assumed to be the external dose rate from every cask evaluated in the particular study. The present study uses the actual predicted external dose rate from NRC-certified casks, as reported in the Safety Analysis Reports (SARs) for those casks.

1.1.3 Chapter 3 and Appendix III

Chapter 3 and Appendix III address the structural analyses used to determine the cask response to accidents and the parameters that determine loss of lead gamma shielding and releases of radioactive material. The results of detailed analyses of the impact of the casks with impact limiters onto rigid targets at speeds of 48 kilometers per hour (kph), 97 kph, 145 kph, and 193 kph (30 miles per hour (mph), 60 mph, 90 mph, and 120 mph) in end, corner, and side-on orientations are given. Results are supplied for impacts onto other surfaces or objects. The response of the fuel assemblies that the casks carry is also discussed.

1.1.4 Chapter 4 and Appendix IV

Chapter 4 and Appendix IV address the thermal analyses used to determine the cask response to accidents and the parameters that determine loss of lead gamma shielding and potential releases of radioactive material. The results from fire analyses that completely engulf the cask as well as those offset from the cask are given. The temperature response of the cask seals, the shielding material, and the spent fuel is provided.

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1 RADTRAN is the radioactive material transportation risk assessment code originally developed for the NRC in the 1970s by Sandia National Laboratories.

1.1.5 Chapter 5 and Appendix V

Chapter 5 and Appendix V address RADTRAN analysis of transportation accidents, development of accident event trees and conditional probabilities, development of the radionuclide inventory and radioactive materials releases and dispersion of released material in the environment. The chapter also discusses accidents where no releases occur (the most likely accidents) and the radioactive cargo is not affected at all, but the vehicle is held for many hours at the accident location before it is permitted to continue.

1.1.6 Chapter 6 and Appendix VI

Chapter 6 summarizes the results of the analyses. Appendix VI contains a "plain language" summary of this study.

1.1.7 Bibliography

The bibliography is located after the Appendices. It contains all cited references and other bibliographic material. Citations in the text (e.g., Sprung et al., 2000, Figure 7.1) include specific page, figure, or table references where appropriate.

1.2 Historical Transportation Risk Studies and the Purpose of this Analysis

The purpose of this study was to analyze the radiological risks of transporting SNF in routine transportation and transportation accidents, using the latest available data and modeling techniques. This study primarily analyzes cask behavior rather than the behavior of the spent fuel being transported. The study is the latest in a series of assessments of this type that analyzes the behavior of NRC-certified casks carrying fuel of known isotopic composition and burnup. The studies preceding this one were based on conservative and generic assumptions.

This study is not intended to be a risk assessment for any particular transportation campaign and does not include the probabilities or consequences of malevolent acts. It does not address the acceptance of the risks associated with transportation of SNF but can be used to inform such discussions.

The NRC certifies casks used to transport SNF under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71, "Packaging and Transportation of Radioactive Material," dated January 26, 2004. The adequacy of these regulations was confirmed in NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes" (NRC, 1977), an environmental impact statement (EIS) for transportation of all types of radioactive material by road, rail, air, and water. Several conclusions drawn from this EIS are listed below.

- The average radiation dose to members of the public from routine transportation of radioactive materials is a fraction of the existing background radiation dose.
- The radiological risk from accidents in transporting radioactive materials is very small compared to the nonradiological risk from accidents involving large trucks or freight trains.

- The regulations in force at the time of the EIS were determined by the Commission to be "adequate to protect the public against unreasonable risk from the transport of radioactive materials" (46 FR 21629; April 13, 1981).

The risk assessment of NUREG-0170 was based on very conservative estimates of risk parameters and on models available at the time; these models would be considered imprecise today. The NRC concluded that the regulations were adequate because even very conservative estimates of risk parameters did not result in unacceptable risk. The NRC also recognized that the agency's policies on radioactive materials transportation should be "subject to close and continuing review." Two comprehensive contractor reports on spent fuel transportation have been issued since 1977: the Modal Study (Fischer et al., 1987) and NUREG/CR-6672 (Sprung et al., 2000).[2] The Modal Study was the first intensive examination of vehicle accident statistics and the first to categorize the frequency of severe accidents by structural and thermal response of a transportation cask. The Modal Study concluded that the frequency of accidents severe enough to produce significant cask damage was considerably less than NUREG-0170 estimated. The Modal Study was not a risk analysis because it did not consider the radiological consequence of accidents, but risks less than those estimated in NUREG-0170 could be inferred.

NUREG/CR-6672 refined the mechanical stress/thermal stress combinations of the Modal Study and recast them as a matrix of accident-related impact speeds and fire temperatures. In addition, NUREG/CR-6672 developed expressions for the behavior of spent fuel in accidents and potential release of this material, and analyzed the potential releases. The enhanced modeling capabilities available for NUREG/CR-6672 allowed analyses of the detailed structural and thermal response of transportation casks to accidents. NUREG/CR-6672 also used results of experiments by Lorenz et al. (1980), Sandoval et al. (1988), and Sanders et al. (1992) to estimate releases of radioactive material from the fuel rods to the cask interior and from the cask interior to the environment, following very severe accidents. The radionuclides available for release in the accidents studied in NUREG/CR-6672 are from relatively low burnup (30 gigawatt days per metric ton uranium (GWD/MTU)) and relatively high burnup (60 GWD/MTU) pressurized-water reactor (PWR) and boiling-water reactor (BWR) fuel, although the transportability of the high burnup fuel was not considered. NUREG/CR-6672 studied the behavior of two generic truck casks and two generic rail casks; each generic cask encompassed design features of several NRC-certified casks.

The risks calculated in NUREG/CR-6672 were several orders of magnitude less than the estimates of NUREG-0170, concluding that no radioactive material would be released in more than 99.99 percent of accidents involving spent fuel shipments. These smaller risk estimates resulted from the use of refined and improved analytical and modeling techniques, exemplified by the finite element (FE) analyses of cask structure, and some experimental data substituted for the engineering judgments used in NUREG-0170.

In addition to the NRC-sponsored risk assessments cited above, there have been many other studies on the subject of spent fuel transportation. Perhaps one of the most independent, objective, authoritative, and recent analyses is the National Research Council report (co-sponsored by the NRC), "Going the Distance?—The Safe Transport of Spent Nuclear Fuel and

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[2] "Modal Study" and "NUREG/CR-6672" are the names by which these documents are referred to in the general transportation literature. The actual titles are in the bibliography of this document.

High-Level Radioactive Waste in the United States" (Committee on Transportation of Radioactive Waste, 2006). This reference is recommended to readers interested in further information on transportation package safety, transportation risk, and particularly for its coverage of societal topics beyond the scope of the technical risk assessment in the present study. One of the "Going the Distance" findings was:

> The radiological risks associated with the transportation of spent fuel and high-level waste are well understood and are generally low, with the possible exception of risks from releases in extreme accidents involving very long duration, fully engulfing fires.

In part because of that finding, the NRC sponsored several studies to investigate the potential consequence from severe historical fire accidents if a spent fuel cask was involved. Two of these studies investigated tunnel fires (Adkins et al., 2006; Adkins et al., 2007) and one investigated the response of a spent fuel cask to an accident below a highway overpass (Bajwa et al., 2011). While these three studies examined environments where fire accidents actually occurred, they made assumptions about the placement of a cask within that environment that would cause the most damage to the cask without considering the probability of the placement. This study also evaluates severe fire accident consequences (but not modeling any particular historical accidents), as well as their associated probabilities, to provide a risk perspective.

The present study analyzes the behavior of three currently certified casks carrying Westinghouse 17×17 PWR fuel assemblies with 45 GWD/MTU burnup, the highest burnup that any of the three casks were certified to carry as of 2008 (the time of the analyses; some of the casks already have had changes to their allowed contents). In the future these casks may be certified to carry higher burnup fuel that has been cooled for a longer time and with a similar source term. A brief discussion on the effect of this change is provided in Section 6.3. For routine transportation, the risks are slightly larger than those estimated in NUREG/CR-6672 because although the actual external dose rates are less than the regulatory maximum used in the other studies, populations along the routes have increased significantly. For accidents, the radiological risks calculated in the current study are at least an order of a magnitude less. The reduction in the estimates of risk from those in NUREG–0170 and NUREG/CR-6672 is the result of new data (such as event trees and accident probabilities) and observations and improved modeling techniques.

1.3 Risk

Understanding transportation risk is integral to understanding the environmental and related human health impact of radioactive materials transportation. A large amount of data exists for deaths, injuries, and damage from traffic accidents, but there are no data on health effects that radioactive materials transportation cause since no such effects have been observed. Therefore, regulators and the public rely on estimates of risk to gauge the potential effects of radioactive materials transportation. The risk estimates consider the potential accidents and events, where they could occur, and how severe they might be. Risk estimates include estimating the likelihood and severity of transportation accidents, as well as the calculation of exposure of workers and members of the public to ionizing radiation from routine transportation.

Risk is usually defined by answering the questions posed by the risk "triplet," which is identified below:

- What can happen (the scenario)?
- How likely is it (the probability)?
- What is the outcome if it happens (i.e., how bad is it (the consequence))?

A risk number (quantitative risk) is calculated by multiplying the probability and consequence for a particular scenario. The probability of a scenario is always less than or equal to 1, because the maximum probability of an event is 1 (100 percent); an event with 100 percent probability (probability=1) of occurrence is an event that is certain to happen. In reality, very few events are certain to happen or certain not to happen (zero probability). The probability of most events is between these two extremes. Transportation accidents involving large trucks, for example, have a very low probability. The probability of a traffic accident for all highway vehicles is about 0.0000012 per km (or 1.2 in 1,000,000 km) (0.000002 per mile (or 2 in 1,000,000 miles)) according to the U.S. Department of Transportation (DOT) Bureau of Transportation Statistics (DOT, 2007), and the probability of a particular traffic accident scenario is even smaller, as shown in the event trees in Appendix V (Figures V-1 and V-2).

1.3.1 Accident Data

The only data available to estimate the future probability of a scenario are how often that scenario has occurred in the past. The probability of the scenario can be considered the same as its historical frequency. In the case of transportation accidents, enough accidents must have occurred in the past so that future accidents per kilometer can be predicted with reasonable accuracy. That is, the sample must be large enough to be sampled randomly. The most applicable frequency would be the frequency of accidents involving vehicles carrying SNF, but there have been too few of these for a statistically valid prediction.[3] The sample size could have been increased by using international data, but regulations and practices in other countries are not consistent with those in the United States. In any case, there have not been enough accidents worldwide involving spent fuel transportation to provide an adequate statistical data base. Even accidents involving all hazardous materials transportation do not provide a large enough database from which to generate statistics on a State-by-State basis. The database used in this study is the frequency of highway accidents involving large semitrailer trucks and the frequency of freight rail accidents (DOT, 2007). Freight rail accident frequency is based on accidents per railcar-mile.

1.3.2 Spent Nuclear Fuel Transportation Scenarios

Several scenarios categorize transportation risk in this study. The most probable is routine transportation of SNF without incidents or accidents between the beginning and end of the trip. Routine transportation is an example of the risk triplet identified previously.

- What can happen? The scenario is routine incident-free transportation.

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[3] The U.S. Department of Transportation's (DOT) Bureau of Transportation Statistics lists accidents per year for all classes of hazardous materials. The 2009 database lists 76 class 7 (radioactive materials) rail and highway incidents in the past 10 years; http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/tenyr_ram.pdf. These data did not specify the type of radioactive material involved. Not all of these incidents are accidents by DOT definition.

- How likely is it? The probability is 100 percent (even if the shipment is involved in an accident, it still has an incident-free segment and dose).

- What if it happens? The consequence is a radiation dose less than 1 percent of background to individuals near the cask or along the route.

The doses and risks from routine transportation are analyzed in Chapter 2.

The accident scenarios discussed in this study are:

(1) 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.

- Accidents in which damage to the vehicle is enough that it cannot move from the scene of the accident under its own power. There is no damage to the spent fuel cask that results in increased radiation in this type of accident.

- Accidents involving a traffic death, injury, or both, but no damage to the spent fuel cask that results in increased radiation in this scenario.

(2) Accidents in which the spent fuel cask is affected.

- Accidents involving loss of shielding (either neutron or gamma shielding) but no release of radioactive material.

- Accidents in which a release of radioactive material occurs.

In the first type of accidents, the only potential radiation dose to the public is from exposure of members of the public to external radiation emanating from the cask while the vehicle is stopped. In the current study all of these accidents assume that the vehicle is stopped for 10 hours. Only the second type of accidents involve release of radioactive material.

Traffic accident statistics (accident frequencies) are used in the analysis to calculate risks. Average traffic accident frequencies since 1996 for large semitrailer trucks are about 1.3 accidents per million highway kilometers (which is about the same as the accident rate for all highway vehicles). For freight rail, average frequencies since 1996 are about 1 accident per 10 million railcar kilometers. The overall accident probability is the product of the probability that an accident will happen and the conditional probability that it will be a particular type of accident.

The consequence of an accident scenario could be a dose of ionizing radiation, either from external radiation from a stationary cask or from radioactive material released in an accident. The risk is the product of the overall accident probability and the consequence and is referred to as "dose risk."

1.4 Regulation of Radioactive Materials Transportation

DOT regulates the transportation of radioactive materials as part of hazardous materials transport regulations, primarily under Title 49, "Transportation," to CFR Part 173, "Shippers—General Requirements for Shipments and Packaging," dated October 1, 2011. Mode specific regulations are given in Parts 174 to 177 and specifications for packagings are given in Part 178. In addition,49CFR174.471 allows the use of packagings certified by the NRC under 10 CFR Part 71. The regulations of 10 CFR Part 20, "Standards for Protections Against Radiation," also are relevant. NRC transportation regulations primarily apply to the transportation of packages. DOT regulations include labeling, occupational and vehicle standards, registration requirements, reporting requirements, and packaging regulations. Generally, DOT packaging regulations apply to industrial and Type A packaging whereas the NRC regulations apply to Type A fissile materials packaging and Type B packaging. Industrial and Type A nonfissile packages are designed to resist the stresses of routine transportation and are not certified to maintain their integrity in accidents, although many do. Type B packages are used to transport very hazardous quantities of radioactive materials. They are designed to maintain their integrity in severe accidents because the NRC recognizes that any transport package and vehicle may be in traffic accidents. This study addresses SNF transportation; therefore, it is only concerned with SNF for Type B packaging. (For the remainder of this report, the term "cask" will be used to refer to the contents plus the packaging.)

Nuclear fuel that has undergone fission in a reactor is extremely hot and radioactive when it is removed from the reactor. To cool the fuel thermally and allow the highly radioactive and short-lived fission products in the fuel to decay, the fuel is discharged from the reactor into a large pool of water. The fuel usually remains in the pool as long as there is space for it. After the fuel has cooled sufficiently, it can be moved to dry surface storage at the reactor or transported to a storage site or other destination. Currently, very little transportation of spent commercial power reactor fuel takes place in the United States and there are no plans to transport SNF before it has cooled for 5 years. The transportation casks are rated for heat load, which often determines the cooling time needed for the fuel to be transported. Shielding or other considerations may also drive the required cooling time.

10 CFR Part 71

The NRC recognizes that vehicles carrying radioactive materials are as likely as any vehicles of similar size traveling on similar routes to be in accidents. Therefore, transportation packages for very radioactive materials such as SNF are designed to maintain their integrity in severe accidents.[4] Packages meeting this requirement are Type B packages, which include the casks considered in this analysis—the NAC-STC (NAC, 2004) and Holtec HI-STAR 100 (Holtec International, 2000) rail casks, and the GA-4 (General Atomics, 1998) legal-weight truck casks.

Type B packages are designed to pass the sequential series of tests described in 10 CFR 71.73, "Hypothetical Accident Conditions." These tests are summarized below.

(1) A 9-meter (30-foot) drop onto an essentially unyielding horizontal surface. "Essentially unyielding" in this context means the target is hard and heavy enough that the package

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[4] Although regulations allow the release of a specific quantity of each radionuclide, Type B casks typically are designed to remain leak-tight.

absorbs nearly all of the impact energy and the target absorbs very little energy. This test condition is more severe than most transportation accidents.

(2) A 1-meter (40-inch)[5] drop onto a fixed 15-centimeter (cm) (6-inch) diameter steel cylinder to test the package's resistance to punctures.

(3) An 800 degrees Celsius (C) (1,475 degrees Fahrenheit (F)) fire that fully engulfs the package for 30 minutes.

(4) Immersion under 0.9 meters (3 feet) of water. Casks carrying spent fuel also are required to withstand a nonsequential immersion in 200 meters (660 feet) of water for 1 hour.

Figure 1-1 illustrates this sequence of tests.

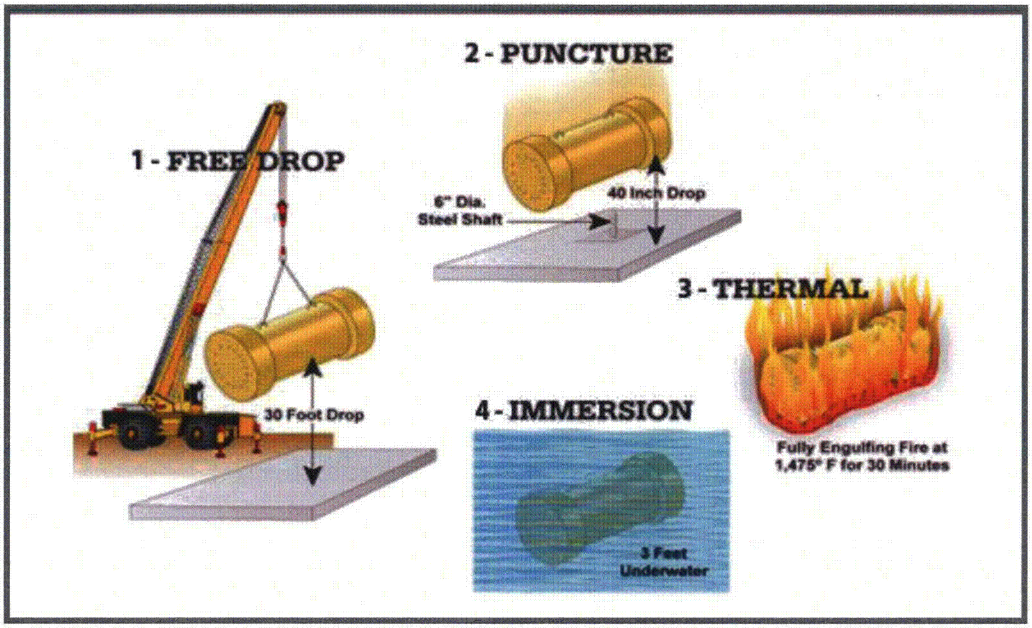

Figure 1-1 The four tests for Type B packages

The package tests in 10 CFR 71.73 were developed to envelope real-life accidents. These tests are not intended to represent any specific transportation route, any specific historical transportation accident, or a "worst-case" accident. These tests are intended to simulate the damaging effects of a severe transportation accident in a manner that provides international acceptability, uniformity, and repeatability. All International Atomic Energy Agency Member States use these tests.

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5 When discussing the regulations, the conversion between SI units and English units are those in the regulations. The actual arithmetic conversion factors are used in other areas of this report rather than the nominal conversions adopted by convention within the regulations.

The tests are performed on a package design (either physically using a full-scale prototype or sub-scale test unit, or via computational modeling), but not on every package that will be used to transport SNF. A package designer may create computer models to evaluate the performance of a package design or components of the package design, build full-size or scale model packages for physical testing, or incorporate references to previous satisfactory demonstrations of a similar nature. In practice, the safety analysis performed for Type B packages often incorporates a combination of physical testing, computer modeling, and engineering evaluation. The SAR packaging contains information on the package design's performance in the tests and an evaluation against the acceptance criteria in 10 CFR Part 71. The SAR is used to apply for package certification. During the certification process, the NRC reviews the SAR to ensure that the package design meets all criteria specified in 10 CFR Part 71.

NRC regulations specify that release of material from the package can be no more than the amount allowed to be shipped in a nonaccident resistant Type A package. The regulation also specifies a maximum post-test external radiation dose rate of 0.01 Sv per hour (1 rem/hr) at 1 meter (40 inches) from the package surface.

10 CFR Part 20

This section of the *Code of Federal Regulations* prescribes the largest allowable radiation dose that a member of the public may receive from NRC-licensed facilities, exclusive of background radiation, diagnostic or therapeutic radiation, or material discharged to the environment in accordance with NRC regulations. This section of the code does not apply to transport, but provides doses that can be compared to those calculated in this study. These doses are listed below.

- 1 mSv per year (100 mrem per year) total effective dose equivalent (TEDE), including both external and committed internal dose.

- 0.02 mSv per hour (2 mrem per hour) in any unrestricted area from external sources. As shown in Table 2-12, for example, doses from routine, incident-free transportation are considerably below these limits.

- 5 mSv per year (500 mrem per year) from a licensed facility if the licensee can show the need and expected duration of doses larger than 1 mSv (100 mrem) per year.

Although the regulations state clearly that these dose limits do not include background, it can provide a useful comparison to other sources of radiation exposure since it affects everyone. The average background radiation dose in the United States is 0.0036 Sv (360 mrem) per year. Part 20 also regulates occupational doses to 0.05 Sv per year (5 rem per year) TEDE.

1.5 Selection of Casks

Past risk assessments of spent fuel transportation have used generic cask designs with features similar to real casks but generally without all of the conservatisms that are part of real cask designs, such as assumptions on material strength and energy-absorbing capabilities of impact limiters. In the current study, the risk assessment was performed using actual cask designs with all of the design margins that contribute to their robustness. Because it is too costly and time consuming to examine all casks, a subset of casks was selected for the risk assessment.

Appendix I lists the various NRC-certified spent fuel casks at the time the study began, provides options for choosing the casks, describes some important features of the various cask designs, and finally concludes with the casks chosen.

Table 1-1 lists the casks that were NRC-certified as of 2006 (the date when the cask selections for this study were made) for the transportation of irradiated commercial light-water power reactor fuel assemblies. Those above the heavy line are older designs that were no longer used, but still had valid certificates. Those below the heavy line were more modern and additional units of these designs could be built. The casks chosen for this study came from the latter group. Appendix I includes brief descriptions of these casks.

Table 1-1 NRC-Certified Commercial Light-Water Power Reactor Spent Fuel Casks

Cask	Package ID	Canister	Contents (Number of assemblies)	Type
IF-300	USA/9001/B( )F	No	7 PWR, 17 BWR	Rail
NLI-1/2	USA/9010/B( )F	No	1 PWR, 2 BWR	Truck
TN-8	USA/9015/B( )F	No	3 PWR	Overweight[a]
TN-9	USA/9016/B( )F	No	7 BWR	Overweight[a]
NLI-10/24	USA/9023/B( )F	No	10 PWR, 24 BWR	Rail
NAC-LWT	USA/9225/B(U)F-96	No	1 PWR, 2 BWR	Truck
GA-4	**USA/9226/B(U)F-85**	**No**	**4 PWR**	**Truck**
NAC-STC	**USA/9235/B(U)F-85**	**Both**	**26 PWR**	**Rail**
NUHOMS®-MP187	USA/9255/B(U)F-85	Yes	24 PWR	Rail
HI-STAR 100	**USA/9261/B(U)F-85**	**Yes**	**24 PWR, 68 BWR**	**Rail**
NAC-UMS	USA/9270/B(U)F-85	Yes	24 PWR, 56 BWR	Rail
TS125	USA/9276/B(U)F-85	Yes	21 PWR, 64 BWR	Rail
TN-68	USA/9293/B(U)F-85	No	68 BWR	Rail
NUHOMS®-MP197	USA/9302/B(U)F-85	Yes	61 BWR	Rail

[a] Overweight truck
Note: The casks in bold type are the ones selected for this study.

The casks chosen for detailed analysis were the NAC-STC (Figure 1-2) and the HI-STAR 100 (Figure 1-3) rail casks. The GA-4 truck cask (Figure 1-4) was used to evaluate truck shipments, but detailed impact analyses of this cask were not performed because previous analyses of both truck and rail casks have shown that truck casks have significantly lower probability of release of radioactive material in impact accidents (Sprung et al., 2000). The impact analyses from Sprung et al. were used to assess the response of the GA-4 cask. Appendix I includes the complete certificate of compliance (COC) for each of these casks (as of April 12, 2010). The NAC-STC cask was chosen because it is certified for transport of spent fuel either with or without an internal welded canister. For transport of spent fuel without an internal canister, the NAC-STC's COC allows the use of elastomeric or metallic o-rings. Although five casks in the group use lead for their gamma shielding, only the NAC-STC cask can transport fuel not contained within an inner welded canister. As noted in the analyses of Chapters 3, 4, and 5, the inclusion of spent fuel without an inner welded canister ensures that the potential pathway for radioactive material release into the environment was considered. The HI-STAR 100 rail cask was chosen because it was the only all-steel cask in the group certified for transport of fuel in an inner welded canister. The GA-4 truck cask was selected because it has a larger capacity than the NAC-LWT; therefore, it was more likely to be used in a large spent fuel transportation campaign. The chosen casks included all three of the most common shielding options: lead, depleted uranium (DU), and steel.

Table 1-2 summarizes the casks chosen.

The choice of rail casks allowed for a comparison between directly loaded and canistered fuel, a comparison between a Steel-Lead-Steel cask and an All-Steel cask, and a comparison between elastomeric and metallic o-ring seals.

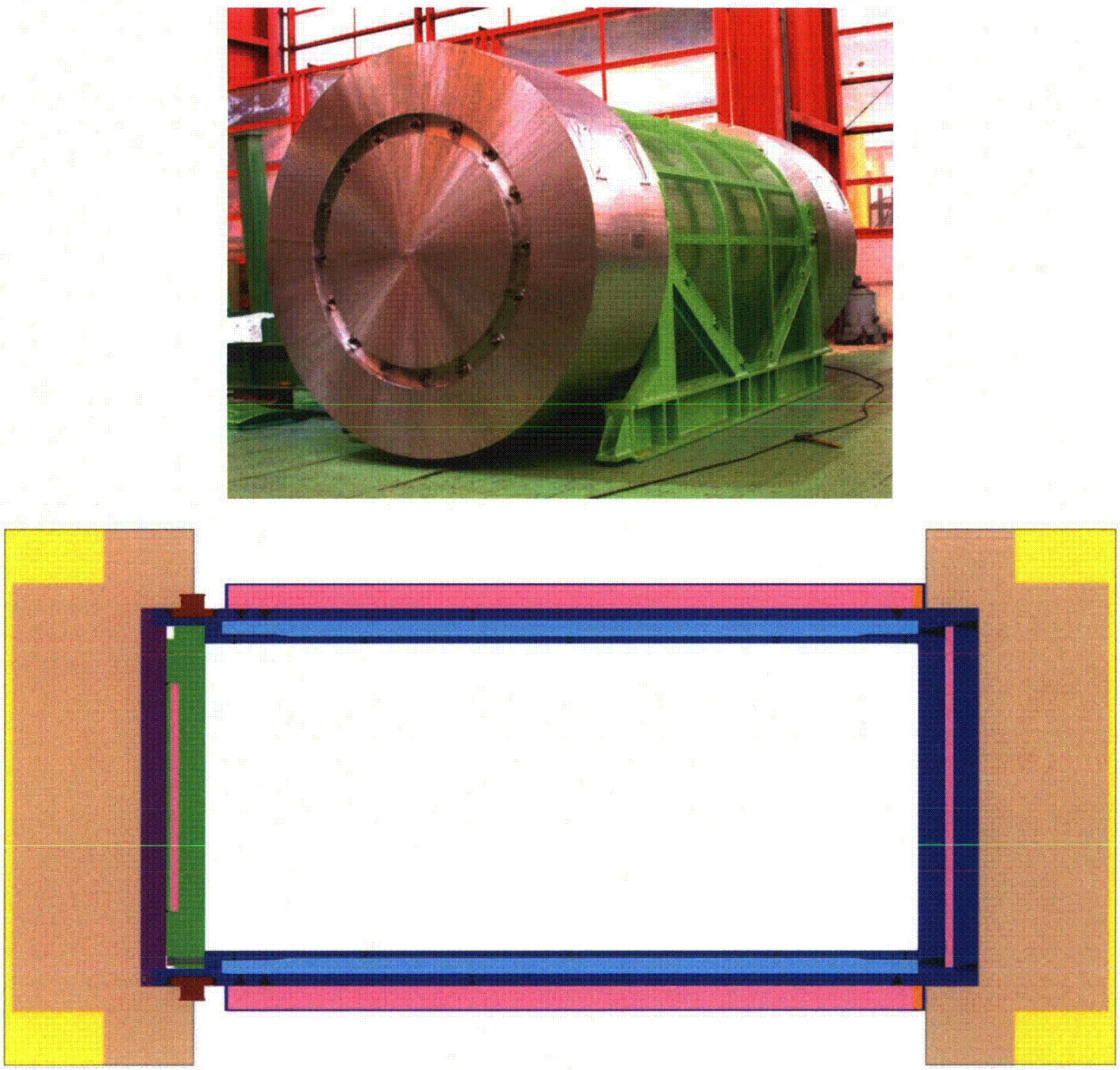

Figure 1-2 Photograph and cross-section of the NAC-STC cask
Figure source: (courtesy of NAC International)

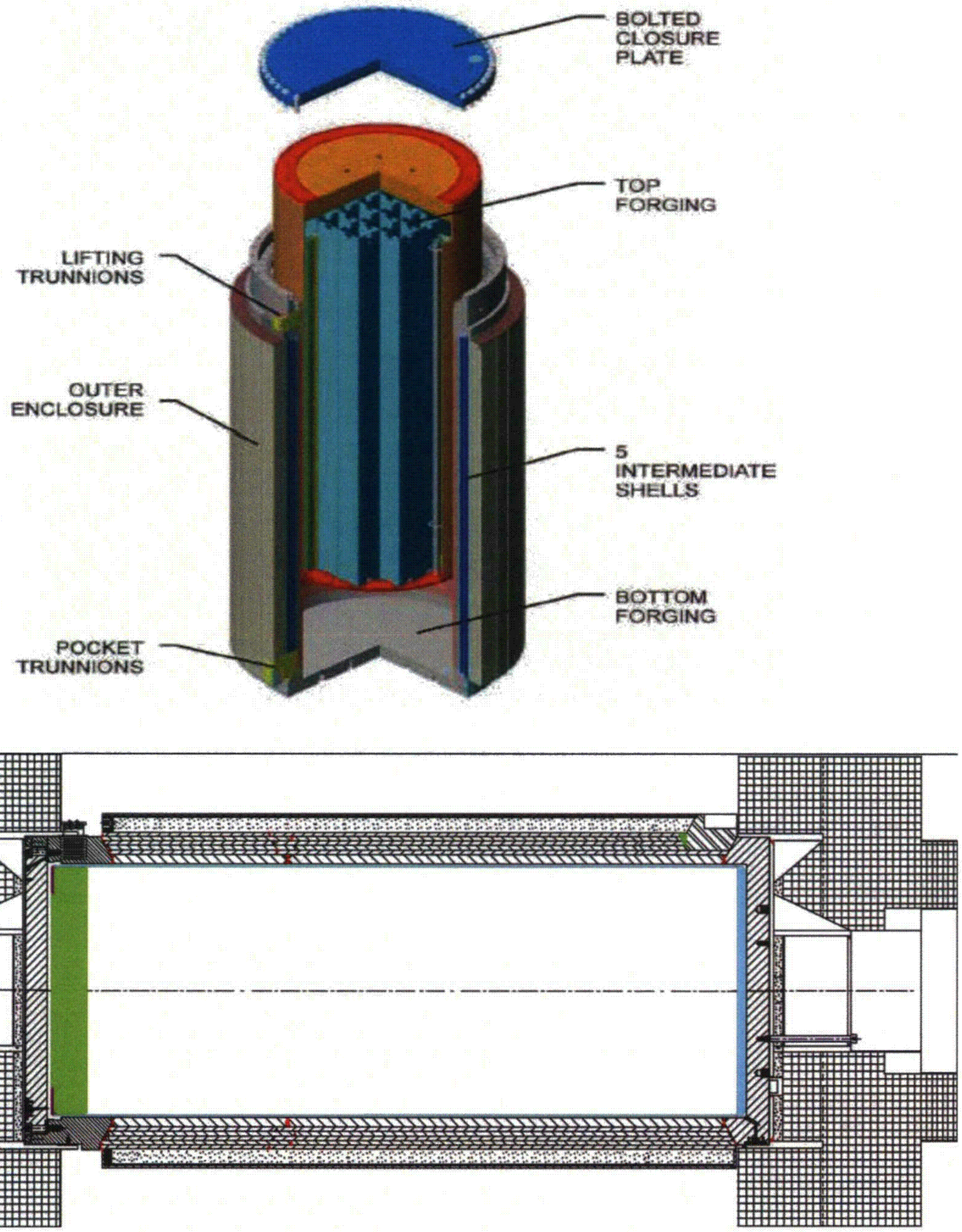

Figure 1-3 Basic layout and cross-section of the HI-STAR 100 rail transport cask
Figure source: (from Haire and Swaney, 2005, and Holtec International, 2000)

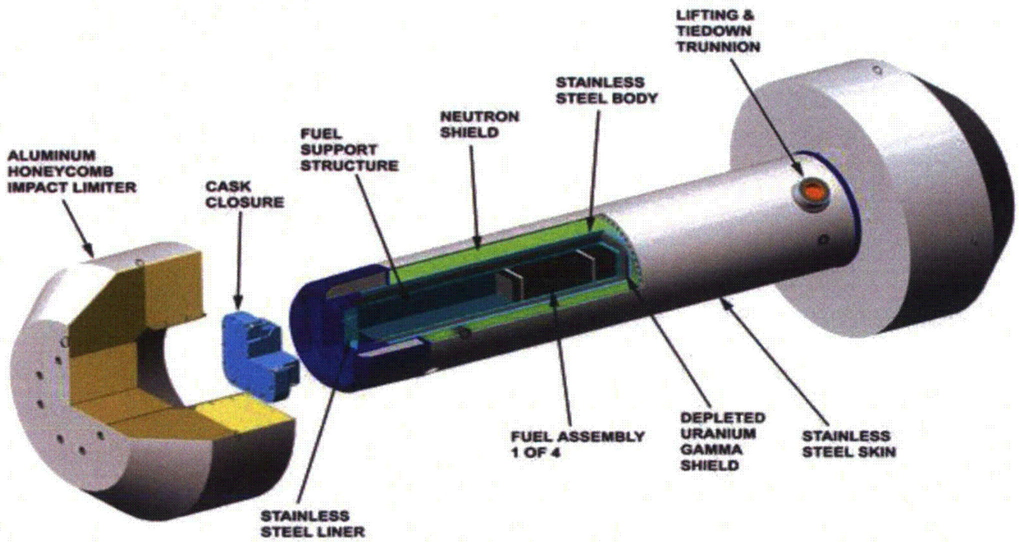

Figure 1-4 GA-4 cask
Figure source: (courtesy of General Atomics)

Detailed analyses in this report use the geometry and properties of the specific casks, but other similar casks are likely to respond in a similar manner. Therefore, the rest of this report refers to the HI-STAR 100 rail cask as Rail-Steel, the NAC-STC rail cask as Rail-Lead, and the GA-4 truck cask as Truck-DU.

Table 1-2 Casks Chosen and Reasons for Selection

Cask Chosen	Type of Cask	Reason for Consideration in this Study
HI-STAR 100 Rail Cask[4]	Rail-Steel Cask	This was the only all-steel cask in the group that was certified for transport of fuel in an inner welded canister
NAC-STC Rail Cask[6]	Rail-Lead Cask	Only the NAC-STC cask of this group can transport fuel that is not contained within an inner welded canister, thus ensuring the maximum potential for radioactive material released into the environment was considered.
GA-4 Truck Cask	Truck-DU	The GA-4 truck cask was chosen because its large capacity made it more likely to be used in any large transportation campaign.

[6] The choice of rail casks allowed comparison between directly loaded and canistered fuel, comparison between a Steel-Lead-Steel cask and an All-Steel cask, and comparison between elastomeric o-ring seals and metallic o-ring seals.

2. RISK ANALYSIS OF ROUTINE TRANSPORTATION

2.1 Introduction

NUREG–0170 (NRC, 1977) was the first comprehensive assessment of the environmental and health impact of transporting radioactive materials. It documented estimates of the radiological consequences and risks associated with shipment by truck, train, plane, or barge of approximately 25 different radioactive materials, including power reactor spent fuel. However, little actual data on spent nuclear fuel (SNF) transportation was available in 1977 and computational modeling of such transportation was in its infancy.

The RADTRAN computer code (Taylor and Daniel, 1977) is used in this chapter to estimate risks from routine[7] transportation of SNF. Sandia National Laboratories initially developed RADTRAN for the NRC's NUREG–0170 risk assessment. During the past several decades, the calculation method and RADTRAN code have improved to stay current with computer technology and supporting input data have been collected and organized. The basic RADTRAN analysis approach has not changed since the original development of the code, and the risk assessment method used in the RADTRAN code is accepted worldwide; about 25 percent of the 500 RADTRAN users are international.[8]

RADTRAN 6.0, integrated with the input file generator RADCAT (Neuhauser et al., 2000,[9] Weiner et al., 2009) is the version used in this study. The incident-free module of RADTRAN, the model used for the analysis in this chapter, was validated by measurement (Steinman et al., 2002), and verification and validation of RADTRAN 6.0 are documented in Dennis et al., 2008.

This chapter discusses risks to the public and workers when transportation of casks containing spent fuel takes place without incident and the transported casks are undamaged. Nonradiological vehicular accident risk, which is orders of magnitude larger than the radiological transportation risk, is not analyzed in this study. The risks and consequences of accidents and incidents interfering with routine transportation are discussed in Chapter 5.

This chapter includes the following:

- A brief discussion of ionizing radiation emitted during transportation
- A description of the RADTRAN model of routine transportation
- Radiation doses from a single routine shipment to:
  - Members of the public who live along the transportation route and near stops
  - Occupants of vehicles that share the route with the radioactive shipment
  - Various groups of people at stops
  - Workers

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7 The term "routine transportation" is used throughout this document to mean incident- or accident-free transportation.

8 The currently registered RADTRAN users are listed on a restricted-access Web site at Sandia National Laboratories.

9 Neuhauser et al. (2000) is the technical manual for RADTRAN 5 and is cited because the basic equations for the incident-free analyses in RADTRAN 6 are the same as those in RADTRAN 5. The technical manual for RADTRAN 6 is not yet available.

Appendix II includes detailed results of the RADTRAN calculations for this analysis. All references are listed in the bibliography. Weiner et al. (2009) provides a discussion of RADTRAN use and applications.

2.2 Radiation Emitted during Routine Transportation

The RADTRAN model for calculating radiation doses is based on the well-understood behavior of ionizing radiation, which is that it can be absorbed by various materials, including air. Absorption of ionizing radiation depends on the energy and type of radiation and the absorbing material.

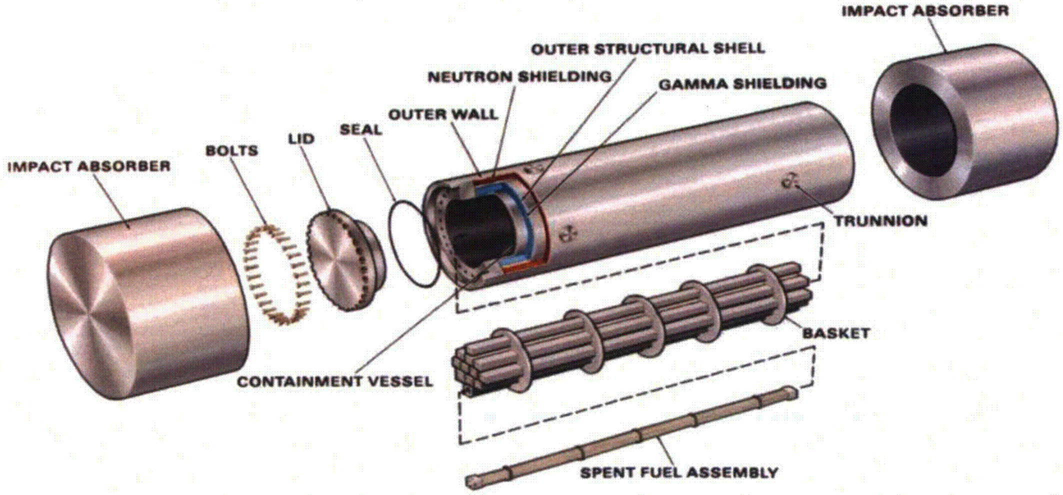
Spent nuclear fuel is very radioactive, emitting ionizing radiation in the form of alpha, beta, gamma, and neutron radiation. Casks used to transport SNF have thick walls that absorb most of the emitted ionizing radiation, thereby shielding workers and the public.

Figure 2-1 shows two generic cask diagrams with the shielding identified. This generic cask does not show the cross section of any of the three casks used in this study.

Alpha and beta radiation cannot penetrate the casks' walls (a few millimeters of paper and plastic actually absorb both well). The steel and lead layers of the cask wall absorb most of the gamma and neutron radiation emitted by spent fuel, although adequate neutron shielding also requires a neutron absorber layer, such as a polymer or boron compound. In certifying spent fuel casks, the NRC allows very low external dose rates for gamma and neutron radiation. For spent uranium-based fuel, the gamma radiation typically dominates the external dose rate.

Absorbed radiation dose is measured in sieverts (Sv) in the International System of Units, rem or millirem in the historic English unit system (millirem is abbreviated as mrem in this document). Average U.S. background radiation from naturally occurring and some medical sources is 0.0036 Sv (360 mrem) per year (Shleien et al., 1998, Figure 1.1). The recent increase in diagnostic use of ionizing radiation, as in computerized tomography, has suggested increasing the average background to 0.0062 Sv (620 mrem). This background value is cited on the NRC Web site[10]. The present study, however, uses the older value of 0.0036 Sv per year. A single dental x ray delivers a dose of 4×10^{-5} Sv (4 mrem) and a single mammogram delivers 1.3×10^{-4} Sv (13 mrem) (Stabin, 2009). The maximum radiation dose rate from a spent fuel cask that regulation allows is 10^{-4} Sv per hour (10 mrem/hour), measured at 2 meters (about 6.6 feet) from the outside of the cask (10 CFR Part 71), or about 0.00014 Sv/hour (14 mrem per hour) at 1 meter (40 inches) from a cask 4 to 5 meters (13 to 17 feet) long.

[10] http://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html



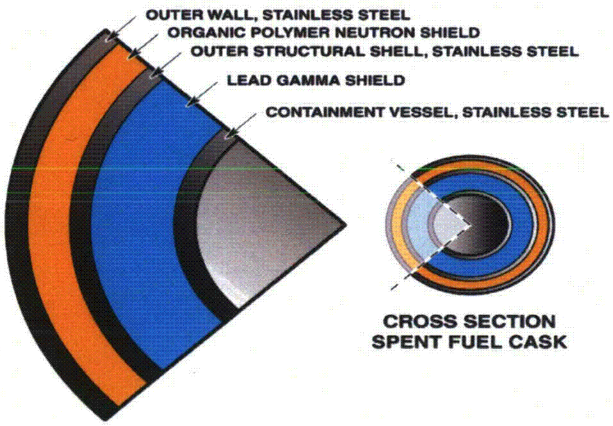


Figure 2-1 The upper figure is an exploded view of a generic spent fuel cask. The lower figure is a cross section of the layers of the cask wall.
Figure source: (Sandia National Laboratories archive)

The external radiation doses from the casks in this study (Figures 1-2 to 1-4), determined from values reported in the cask SARs, are shown in Table 2-1 (Holtec, 2000; NAC, 2004; General Atomics, 1998).

Table 2-1 External Radiation Doses from the Casks in this Study

	Truck-DU	Rail-Lead	Rail-Steel
Transportation mode	Highway	Rail	Rail
Dose rate Sv/h (mrem/h) at 1 m (40 inches)	0.00014 (14)	0.00014 (14)	0.000103 (10.3)
Gamma fraction	0.77	0.89	0.90
Neutron fraction	0.23	0.11	0.10

The calculated radiation dose to workers and members of the public from a routine shipment is based on the external dose rate at 1 meter from the spent fuel cask as shown in Figure 2-2. This dose rate, when expressed in mrem per hour (or mSv per hour times 100), is numerically equal to the transport index (TI). Doses from the external radiation from the cask depend on the external dose rate, the distance of the receptor from the cask, the exposure time, and intervening shielding.

2.3 The RADTRAN Model of Routine, Incident-Free Transportation

2.3.1 The Basic RADTRAN Model

For analysis of routine transportation, RADTRAN models the cask as a sphere with a radiation source at its center and assumes that the dimensions of the trailer or railcar carrying the cask are the same as the cask dimensions. The emission rate of the radiation source is based on the TI instead of a shielding calculation. The radiation source is modeled as a virtual source at the center of the sphere shown in Figure 2-2 that produces the same TI as the cask. The diameter of this spherical model, called the "critical dimension," is the longest dimension of the actual spent fuel cask.

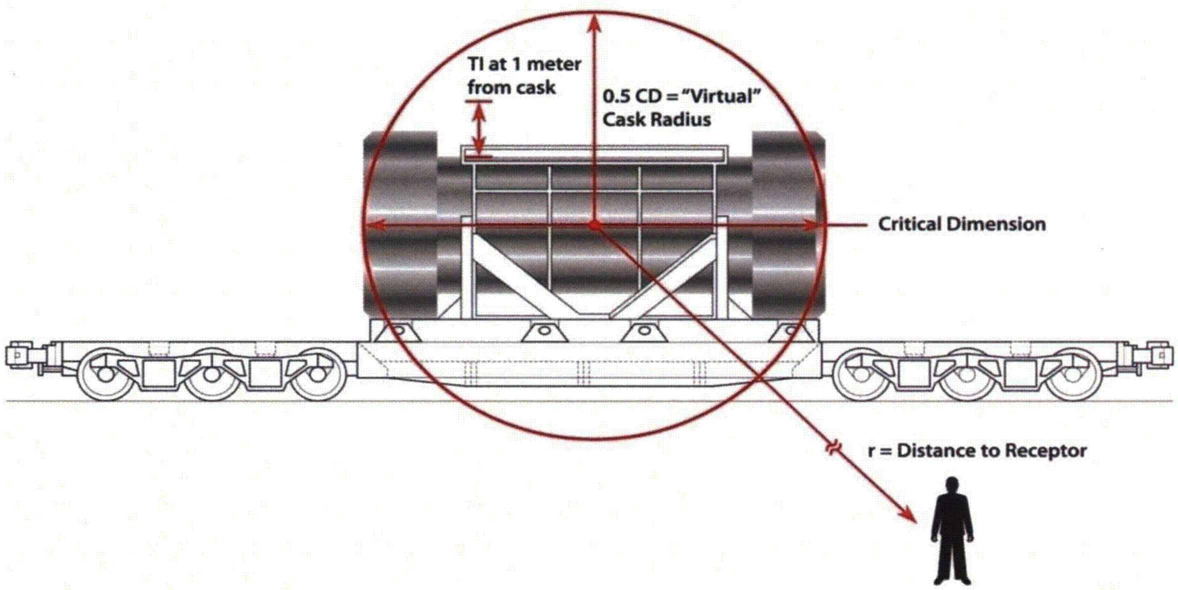


Figure 2-2 RADTRAN model of the vehicle in routine, incident-free transportation. The cask in this diagram is positioned horizontally and the critical dimension is the cask length.
Figure note: (TI = transport index, CD = critical dimension, r = radius)

When the distance to the receptor (*r* in Figure 2-2) is much larger than the critical dimension, RADTRAN models the dose to the receptor as proportional to $1/r^2$. When the distance to the receptor *r* is similar to or less than the critical dimension, as for crew or first responders, RADTRAN models the dose to the receptor as proportional to $1/r$. The RADTRAN spherical model overestimates the measured dose by a few percent (Steinman et al., 2002).

2.3.2 Individual and Collective Doses

The dose to workers and the public from a cask during routine transportation depends on the amount of time workers or the public are exposed to the cask, the distance from the cask, the external radiation from the cask, and intervening shielding. When the vehicle carrying the cask is traveling along the route, the faster the vehicle goes, the less exposure there is to anyone along the vehicle's route. Therefore, an individual member of the public residing near the transport route receives the largest dose from a moving vehicle when he or she is as close as possible to the vehicle and the vehicle is traveling as slowly as possible. For trucks and trains carrying spent fuel at a speed of 24 kilometers per hour (kph) (15 miles per hour (mph)) and a distance of 30 meters (approximately 100 feet) are assumed for maximum exposure.[11] Table 2-2 shows the maximum dose to an individual member of the public under these conditions. The Rail-Lead cask has a higher dose than the Rail-Steel cask because it has a higher TI. The Truck-DU cask has a higher dose than the Rail-Lead cask (same TI) because it has a longer critical dimension; therefore, it takes more time to pass a receptor. The transit speed used for both rail and truck transport in the calculation of the maximum individual dose is 24 kph (15 mph). These doses are about the same as 1 minute of average background: 6.9×10^{-9} Sv (6.9×10^{-4} mrem).

Table 2-2 Maximum Individual In-Transit Doses

Cask (mode)	Dose, Sv (mrem)
Rail-Lead (rail)	$5.7\text{x}10^{-9}$ ($5.7\text{x}10^{-4}$)
Rail-Steel (rail)	$4.3\text{x}10^{-9}$ ($4.3\text{x}10^{-4}$)
Truck-DU (truck)	$6.7\text{x}10^{-9}$ ($6.7\text{x}10^{-4}$)

When a vehicle carrying a spent fuel cask travels along a route, the people who live along that route and the people in vehicles that share the route are exposed to the external radiation from the cask. Doses to groups of people are collective doses; the units of a collective dose are person-Sv (person-rem). A collective dose, sometimes called a population dose, is essentially an average individual dose multiplied by the number of people exposed.[12] RADTRAN calculates collective doses along transportation routes by integrating over the width of a band along the route where the population resides (the *r* in Figure 2-2) and then integrating along the route. Collective doses to people on both sides of the route are included. The exposed population is in a band 770 meters (approximately 0.5 miles) on either side of the route: from 30 meters (100 feet) from the center of the route to 800 meters (0.5 miles).

Figure 2-3 shows how these bands are defined with examples of distances within the bands.

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[11] Thirty meters is typically as close as a person on the side of the road can get to a vehicle traveling on an interstate highway.

[12] Appendix II contains a detailed discussion on the collective dose.

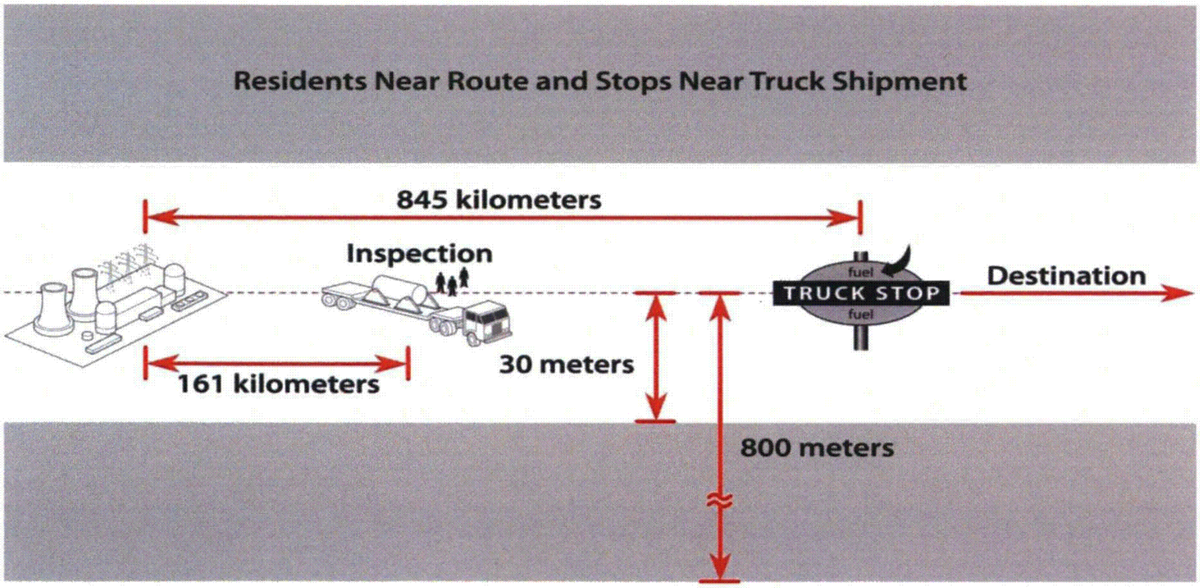

Figure 2-3 Diagram of a truck route as modeled in RADTRAN (not to scale)

Occupants of vehicles that share the route with the radioactive shipment also receive a radiation dose from the spent fuel cask. The collective dose to occupants depends on the average number of occupants per vehicle and the number of vehicles per hour that pass the radioactive shipment in both directions.

Any route can be divided into as many sections as desired for dose calculation (e.g., the dose to residents of a single house or city block). However, as a practical matter, routes are divided into rural, suburban, and urban segments according to the population per square mile (population density).
Table 2-3 summarizes the characteristics of each population type that is part of the RADTRAN dose calculation. References for these parameter values can be found in the Table 2-3 footnotes.

Table 2-3 Characteristics of Rural, Suburban, and Urban Routes Used in RADTRAN. Highway routes are Interstate or other limited-access highways.

	Basis	Highway			Rail		
		Rural	Suburban	Urban	Rural	Suburban	Urban
Population density per km^2 (per mi^2)[a]	TRAGIS	0 to 54 (0 to 139)	54 to 1,284 (139 to 3,326)	>1,284 (>3,326)	0 to 54 (0 to 139)	54 to 1,284 (139 to 3,326)	>1,284 (>3,326)
Nonresident/ resident ratio[b]	Urban Areas	NA	NA	6	NA	NA	6
Shielding by buildings[b]	Historic RADTRAN use	0 (outside)	13% (wood)	98.2% (concrete, brick)	0 (outside)	13% (wood)	98.2% (concrete, brick)
U.S. average vehicle speed[c] kph (mph)[c,d]	DOT	108 (67)	108 (67)	102(63)	40 (25)	40 (25)	24 (15)
U.S. average vehicles per hour[b,e]	DOT	1119	2,464	5,384	17	17	17
Occupants of other vehicles[b,f]	DOT	1.5	1.5	1.5	1	1	5

[a] Johnson and Michelhaugh, 2003; [b]Weiner et al., 2009; [c]DOT, 2004a; [d]DOT, 2004b, Appendix D; [e]DOT, 2009 (these are average railcars per hour); [f]DOT, 2008, Table 1-11.

Each route clearly has a distribution of rural, urban, and suburban areas, as indicated in the example of the truck route in Figure 2-4, which shows a segment of Interstate 80 through Salt Lake City, UT. The broad stripe is the half-mile band on either side of the highway. The red areas are urban populations, the yellow areas are suburban, and the green areas are rural. Instead of analyzing each separate, rural, urban, and suburban segment of this stretch of highway, the rural, suburban, and urban areas are each combined for RADTRAN dose calculations. The routing code WebTRAGIS (Johnson and Michelhaugh, 2003) provides these combinations for each State traversed by a particular route.

I-80 Corridor
Salt Lake City

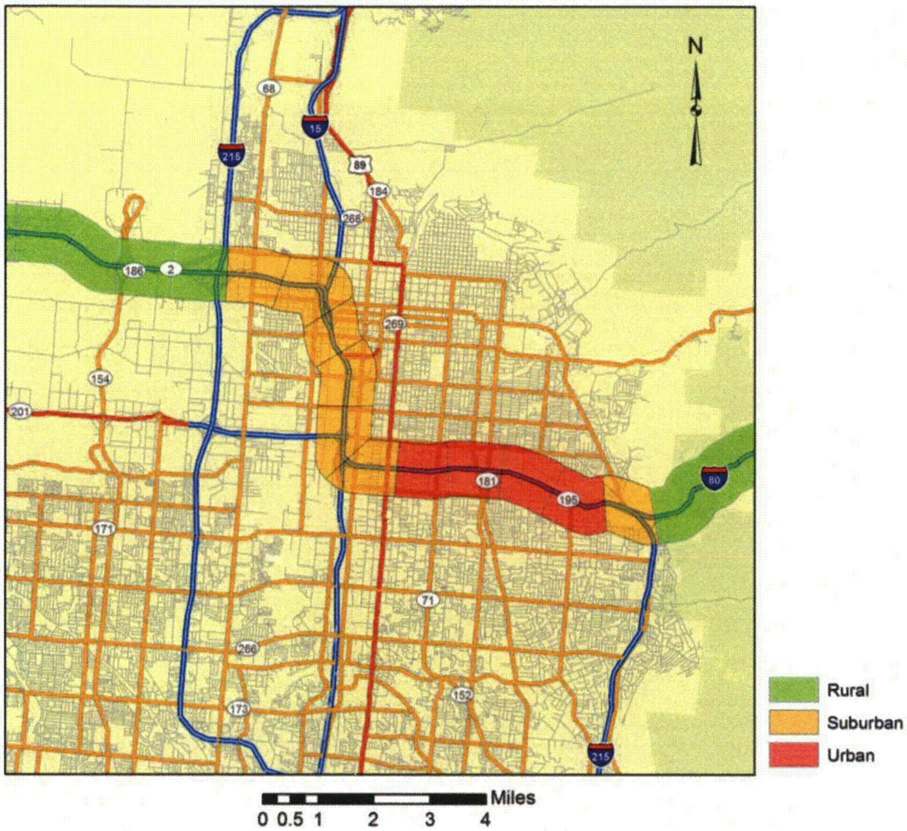

Figure 2-4 A segment of I-80 through Salt Lake City, UT

Table 2-4 shows the WebTRAGIS output for a truck route from Kewaunee Nuclear Plant (NP), WI, to Skull Valley, UT.

Table 2-4 Truck Route Segment Lengths and Population Densities, Kewaunee NP to Skull Valley. The route segment of Figure 2-4 is in bold.

State	Kilometers (miles)			Persons/km^2 (persons/mi^2)[a]		
	Rural	Suburban	Urban	Rural	Suburban	Urban
Illinois		45 (28)	1.2 (0.7)	15.4 (40)	267 (691)	2,049 (5,301)
Iowa	394 (245)	95 (59.1)	5.1(3.2)	15.7 (41)	268 (693)	2,185 (5,653)
Nebraska	652 (405)	76 (47.2)	7 (4.4)	10 (26)	269 (696)	2,401 (6,212)
Utah	197 (123)	**38 (23.6)**	**15 (9.3)**	7.5 (19.4)	**407 (1,053)**	**2,412 (6,240)**
Wisconsin	191 (119)	85 (52.8)	19.9 (12.4)	21.4 (55)	337 (872)	2,660 (6,882)
Wyoming	607 (377)	34 (21.1)	3.4 (2.1)	4.9 (13)	399 (1,032)	1,967 (5,089)

[a] The populations density is a WebTRAGIS output, calculated by averaging the population density along the rural, suburban, or urban route length within each State.

The maps in Figures 2-5 through 2-8 show the 16 truck and 16 rail routes analyzed in this report. These routes were selected as representative of possible cross-country transport. No actual spent fuel transport has occurred from any of these plants to any of these destinations. The maps are adapted from the output of the routing code WebTRAGIS (Johnson and Michelhaugh, 2003).

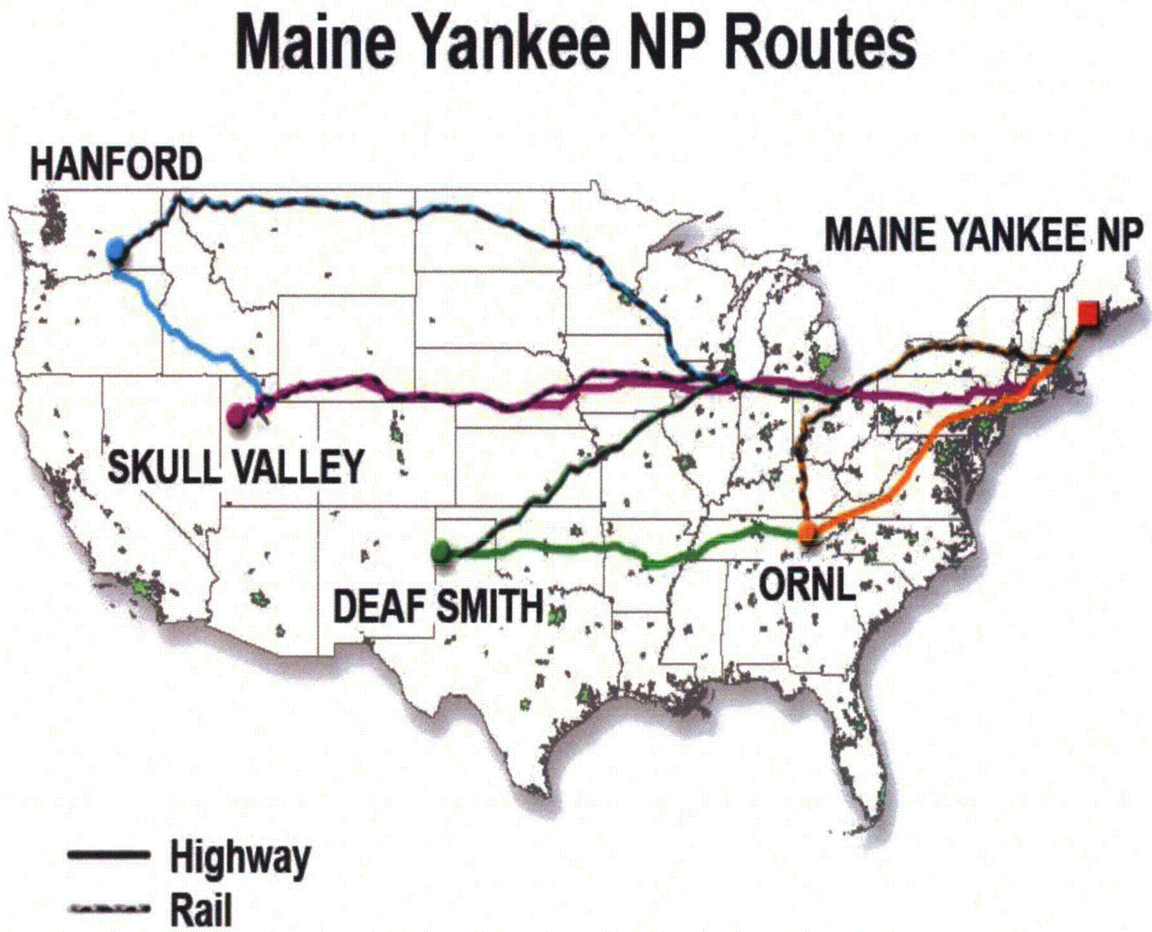

Figure 2-5 Highway and rail routes from Maine Yankee Nuclear Plant site
Figure note: (NP stands for Nuclear Plant and ORNL stands for Oak Ridge National Laboratory.)

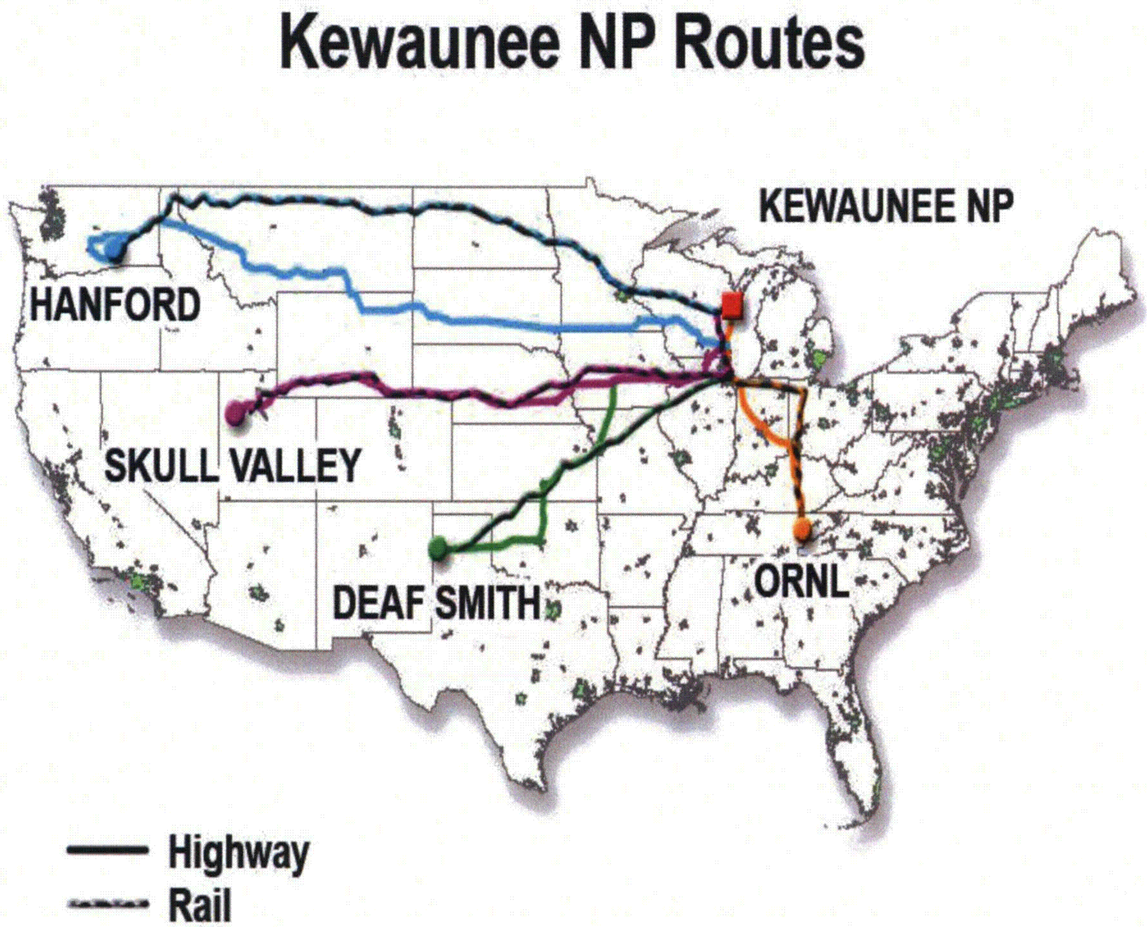

Figure 2-6 Highway and rail routes from Kewaunee Nuclear Plant
Figure note: (NP stands for Nuclear Plant and ORNL stands for Oak Ridge National Laboratory.)

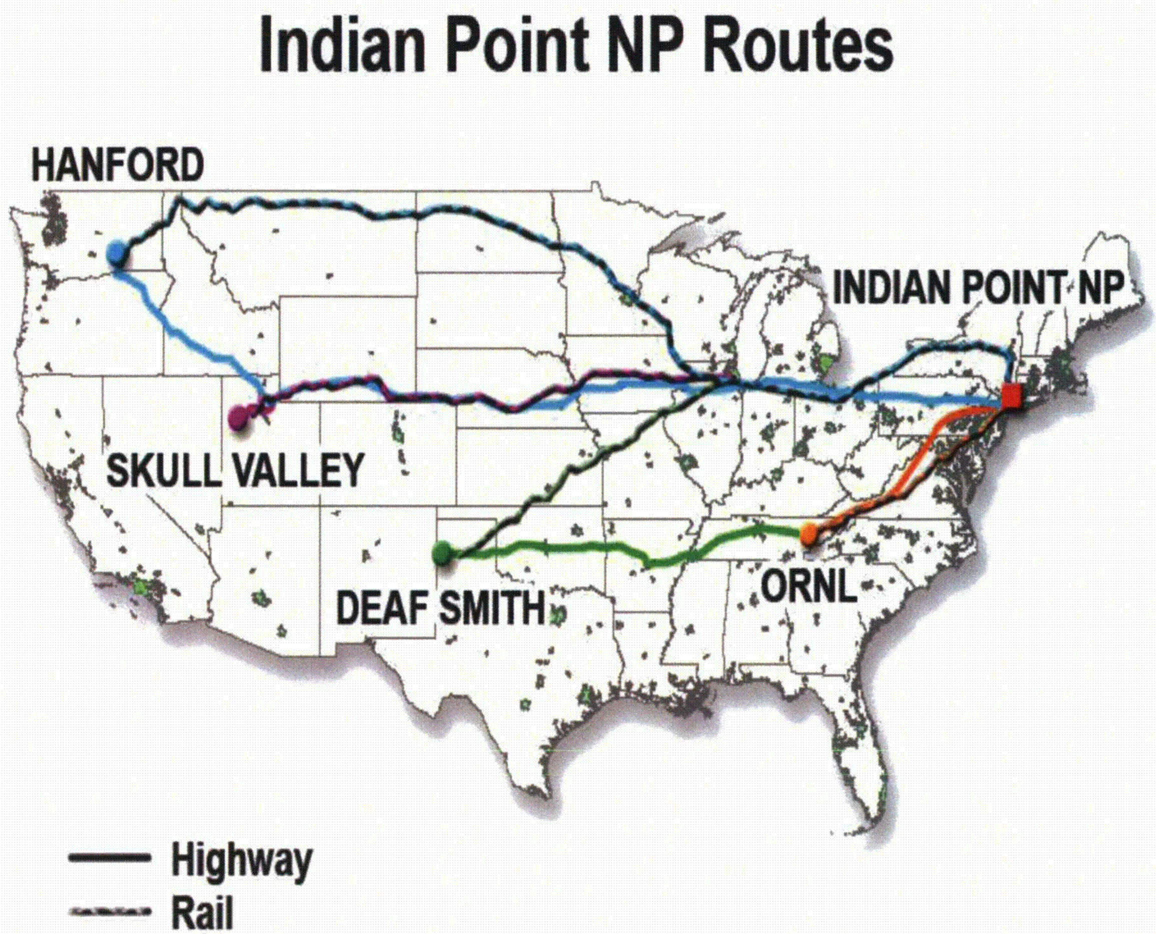

Figure 2-7 Highway and rail routes from Indian Point Nuclear Plant
Figure note: (NP stands for Nuclear Plant and ORNL stands for Oak Ridge National Laboratory.)

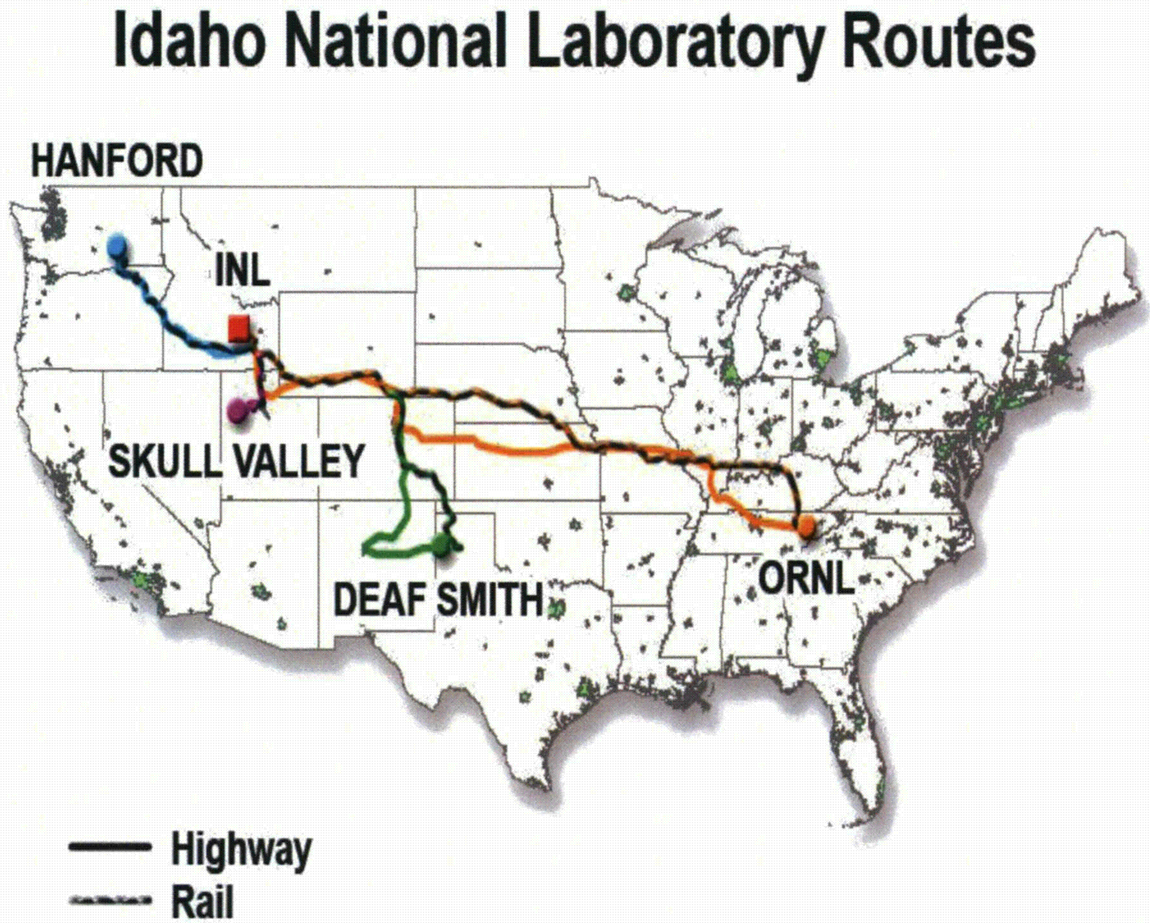

Figure 2-8 Highway and rail routes from Idaho National Laboratory
Figure note: (INL stands for Idaho National Laboratory and ORNL stands for Oak Ridge National Laboratory.)

The route segment lengths and population densities are entered into RADTRAN, which then calculates the collective doses to residents along the route segments. Collective doses, which depend on route length and on the populations along the route, were calculated for 1 shipment over each of 16 truck and 16 rail routes. Collective doses are reported as person-Sv.

The sites where the shipments originated include two nuclear generating plants (Indian Point and Kewaunee), a storage site at a fully decommissioned nuclear plant (Maine Yankee), and INL. The routes modeled are shown in Table 2-5. Both truck and rail versions of each route are analyzed.

Table 2-5 Specific Routes Modeled
Table note: Urban Kilometers are Included in Total Kilometers, (1 Kilometer = 0.6214 miles)

Origin	Destination	Population within 800 m (1/2 mile)		Total Kilometers		Urban Kilometers	
		Rail	Truck	Rail	Truck	Rail	Truck
Maine Yankee Site, ME	Hanford, WA	1,647,190	1,129,685	5,084	5,013	355	116
	Deaf Smith County, TX	1,321,024	1,427,973	3,362	3,596	211	165
	Skull Valley, UT	1,451,325	1,068,032	4,068	4,174	207	115
	Oak Ridge, TN	1,146,478	1,137,834	2,125	1,748	161	135
Kewaunee NP, WI	Hanford, WA	476,914	423,163	3,028	3,453	60	52
	Deaf Smith County, TX	677,072	494,920	1,882	2,146	110	60
	Skull Valley, UT	806,115	505,226	2,755	2,620	126	58
	Oak Ridge, TN	779,613	646,034	1,395	1,273	126	92
Indian Point NP, NY	Hanford, WA	961,026	869,763	4,781	4,515	229	97
	Deaf Smith County, TX	1,027,974	968,282	3,088	3,074	204	109
	Skull Valley, UT	1,517,758	808,107	3,977	3,672	229	97
	Oak Ridge, TN	1,146,245	561,723	1,264	1,254	207	60
Idaho National Lab, ID	Hanford, WA	164,399	132,662	1,062	959	20	15
	Deaf Smith County, TX	298,590	384,912	1,913	2,291	40	52
	Skull Valley, UT	169,707	132,939	455	466	26	19
	Oak Ridge, TN	593,680	569,240	3,306	3,287	75	63

These routes represent a variety of route lengths and populations. The routes include the eastern United States, western United States, and cross-country routes. They vary in length and include a variety of urban areas. Two of the three nuclear plants chosen as origin sites (Kewaunee, WI, and Maine Yankee, ME) and two of the destination sites (Hanford, WA, and Skull Valley, UT) are origins and destinations used in NUREG/CR-6672 (Sprung et al., 2000). Indian Point Nuclear Plant, NY, involves a different set of cross-country and east coast routes than Maine Yankee. It also is an operating nuclear plant whereas Maine Yankee has been decommissioned and is now a surface storage facility. Since this study could be used for both commercial nuclear power plant and U.S. Department of Energy spent fuel shipments, INL was included as an origin site. The destination sites include two proposed repository sites (Deaf Smith County, TX, and Hanford, WA) (DOE, 1986), the site of the proposed private fuel storage facility (Skull Valley, UT), and ORNL. These routes were not intended to provide a "worst case" result, but were chosen to provide representative results over a broad range of conditions and large segments of the country.

The route segments and population densities were provided by WebTRAGIS. Population densities were updated from the 2000 census using the 2008 Statistical Abstract (U.S. Bureau of the Census, 2008, Tables 13 and 21). Updates were only made when the difference between the 2006 and 2000 population densities was 1 percent or more. The collective doses reported in Table 2-6 and Table 2-7 are in units of person-Sv. Table 2-6 and Table 2-7 present collective doses for rail and truck, respectively, for the 16 routes. State-by-State collective doses are tabulated in Appendix II.

Table 2-6 Collective Doses to Residents near the Route (Person-Sv) per Shipment for Rail Transportation (1 Sv = 10^5 mrem)

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban	Total	Rural	Suburban	Urban	Total
MAINE YANKEE								
ORNL	1.5×10^{-5}	1.8×10^{-4}	9.0×10^{-6}	2.1×10^{-4}	1.2×10^{-5}	1.4×10^{-4}	6.8×10^{-6}	1.6×10^{-4}
DEAF SMITH	1.9×10^{-5}	2.2×10^{-4}	1.1×10^{-5}	2.5×10^{-4}	1.4×10^{-5}	1.7×10^{-4}	8.7×10^{-6}	1.9×10^{-4}
HANFORD	2.4×10^{-5}	2.6×10^{-4}	1.3×10^{-5}	2.9×10^{-4}	1.8×10^{-5}	2.0×10^{-4}	9.9×10^{-6}	2.3×10^{-4}
SKULL VALLEY	2.6×10^{-5}	2.7×10^{-4}	1.0×10^{-5}	2.9×10^{-4}	2.0×10^{-5}	2.0×10^{-4}	7.6×10^{-6}	2.2×10^{-4}
KEWAUNEE								
ORNL	1.0×10^{-5}	1.1×10^{-4}	6.7×10^{-6}	1.3×10^{-4}	7.9×10^{-6}	8.3×10^{-5}	5.1×10^{-6}	9.6×10^{-5}
DEAF SMITH	8.2×10^{-6}	9.5×10^{-5}	5.8×10^{-6}	1.1×10^{-4}	6.3×10^{-6}	7.2×10^{-5}	4.4×10^{-6}	8.3×10^{-5}
HANFORD	1.2×10^{-5}	9.3×10^{-5}	3.0×10^{-6}	1.1×10^{-4}	9.3×10^{-6}	7.1×10^{-5}	2.3×10^{-6}	8.3×10^{-5}
SKULL VALLEY	1.4×10^{-5}	1.2×10^{-4}	6.6×10^{-6}	1.4×10^{-4}	1.1×10^{-5}	9.0×10^{-5}	5.0×10^{-6}	1.1×10^{-4}
INDIAN POINT								
ORNL	7.5×10^{-6}	1.4×10^{-4}	1.4×10^{-5}	1.6×10^{-4}	5.7×10^{-6}	1.1×10^{-4}	1.1×10^{-5}	1.2×10^{-4}
DEAF SMITH	1.7×10^{-5}	1.8×10^{-4}	1.2×10^{-5}	2.0×10^{-4}	1.3×10^{-5}	1.3×10^{-4}	8.9×10^{-6}	1.5×10^{-4}
HANFORD	2.2×10^{-5}	2.1×10^{-4}	1.3×10^{-5}	2.5×10^{-4}	1.7×10^{-5}	1.6×10^{-4}	9.9×10^{-6}	1.9×10^{-4}
SKULL VALLEY	2.3×10^{-5}	2.0×10^{-4}	1.3×10^{-5}	2.4×10^{-4}	1.7×10^{-5}	1.5×10^{-4}	1.0×10^{-5}	1.8×10^{-4}
IDAHO NATIONAL LAB								
ORNL	1.8×10^{-5}	1.1×10^{-4}	3.7×10^{-6}	1.3×10^{-4}	1.4×10^{-5}	8.6×10^{-5}	2.8×10^{-6}	1.0×10^{-4}
DEAF SMITH	6.6×10^{-6}	5.8×10^{-5}	2.2×10^{-6}	6.7×10^{-5}	5.0×10^{-6}	4.5×10^{-5}	1.7×10^{-6}	5.2×10^{-5}
HANFORD	5.3×10^{-6}	3.0×10^{-5}	1.1×10^{-6}	3.6×10^{-5}	4.0×10^{-6}	2.3×10^{-5}	8.2×10^{-7}	2.8×10^{-5}
SKULL VALLEY	3.0×10^{-6}	2.5×10^{-5}	1.5×10^{-6}	3.0×10^{-5}	2.3×10^{-6}	1.9×10^{-5}	1.1×10^{-6}	2.2×10^{-5}

Table 2-7 Collective Doses to Residents near the Route (person-Sv) for Truck Transportation per Shipment (1 Sv=10^5 mrem)

FROM	TO	Truck-DU				
		Rural	Suburban	Urban	Urban Rush Hour[a]	Total
MAINE YANKEE	ORNL	5.0×10^{-6}	8.9×10^{-5}	2.0×10^{-6}	4.5×10^{-7}	9.6×10^{-5}
	DEAF SMITH	1.0×10^{-5}	1.2×10^{-4}	2.1×10^{-6}	4.8×10^{-7}	1.4×10^{-4}
	HANFORD	1.4×10^{-5}	1.0×10^{-4}	1.5×10^{-6}	3.2×10^{-7}	1.2×10^{-4}
	SKULL VALLEY	1.1×10^{-5}	9.5×10^{-5}	1.5×10^{-6}	3.3×10^{-7}	1.1×10^{-4}
KEWAUNEE	ORNL	4.1×10^{-6}	4.6×10^{-5}	1.1×10^{-6}	2.5×10^{-7}	5.2×10^{-5}
	DEAF SMITH	6.6×10^{-6}	3.9×10^{-5}	7.6×10^{-7}	1.7×10^{-7}	4.7×10^{-5}
	HANFORD	9.1×10^{-6}	4.1×10^{-5}	7.0×10^{-7}	1.5×10^{-7}	5.1×10^{-5}
	SKULL VALLEY	7.3×10^{-6}	3.1×10^{-5}	6.7×10^{-7}	1.5×10^{-7}	3.9×10^{-5}
INDIAN POINT	ORNL	4.1×10^{-6}	6.4×10^{-5}	1.6×10^{-7}	1.6×10^{-7}	6.9×10^{-5}
	DEAF SMITH	1.3×10^{-5}	1.3×10^{-4}	6.9×10^{-7}	3.1×10^{-7}	1.4×10^{-4}
	HANFORD	1.3×10^{-5}	7.6×10^{-5}	2.6×10^{-7}	2.6×10^{-7}	8.9×10^{-5}
	SKULL VALLEY	1.0×10^{-5}	6.6×10^{-5}	2.7×10^{-7}	2.7×10^{-7}	7.7×10^{-5}
IDAHO NATIONAL LAB	ORNL	8.8×10^{-6}	5.3×10^{-5}	7.7×10^{-7}	1.7×10^{-7}	6.3×10^{-5}
	DEAF SMITH	4.6×10^{-6}	3.0×10^{-5}	6.9×10^{-7}	1.5×10^{-7}	3.7×10^{-5}
	HANFORD	5.5×10^{-6}	8.8×10^{-6}	1.1×10^{-7}	4.2×10^{-8}	1.4×10^{-5}
	SKULL VALLEY	1.2×10^{-6}	1.0×10^{-5}	2.7×10^{-7}	5.9×10^{-8}	1.2×10^{-5}

[a] During rush hour RADTRAN halves the truck speed and doubles the vehicle density to take into account traffic jams. Detailed data for the actual traffic speed and density on a city-by-city basis is not available. The rush-hour collective dose is in addition to the urban (non-rush-hour) collective dose; both are included in the total.

Collective dose is best used in making comparisons (e.g., in comparing the risks of routine transportation along different routes, by different modes (truck or rail), or in different casks). Several comparisons can be made from the results shown in Table 2-6 and Table 2-7.

- Suburban residents sustain the largest dose for all routes and shipment modes.
- Urban residents sustain a larger dose from a single rail shipment than a truck shipment on the same State route even though urban population densities are similar and the external dose rates from the cask are nearly the same. As shown in Table 2-5, most (though not all) rail routes have more urban miles than the analogous truck route. Train tracks go from city center to city center whereas trucks carrying spent fuel must use interstates and bypasses. In several cases shown in Table 2-5, the rail route had twice as many urban miles as the corresponding truck route. Also, train speeds in urban areas are only one-fourth of truck speeds.
- Overall, collective doses are larger for a single shipment on rail routes than truck routes because rail routes are often longer, especially in the western United States, where there is rarely a choice of railroads and train speeds are lower than truck speeds, especially in urban areas. However, rail casks hold about six times as much spent fuel

as the truck cask. Therefore, to move a given amount of spent fuel would take six truck shipments for each rail shipment, making the total dose from shipping by truck higher.

- The collective doses shown in Table 2-6 and Table 2-7 are all very small. However, they are not the only doses people along the route receive. Background radiation is 0.0036 Sv (360 mrem) per year in the United States, or 4.1×10^{-7} Sv/hour (0.041 mrem/hr). The contribution of a single shipment to the population's collective dose is illustrated in the following example of the Maine Yankee to ORNL truck route:
  - From Table 2-7 the total collective dose to residents for this route is 9.6×10^{-5} person-Sv (9.6 person-mrem).
  - From Table 2-5, there are 1,137,834 people within 800 meters (1/2 mile) of the route.
  - Background is 4.1×10^{-7} Sv/hour (0.041 mrem/hr), which everyone is exposed to all the time, whether a shipment occurs or not.
  - A truck traveling at an average of 108 km per hour (67 mph) travels the 1,748 km (1086 miles) in 16 hours.
  - During those 16 hours, the 1,137,834 people will have received a collective background dose of 7.56 person-Sv, (756 person-rem) about 80,000 times the collective dose from the shipment.
  - To illustrate, the total collective dose during a shipment to these 1,137,834 people is not 9.6×10^{-5} person-Sv (9.6×10^{-3} person-rem), but 7.560096 person-Sv (756.0096 person-rem).
  - The NRC recommends that collective dose only be used for comparative purposes (NRC, 2008).
  - The appropriate comparison between the collective dose from this shipment of spent fuel is not a comparison between 9.6×10^{-5} person-Sv (9.6×10^{-3} person-rem) from the shipment and zero dose if there is no shipment, but between 7.560096 person-Sv (756.0096 person-rem) if there is a shipment and 7.560000 person-Sv (756.0000 person-rem) if there is no shipment.

Appendix II, Section II.6 contains a more complete discussion of collective dose.

2.3.3 Doses to Members of the Public Occupying Vehicles that Share the Route

Rail

Most U.S. rail is either double track or equipped with "passing tracks" that let one train pass another. When a train passes the train carrying the spent fuel cask, occupants of the passing train will receive some external radiation. Most trains in the United States carry freight, and the only occupants of the passing train are crew members. Only about 1 railcar in 60 has an occupant.

The dose to occupants of other trains in this situation depends on train speed and the external dose rate from the spent fuel casks. Table 2-8 shows the collective dose to public passengers of trains sharing the route, assuming for calculation purposes that train occupants are represented by one person in each passing railcar in rural and suburban areas, and five people in urban areas.[13] The rural and suburban collective doses probably are unrealistically high, since most freight rail going through rural and many suburban areas never encounters a passenger train. Data were not available to account for the occupancy of actual passenger trains, including commuter rail, that share rail routes with freight trains.

Table 2-8 Collective Doses (Person-Sv) per Shipment to Occupants of Trains Sharing Rail Routes (1 Sv=10^5 mrem)

SHIPMENT ORIGIN/ DESTINATION	Rail-Lead Cask				Rail-Steel Cask			
	Rural	Suburban	Urban	Total	Rural	Suburban	Urban	Total
MAINE YANKEE								
ORNL	$2.0x10^{-5}$	$1.2x10^{-5}$	$7.5x10^{-6}$	$4.0x10^{-5}$	$1.5x10^{-5}$	$9.3x10^{-6}$	$5.6x10^{-6}$	$3.0x10^{-5}$
DEAF SMITH	$3.8x10^{-5}$	$1.3x10^{-5}$	$9.7x10^{-6}$	$6.1x10^{-5}$	$2.9x10^{-5}$	$1.0x10^{-5}$	$7.4x10^{-6}$	$4.6x10^{-5}$
HANFORD	$6.2x10^{-5}$	$1.7x10^{-5}$	$1.6x10^{-5}$	$9.0x10^{-5}$	$4.7x10^{-5}$	$1.3x10^{-5}$	$1.2x10^{-5}$	$6.8x10^{-5}$
SKULL VALLEY	$4.8x10^{-5}$	$1.6x10^{-5}$	$9.6x10^{-6}$	$7.4x10^{-5}$	$3.6x10^{-5}$	$1.2x10^{-5}$	$7.3x10^{-6}$	$5.5x10^{-5}$
KEWAUNEE								
ORNL	$1.4x10^{-5}$	$7.0x10^{-6}$	$5.8x10^{-6}$	$2.7x10^{-5}$	$1.0x10^{-5}$	$5.3x10^{-6}$	$4.4x10^{-6}$	$2.0x10^{-5}$
DEAF SMITH	$2.4x10^{-5}$	$5.2x10^{-6}$	$5.1x10^{-6}$	$3.4x10^{-5}$	$1.8x10^{-5}$	$4.0x10^{-6}$	$3.9x10^{-6}$	$2.6x10^{-5}$
HANFORD	$4.2x10^{-5}$	$6.7x10^{-6}$	$2.8x10^{-6}$	$5.2x10^{-5}$	$3.2x10^{-5}$	$5.1x10^{-6}$	$2.1x10^{-6}$	$3.9x10^{-5}$
SKULL VALLEY	$3.5x10^{-5}$	$7.8x10^{-6}$	$5.8x10^{-6}$	$4.9x10^{-5}$	$2.7x10^{-5}$	$5.9x10^{-6}$	$4.4x10^{-6}$	$3.7x10^{-5}$
INDIAN POINT								
ORNL	$9.2x10^{-6}$	$8.1x10^{-6}$	$9.6x10^{-6}$	$2.7x10^{-5}$	$7.0x10^{-6}$	$6.1x10^{-6}$	$7.2x10^{-6}$	$2.0x10^{-5}$
DEAF SMITH	$3.6x10^{-5}$	$1.1x10^{-5}$	$9.4x10^{-6}$	$5.6x10^{-5}$	$2.8x10^{-5}$	$8.2x10^{-6}$	$7.1x10^{-6}$	$4.3x10^{-5}$
HANFORD	$6.0x10^{-5}$	$1.4x10^{-5}$	$1.1x10^{-5}$	$8.5x10^{-5}$	$4.6x10^{-5}$	$1.1x10^{-5}$	$8.0x10^{-6}$	$6.5x10^{-5}$
SKULL VALLEY	$4.8x10^{-5}$	$1.3x10^{-5}$	$1.1x10^{-5}$	$6.5x10^{-5}$	$3.6x10^{-5}$	$1.0x10^{-5}$	$8.0x10^{-6}$	$4.9x10^{-5}$
INL								
ORNL	$4.6x10^{-5}$	$7.1x10^{-6}$	$3.4x10^{-6}$	$5.7x10^{-5}$	$3.5x10^{-5}$	$5.4x10^{-6}$	$2.6x10^{-6}$	$4.3x10^{-5}$
DEAF SMITH	$2.7x10^{-5}$	$3.2x10^{-6}$	$1.9x10^{-6}$	$3.2x10^{-5}$	$2.1x10^{-5}$	$2.5x10^{-6}$	$1.4x10^{-6}$	$2.5x10^{-5}$
HANFORD	$1.5x10^{-5}$	$1.7x10^{-6}$	$9.3x10^{-7}$	$1.8x10^{-5}$	$1.2x10^{-5}$	$1.3x10^{-6}$	$7.0x10^{-7}$	$1.4x10^{-5}$
SKULL VALLEY	$5.5x10^{-6}$	$1.5x10^{-6}$	$1.2x10^{-6}$	$8.2x10^{-6}$	$4.2x10^{-6}$	$1.1x10^{-6}$	$9.0x10^{-7}$	$6.2x10^{-6}$

Truck

Unlike trains, trucks carrying spent fuel share the primary highway system with many cars, light trucks, and other vehicles. The occupants of any car or truck that passes the spent fuel cask in

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[13] The five persons per railcar in urban areas are assumed to include occupants of passenger trains. Passenger trains carry more than five per car, but the majority of railcars even in urban areas carry freight only. This estimate is consistent with estimates made in past studies.

either direction will receive a small radiation dose. This does is modeled in RADTRAN as shown in Figure 2-9.

The radiation dose to occupants of other vehicles depends on the exposure distance and time, the number of other vehicles on the road, and the number of people in the other vehicles. Occupants of the vehicles that share the route are closer to the cask than residents or others beside the route. Occupants of vehicles moving in the opposite direction from the cask are exposed to radiation from the cask for considerably less time because the vehicles involved are moving past each other. The exposure time for vehicles traveling in the same direction as the cask is assumed to be the time needed to travel the link at the average speed (Neuhauser et al., 2000). The number of other vehicles that share truck routes is very large; the average number of vehicles per hour on U.S. interstate and primary highways in 2004[14] (Weiner et al., 2009, Appendix D) were:

- 1,119 on rural segments, about 2.5 times the 1977 vehicle density
- 2,464 on suburban segments, almost four times the 1977 vehicle density
- 5,384 on urban segments, about twice the 1977 vehicle density

Each vehicle was assumed to have an average of 1.5 occupants since most cars and light trucks traveling on freeways have one or two occupants. State highway departments provide traffic count data but do not provide vehicle occupancy data. If two occupants are assumed, the collective doses are one-third larger.

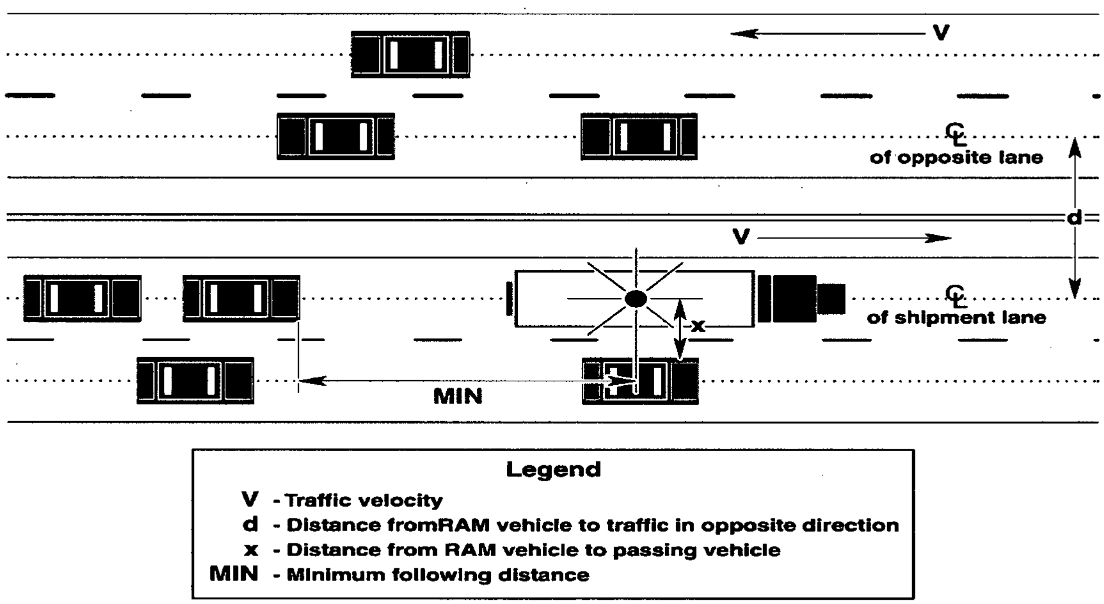


Figure 2-9 Diagram used in RADTRAN for calculating radiation doses to occupants of other vehicles
Figure source: (from Neuhauser et al., 2000)

[14] 2004 is the most recent year for which data have been validated.

Detailed discussion and State-by-State results are presented in Appendix II. The collective doses for truck traffic are shown in Table 2-9.

Table 2-9 Collective Doses (Person-Sv) per Shipment to Occupants of Vehicles Sharing Truck Routes (1 Sv=10^5 mrem)

FROM	TO	Truck-DU				
		Rural	Suburban	Urban	Urban Rush Hour[a]	Total[b]
MAINE YANKEE	ORNL	1.3×10^{-4}	2.4×10^{-4}	5.2×10^{-5}	4.8×10^{-5}	4.6×10^{-4}
	DEAF SMITH	2.8×10^{-4}	3.3×10^{-4}	6.9×10^{-5}	6.4×10^{-5}	7.3×10^{-4}
	HANFORD	4.5×10^{-4}	3.0×10^{-4}	4.3×10^{-5}	4.0×10^{-5}	8.3×10^{-4}
	SKULL VALLEY	3.7×10^{-4}	2.5×10^{-4}	4.4×10^{-5}	4.5×10^{-5}	7.0×10^{-4}
KEWAUNEE	ORNL	9.6×10^{-5}	1.4×10^{-4}	4.8×10^{-5}	4.4×10^{-5}	3.3×10^{-4}
	DEAF SMITH	1.8×10^{-4}	8.9×10^{-5}	2.2×10^{-5}	2.0×10^{-5}	3.1×10^{-4}
	HANFORD	3.4×10^{-4}	1.4×10^{-4}	3.3×10^{-5}	3.0×10^{-5}	5.4×10^{-4}
	SKULL VALLEY	2.4×10^{-4}	8.6×10^{-5}	2.5×10^{-5}	2.3×10^{-5}	3.8×10^{-4}
INDIAN POINT	ORNL	1.8×10^{-4}	2.1×10^{-4}	3.3×10^{-5}	3.0×10^{-5}	4.6×10^{-4}
	DEAF SMITH	2.8×10^{-4}	3.1×10^{-4}	5.6×10^{-5}	5.2×10^{-5}	6.9×10^{-4}
	HANFORD	4.2×10^{-4}	2.2×10^{-4}	4.8×10^{-5}	4.4×10^{-5}	7.2×10^{-4}
	SKULL VALLEY	3.6×10^{-4}	2.2×10^{-4}	4.5×10^{-5}	4.1×10^{-5}	6.6×10^{-4}
IDAHO NATIONAL LAB	ORNL	3.0×10^{-4}	1.5×10^{-4}	2.4×10^{-5}	2.2×10^{-5}	5.0×10^{-4}
	DEAF SMITH	2.2×10^{-4}	7.3×10^{-5}	2.7×10^{-5}	2.5×10^{-5}	3.4×10^{-4}
	HANFORD	1.0×10^{-4}	8.5×10^{-5}	9.5×10^{-6}	8.7×10^{-6}	2.0×10^{-4}
	SKULL VALLEY	3.7×10^{-5}	3.2×10^{-5}	8.5×10^{-6}	7.8×10^{-6}	8.5×10^{-5}

[a] During rush hour the truck speed is halved and the vehicle density is doubled, for details see Section II-5.3 in Appendix II.

[b] Total includes the sum of Rural, Suburban, Urban, and Urban Rush Hour.

Comparing Table 2-6 to Table 2-8, the collective dose to residents for rail transport is generally larger (except in rural areas) than the collective dose to people sharing the rail line. In contrast, comparing Table 2-7 to Table 2-9 shows that for all routes and population densities the collective dose to those sharing the highway is greater than the collective dose to nearby residents.

2.3.4 Doses at Truck and Train Stops

Trucks and trains occasionally stop on long trips. Common carrier freight trains stop to exchange freight cars, change crews, and, when necessary, change railroads. The rail stops at the origin and destination of a trip are called "classification stops" and are 27 hours long. Spent fuel casks may be carried on both dedicated trains and regular freight trains; however, in practice, previous spent fuel shipments have been carried on dedicated trains. A dedicated train is a train that carries a single cargo from origin to destination. Coal unit trains are an example of dedicated trains. The analyses conducted in this study assume that the casks are transported on dedicated trains, which eliminates the need for intermediate classification stops.

When a train is stopped, the dose to anyone nearby depends on the distance between that person and the cask and the time that the individual is exposed. People exposed at a rail stop include those listed below.

- railyard workers (including inspectors)
- train crew (passenger trains do not typically enter railyards)
- residents who live near the rail yard

The semi-tractor trucks that carry Truck-DU casks each have two 300-liter (80-gallon) fuel tanks. They generally stop to refuel when half of the fuel is gone, approximately every 845 km (525 miles) (DOE, 2002). Trucks carrying spent fuel also are stopped at the origin and destination of each trip. Mandatory rest and crew changes are combined with refueling stops whenever possible.

The people likely to be exposed at a refueling truck stop are listed below.

- the truck crew of two; usually one crew member at a time fills the tanks
- other people using the truck stop (since these trucks stop at public truck stops)
- residents of areas near the stop

Some States inspect spent fuel cask shipments when the trucks enter the State. Inspection stations may be combined with truck weigh stations; therefore, inspectors of both the truck carrying the spent fuel and the trucks carrying other goods can be exposed in addition to crew from other trucks. When the vehicle is stopped, receptor doses depend only on distance from the source and exposure time, so that any situation in which the cask and the receptor stay at a fixed distance from each other can be modeled as a stop. These stop-like exposure situations include inspections, vehicle escorts, vehicle crew when the vehicle is in transit, and occupants of other vehicles near the stopped vehicle. Any of these situations can be modeled in RADTRAN. Appendix II provides details on the calculations performed for situations in this analysis.

Figure 2-10 is a diagram of the model used to calculate doses at truck stops. The inner circle defines the area occupied by people who share the stop with the spent fuel truck, who are between the truck and the building, and who are not shielded from the truck's external radiation. People in buildings at the stop are shielded.

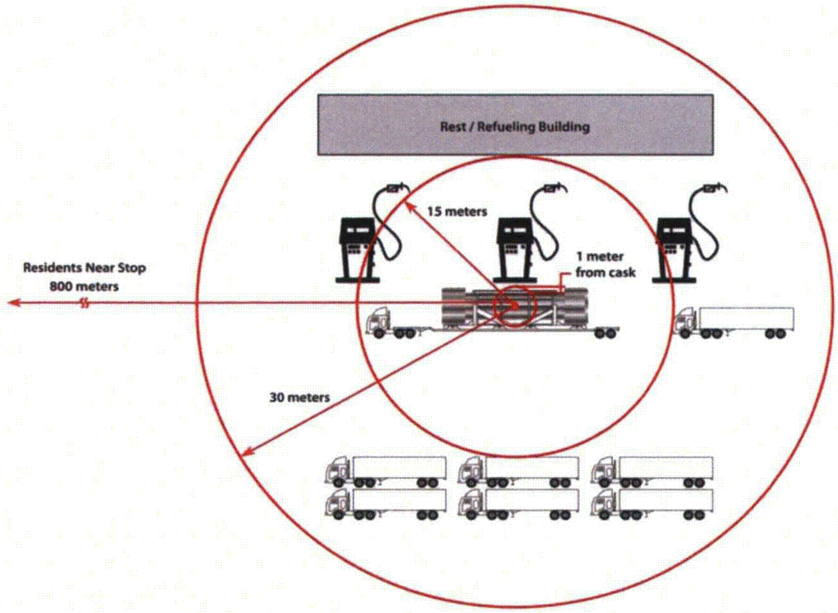


Figure 2-10 Diagram of truck stop model (not to scale).

Table 2-10 lists the input data used to calculate doses at truck and train stops.

Table 2-10 Input Data for Calculating Doses at Truck and Train Stops

Data	Interstate Highway	Freight Rail
Minimum distance from nearby residents, m (ft)	30 (100)	200 (660)
Maximum distance from nearby residents, m (miles)	800 (1/2)	800 (1/2)
Stop time for rail classification (hours)	NA	27
Stop time in transit for railroad change (hours)	NA	<<1 to 4
Stop time at truck stops (hours)	0.83	NA
Minimum distance to people sharing the stop, m (ft)	1 (3.3)[a]	NA
Maximum distance to people sharing the stop, m (ft)	15 (50)[a]	NA

[a] From Griego et al., 1996

Rail

Trains are stopped for classification for 27 hours at the beginning and end of a trip. The collective dose from the radioactive cargo to the railyard workers at these classification stops for the two rail casks studied is:

- 1.46×10^{-5} person-Sv (1.46 person-mrem) for the Rail-Lead

- 1.09×10^{-5} person-Sv (1.09 person-mrem) for the Rail-Steel

The average dose (calculated by dividing the collective dose by the number of exposed people) to an individual living between 200 and 800 meters from a classification yard is:

- 3.5×10^{-7} Sv (0.035 mrem) from the Rail-Lead cask
- 2.7×10^{-7} Sv (0.027 mrem) from the Rail-Steel cask

Table 2-11 shows the train stops doses to yard workers and residents near the stops for the Maine Yankee-to-Hanford rail route calculated using the input data from Table 2-10. The doses for all 16 rail routes were calculated in a similar fashion and are presented in Table 2-12. The difference in collective dose to residents near stops from route-to-route is primarily due to the different population densities at the classification stops, which may be either in rural or suburban areas.

Table 2-11 Collective Doses at Rail Stops on the Maine Yankee-to-Hanford Route (Person-Sv) (1 Sv=10^5 mrem)

Stop	Route type (R, S, U) and State	Time (hours)	Railyard Worker		Residents Near Stop	
			Rail-Lead	Rail-Steel	Rail-Lead	Rail-Steel
Classification, origin	S, ME	27	1.5×10^{-5}	1.1×10^{-5}	2.3×10^{-5}	1.8×10^{-5}
In route1	S, ME	4.0	2.2×10^{-6}	1.6×10^{-6}	3.4×10^{-6}	2.6×10^{-6}
In route 2	R, NY	4.0	2.2×10^{-6}	1.6×10^{-6}	9.2×10^{-7}	6.9×10^{-7}
In route 3	S, IL	2.0	1.1×10^{-6}	8.1×10^{-7}	1.2×10^{-5}	9.4×10^{-6}
Classification, destination	S, WA	27	1.5×10^{-5}	1.1×10^{-5}	1.9×10^{-5}	1.4×10^{-5}

Table 2-12 Collective Dose to Residents near Stops and Workers at Stops and Onboard the Train (Person-Sv) (1 Sv=10^5 mrem)

		RESIDENTS NEAR STOPS		RAILYARD WORKERS, CREW, AND ESCORTS	
ORIGIN	**DESTINATION**	**RAIL LEAD**	**RAIL STEEL**	**RAIL LEAD**	**RAIL STEEL**
MAINE YANKEE	ORNL	1.1×10^{-4}	8.5×10^{-5}	3.4×10^{-4}	2.3×10^{-4}
	DEAF SMITH	5.3×10^{-5}	5.0×10^{-5}	5.1×10^{-4}	3.7×10^{-4}
	HANFORD	1.1×10^{-4}	8.8×10^{-5}	7.6×10^{-4}	5.6×10^{-4}
	SKULL VALLEY	5.4×10^{-5}	4.1×10^{-5}	6.2×10^{-4}	4.5×10^{-4}
KEWAUNEE	ORNL	1.1×10^{-4}	8.3×10^{-5}	2.3×10^{-4}	1.5×10^{-4}
	DEAF SMITH	6.8×10^{-5}	5.2×10^{-5}	3.0×10^{-4}	2.1×10^{-4}
	HANFORD	1.1×10^{-4}	8.7×10^{-5}	4.7×10^{-4}	3.3×10^{-4}
	SKULL VALLEY	1.2×10^{-4}	9.1×10^{-5}	4.3×10^{-4}	3.0×10^{-4}
INDIAN POINT	ORNL	1.3×10^{-4}	1.0×10^{-4}	2.1×10^{-4}	1.4×10^{-4}
	DEAF SMITH	5.9×10^{-5}	4.5×10^{-5}	4.8×10^{-4}	3.4×10^{-4}
	HANFORD	1.1×10^{-4}	8.3×10^{-5}	7.2×10^{-4}	5.2×10^{-4}
	SKULL VALLEY	5.6×10^{-5}	4.3×10^{-5}	6.0×10^{-4}	4.4×10^{-4}
INL	ORNL	9.5×10^{-5}	7.2×10^{-5}	5.1×10^{-4}	3.6×10^{-4}
	DEAF SMITH	7.7×10^{-5}	5.8×10^{-5}	3.1×10^{-4}	2.1×10^{-4}
	HANFORD	5.6×10^{-5}	4.3×10^{-5}	1.8×10^{-4}	1.2×10^{-4}
	SKULL VALLEY	3.1×10^{-6}	2.4×10^{-6}	9.5×10^{-5}	5.0×10^{-5}

Truck

Table 2-13 shows the collective doses to residents near stops for the rural and suburban segments of the 16 truck routes studied calculated using the input data from Table 2-10. Urban stops were not modeled because trucks carrying spent fuel casks are unlikely to stop in urban areas (this is because most truck stops are not within urban areas, those that are within metropolitan areas are usually in industrial areas that do not have urban population density, and because the DOT routing rules require using urban bypass routes). Appendix II provides a detailed discussion and example of the calculations performed to derive this table.

Table 2-13 Collective Doses to Residents near Truck Stops (Person-Sv) (1 Sv=10^5 mrem)

Origin	Destination	Type	Persons/km^2 (persons/mi^2)	Number of Stops	Dose
MAINE YANKEE	ORNL	Rural	19.9 (51.5)	1.14	7.4×10^{-7}
		Suburban	395 (1023)	0.93	1.0×10^{-5}
	Deaf Smith	Rural	18.6 (48.2)	2.47	1.5×10^{-6}
		Suburban	371 (961)	1.6	1.7×10^{-5}
	Hanford	Rural	15.4 (39.9)	4.33	2.2×10^{-6}
		Suburban	325 (842)	1.5	1.4×10^{-5}
	Skull Valley	Rural	16.9 (43.8)	3.5	1.9×10^{-6}
		Suburban	333 (861)	1.3	1.2×10^{-5}
KEWAUNEE	ORNL	Rural	19.8 (51.3)	0.81	5.2×10^{-7}
		Suburban	361 (935)	0.59	6.0×10^{-6}
	Deaf Smith	Rural	13.5 (35.0)	2.0	8.6×10^{-7}
		Suburban	339 (878)	0.52	5.0×10^{-6}
	Hanford	Rural	10.5 (27.2)	3.4	1.2×10^{-6}
		Suburban	316 (818)	0.60	5.4×10^{-6}
	Skull Valley	Rural	12.5 (32.4)	2.6	1.1×10^{-6}
		Suburban	325 (840)	0.44	4.1×10^{-6}
INDIAN POINT	ORNL	Rural	20.5 (53.1)	0.71	4.7×10^{-7}
		Suburban	388 (1005)	0.71	7.8×10^{-6}
	Deaf Smith	Rural	17.1 (44.3)	2.3	1.3×10^{-6}
		Suburban	370 (958)	1.2	1.3×10^{-5}
	Hanford	Rural	13.0 (33.7)	4.1	1.8×10^{-6}
		Suburban	338 (875)	1.1	1.1×10^{-5}
	Skull Valley	Rural	14.2 (36.8)	3.3	1.5×10^{-6}
		Suburban	351 (909)	0.93	9.3×10^{-6}
IDAHO NATIONAL LAB	ORNL	Rural	12.4 (32.1)	3.1	1.3×10^{-6}
		Suburban	304 (787)	0.72	6.3×10^{-6}
	Deaf Smith	Rural	7.8 (20.2)	2.3	5.8×10^{-7}
		Suburban	339 (878)	0.35	3.4×10^{-6}
	Hanford	Rural	6.5 (16.8)	0.43	9.0×10^{-8}
		Suburban	200 (518)	0.57	3.2×10^{-6}
	Skull Valley	Rural	10.1 (26.2)	0.42	1.4×10^{-7}
		Suburban	343 (888)	0.11	1.1×10^{-6}

The rural and suburban population densities in Table 2-13 are averages for the entire route. An analogous calculation can be made for each State traversed. However, in neither case can it be determined beforehand exactly where the truck will stop to refuel. In some cases (e.g., INL to Skull Valley) the truck may not stop at all since the total distance from INL to the Skull Valley site is only 466.2 km (290 miles). The route from Indian Point to ORNL illustrates another situation. This route is 1,028 km (639 miles) long and would include one truck stop. This stop could occur in a rural or suburban area. The results shown in Table 2-13 are general average doses at stops.

2.4 Doses to Workers

Radiation doses to workers are limited in accordance with the regulations in 10 CFR Part 20, which states maintaining worker exposure to ionizing radiation "as low as is reasonably achievable" (ALARA). ALARA applies to occupational doses since workers potentially are exposed to much larger doses than the general public. For example, the cab of a truck carrying a loaded Truck-DU cask is shielded so that 63 percent of the radiation from the end of the cask is blocked.

Occupational doses from routine, incident-free radioactive materials transportation include doses to truck and train crew, railyard workers, truck-stop workers, inspectors, and escorts. Workers not included are those who handle spent fuel containers in storage, load and unload casks from vehicles or during intermodal transfer, and attendants who refuel trucks in areas where truck refueling stops in the United States no longer have such attendants.[15]

Table 2-14 summarizes the occupational doses. All doses are reported per hour except for the truck stop worker (reported for the maximum truck stop time) and the rail classification yard workers. All doses are individual doses (Sv) except for the railyard worker collective doses.

Table 2-14 Occupational Doses and Dose Rates from Routine Incident-Free Transportation (1 Sv=10^5 mrem)

Cask and route type	Train crew in transit: 3 people; person-Sv/km	Truck crew in transit 2 people; person-Sv/km[a]	Escort: Sv/hour[a]	Inspector: Average Sv per 8 inspections[c]	Truck stop worker: Sv per stop	Rail classification yard workers: person-Sv /stop
Rail-Lead rural/suburban	4.3×10^{-7}		5.8×10^{-6}			1.5×10^{-5}
Rail-Lead urban	7.2×10^{-7}		5.8×10^{-6}			b
Rail-Steel rural/suburban	3.3×10^{-7}		4.4×10^{-6}			1.1×10^{-5}
Rail-Steel urban	5.5×10^{-7}		4.4×10^{-6}			b
Truck - DU rural/suburban		3.8×10^{-7}	4.9×10^{-9}	1.5×10^{-3}	6.7×10^{-6}	
Truck - DU urban		3.6×10^{-7}	4.9×10^{-9}			

a The truck crew is shielded while in transit to sustain a maximum dose of 0.02 mSv/hour

b Even classification yards within metropolitan areas do not typically have urban population densities because of the large area the classification yard occupies.

c The average number of state boundaries crossed for all 16 routes is eight. The average dose to an inspector from each of these inspections is 1.64×10^{-4} Sv (0.0164 rem).

Doses to rail crew and rail escorts are similar. Spent fuel may be transported in dedicated trains so that both escorts and train crew are assumed to be within a distance of one railcar length of the railcar carrying the spent fuel. Escorts in the escort car are not shielded because they must maintain line-of-sight to the railcar carrying spent fuel. Train crew members are in a crew

[15] The States of Oregon and New Jersey still require gas station attendants to refuel cars and light duty vehicles, but heavy truck crews do their own refueling.

compartment and were assumed to have some shielding, resulting in an estimated dose about 25 percent less than the escort. The largest collective doses are to railyard workers. The number of workers in railyards is not constant and the number of activities that brings these workers into proximity with the shipment varies as well. This analysis assumes the dose to the worker doing an activity for each activity (e.g., inspection, coupling and decoupling the railcars, moving the railcar into position for coupling). The differences between doses in the Rail-Lead case and the Rail-Steel case reflect differences in cask dimensions and in external dose rate.

Truck crew members are shielded so that they receive a maximum dose of 2.0×10^{-5} Sv/hr (2.0 mrem/hr). This regulatory maximum was imposed in the RADTRAN calculation. Truck inspectors generally spend about 1 hour within 1 meter of the cargo (Weiner and Neuhauser, 1992), resulting in a relatively large dose. An upper bound to the duration of a truck refueling stop is about 50 minutes (0.83 hours) (Griego et al., 1996). The truck stop worker whose dose is reflected in

Table 2-14 is assumed to be outside (unshielded) at 15 meters from the truck during the stop. Truck stop workers in concrete or brick buildings are shielded from any radiation.

2.5 Chapter Summary

A summary of the results for the incident-free transport of spent fuel in the three casks analyzed in this study are presented in Table 2-15, Table 2-16, and Table 2-17.

Table 2-15 Total Collective Dose in Person-Sv from Routine Transportation for Each Rail Route for the Rail-Lead Cask (1 Sv=10^5 mrem)

Origin	Destination	Residents Along Route	Occupants of Vehicles Sharing Route	Residents near Stop	Railyard Crew and Escorts	Total
MAINE YANKEE	ORNL	2.1×10^{-4}	4.0×10^{-5}	1.1×10^{-4}	3.4×10^{-4}	7.0×10^{-4}
	Deaf Smith	2.5×10^{-4}	6.1×10^{-5}	5.3×10^{-5}	5.1×10^{-4}	8.7×10^{-4}
	Hanford	2.9×10^{-4}	9.0×10^{-5}	1.1×10^{-4}	7.6×10^{-4}	1.2×10^{-3}
	Skull Valley	2.9×10^{-4}	7.4×10^{-5}	5.4×10^{-5}	6.2×10^{-4}	1.1×10^{-3}
KEWAUNEE	ORNL	1.3×10^{-4}	2.7×10^{-5}	1.1×10^{-4}	2.3×10^{-4}	5.0×10^{-4}
	Deaf Smith	1.1×10^{-4}	3.4×10^{-5}	6.8×10^{-5}	3.0×10^{-4}	5.1×10^{-4}
	Hanford	1.1×10^{-4}	5.2×10^{-5}	1.1×10^{-4}	4.7×10^{-4}	7.4×10^{-4}
	Skull Valley	1.4×10^{-4}	4.9×10^{-5}	1.2×10^{-4}	4.3×10^{-4}	7.4×10^{-4}
INDIAN POINT	ORNL	1.6×10^{-4}	2.7×10^{-5}	1.3×10^{-4}	2.1×10^{-4}	5.3×10^{-3}
	Deaf Smith	2.0×10^{-4}	5.6×10^{-5}	5.9×10^{-5}	4.8×10^{-4}	8.0×10^{-3}
	Hanford	2.5×10^{-4}	8.5×10^{-5}	1.1×10^{-4}	7.2×10^{-4}	1.2×10^{-3}
	Skull Valley	2.4×10^{-4}	6.5×10^{-5}	5.6×10^{-5}	6.0×10^{-4}	9.3×10^{-3}
INL	ORNL	1.3×10^{-4}	5.7×10^{-5}	9.5×10^{-5}	5.1×10^{-4}	8.0×10^{-4}
	Deaf Smith	6.7×10^{-5}	3.2×10^{-5}	7.7×10^{-5}	3.1×10^{-4}	4.9×10^{-4}
	Hanford	3.6×10^{-5}	1.8×10^{-5}	5.6×10^{-5}	1.8×10^{-4}	3.0×10^{-4}
	Skull Valley	3.0×10^{-5}	8.2×10^{-6}	3.1×10^{-6}	9.5×10^{-5}	1.4×10^{-4}

Table 2-16 Total Collective Dose in Person-Sv from Routine Transportation for Each Rail Route for the Rail-Steel Cask (1 Sv=10^5 mrem)

Origin	Destination	Residents Along Route	Occupants of Vehicles Sharing Route	Residents Near Stop	Railyard Crew and Escorts	Total
MAINE YANKEE	ORNL	$1.6x10^{-4}$	$3.0x10^{-5}$	8.5×10^{-5}	$2.3x10^{-4}$	$5.1x10^{-4}$
	Deaf Smith	$1.9x10^{-4}$	$4.6x10^{-5}$	5.0×10^{-5}	$3.7x10^{-4}$	$6.7x10^{-4}$
	Hanford	$2.3x10^{-4}$	$6.8x10^{-5}$	8.8×10^{-5}	$5.6x10^{-4}$	$9.5x10^{-4}$
	Skull Valley	$2.2x10^{-4}$	$5.5x10^{-5}$	4.1×10^{-5}	$4.5x10^{-4}$	$7.7x10^{-4}$
KEWAUNEE	ORNL	$9.6x10^{-5}$	$2.0x10^{-5}$	8.3×10^{-5}	$1.5x10^{-4}$	$3.5x10^{-4}$
	Deaf Smith	$8.3x10^{-5}$	$2.6x10^{-5}$	5.2×10^{-5}	$2.1x10^{-4}$	$3.7x10^{-4}$
	Hanford	$8.3x10^{-5}$	$3.9x10^{-5}$	8.7×10^{-5}	$3.3x10^{-4}$	$5.4x10^{-4}$
	Skull Valley	$1.1x10^{-4}$	$3.7x10^{-5}$	9.1×10^{-5}	$3.0x10^{-4}$	$5.4x10^{-4}$
INDIAN POINT	ORNL	$1.2x10^{-4}$	$2.0x10^{-5}$	1.0×10^{-4}	$1.4x10^{-4}$	$3.8x10^{-4}$
	Deaf Smith	$1.5x10^{-4}$	$4.3x10^{-5}$	$4.5 x10^{-5}$	$3.4x10^{-4}$	$5.8x10^{-4}$
	Hanford	$1.9x10^{-4}$	$6.5x10^{-5}$	8.3×10^{-5}	$5.2x10^{-4}$	$8.6x10^{-4}$
	Skull Valley	$1.8x10^{-4}$	$4.9x10^{-5}$	4.3×10^{-5}	$4.4x10^{-4}$	$7.1x10^{-4}$
INL	ORNL	$1.0x10^{-4}$	$4.3x10^{-5}$	7.2×10^{-5}	$3.6x10^{-4}$	$5.7x10^{-4}$
	Deaf Smith	$5.2x10^{-5}$	$2.5x10^{-5}$	$5.8 x10^{-5}$	$2.1x10^{-4}$	$3.4x10^{-4}$
	Hanford	$2.8x10^{-5}$	$1.4x10^{-5}$	$4.3x 10^{-5}$	$1.2x10^{-4}$	$2.0x10^{-4}$
	Skull Valley	$2.2x10^{-5}$	$6.2x10^{-6}$	2.4×10^{-6}	$5.0x10^{-5}$	$8.0x10^{-5}$

Table 2-17 Total Collective Dose in Person-Sv from Routine Transportation for Each Highway Route for the Truck Cask (1 Sv=10^5 mrem)

Origin	Destination	Residents Along Route	Occupants of Vehicles Sharing Route	Residents Near Stop	Persons Sharing Stop	Crew/ Truck Stop Worker	Total
MAINE YANKEE	ORNL	9.6×10^{-5}	4.6×10^{-4}	1.2×10^{-5}	8.6×10^{-4}	6.8×10^{-4}	1.7×10^{-3}
	Deaf Smith	1.4×10^{-4}	7.3×10^{-4}	1.8×10^{-5}	9.2×10^{-4}	1.4×10^{-3}	3.2×10^{-3}
	Hanford	1.2×10^{-4}	8.3×10^{-4}	1.4×10^{-5}	1.3×10^{-3}	1.9×10^{-3}	4.2×10^{-3}
	Skull Valley	1.1×10^{-4}	7.0×10^{-4}	1.4×10^{-5}	1.1×10^{-3}	1.6×10^{-3}	3.5×10^{-3}
KEWAUNEE	ORNL	5.2×10^{-5}	3.3×10^{-4}	6.6×10^{-6}	3.2×10^{-4}	4.9×10^{-4}	1.2×10^{-3}
	Deaf Smith	4.7×10^{-5}	3.1×10^{-4}	5.8×10^{-6}	5.7×10^{-4}	8.3×10^{-4}	1.8×10^{-3}
	Hanford	5.1×10^{-5}	5.4×10^{-4}	6.6×10^{-6}	9.0×10^{-4}	1.3×10^{-3}	2.9×10^{-3}
	Skull Valley	3.9×10^{-5}	3.8×10^{-4}	5.1×10^{-6}	6.8×10^{-4}	1.0×10^{-3}	2.2×10^{-3}
INDIAN POINT	ORNL	6.9×10^{-5}	4.6×10^{-4}	8.3×10^{-6}	3.2×10^{-4}	4.9×10^{-4}	1.3×10^{-3}
	Deaf Smith	1.4×10^{-4}	6.9×10^{-4}	1.4×10^{-5}	7.9×10^{-4}	1.2×10^{-3}	2.9×10^{-3}
	Hanford	8.9×10^{-5}	7.2×10^{-4}	1.2×10^{-5}	1.2×10^{-3}	1.7×10^{-3}	3.9×10^{-3}
	Skull Valley	7.7×10^{-5}	6.6×10^{-4}	1.1×10^{-5}	9.5×10^{-4}	1.4×10^{-3}	3.1×10^{-3}
INL	ORNL	6.3×10^{-5}	5.0×10^{-4}	7.5×10^{-6}	8.6×10^{-4}	1.3×10^{-3}	2.7×10^{-3}
	Deaf Smith	3.7×10^{-5}	3.4×10^{-4}	4.0×10^{-6}	6.0×10^{-4}	8.8×10^{-4}	1.9×10^{-3}
	Hanford	1.4×10^{-5}	2.0×10^{-4}	1.1×10^{-6}	2.3×10^{-4}	3.7×10^{-4}	8.5×10^{-4}
	Skull Valley	1.2×10^{-5}	8.5×10^{-5}	1.2×10^{-6}	1.2×10^{-4}	1.8×10^{-4}	1.6×10^{-3}

A code that estimates risk is never completely precise because the input data are estimates and projections. To account for this imprecision, RADTRAN uses assumptions and values that overestimate doses. Actual measurements confirm that RADTRAN overestimates doses by a small margin. Therefore, the doses calculated in this chapter should be regarded as overestimates.

The individual and collective doses calculated are for a single shipment and, even though overestimated, they are uniformly very small. Individual doses are comparable to background doses and are less than doses from many medical diagnostic procedures. Collective doses are orders of magnitude less than the collective background dose, as shown in Figure 2-11 for an example shipment from Maine Yankee to ORNL. This route assumes ten inspection stops at state boundaries. The NRC recommends that collective doses (average doses integrated over a population) only be used for comparisons (NRC, 2008). The proper comparison for collective doses is between the background collective dose plus the shipment dose and the background dose if there is no shipment. The collective dose, however, is *never* zero in the absence of a shipment.

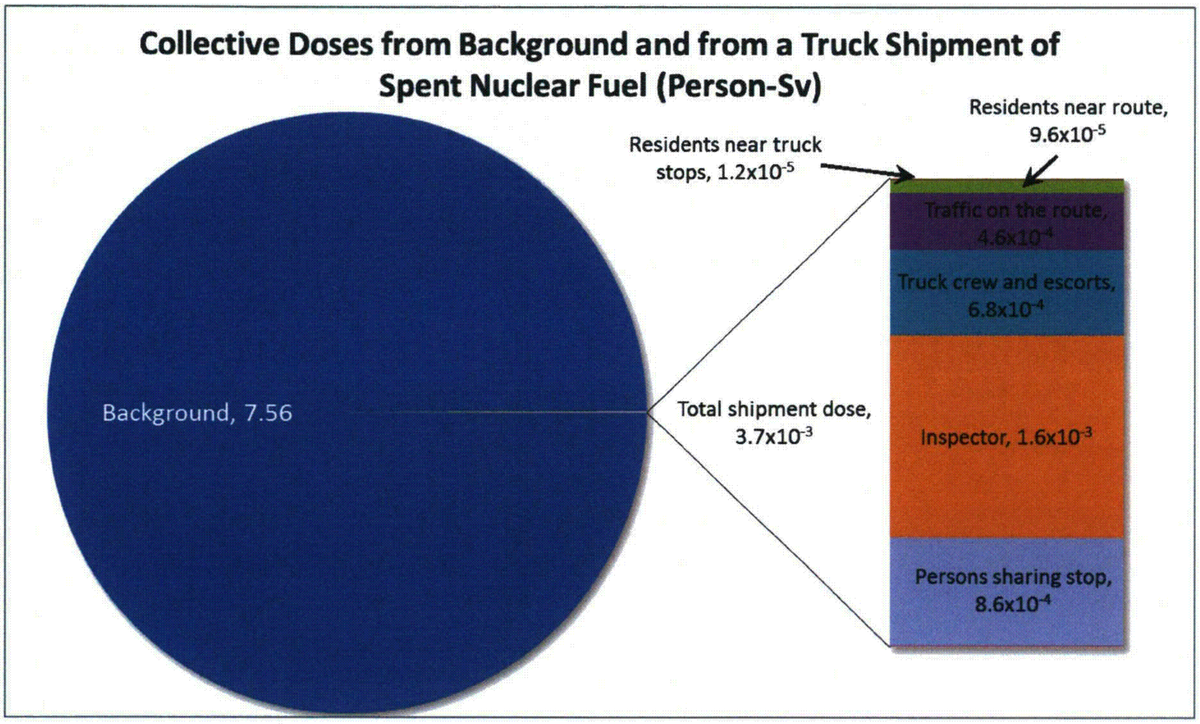


Figure 2-11 Collective doses from background and from Maine Yankee to ORNL truck shipments of spent nuclear fuel (person-Sv) (1 Sv=10^5 mrem)

3. CASK RESPONSE TO IMPACT ACCIDENTS

3.1 Introduction

Spent fuel casks are required to be accident resistant. During the NRC certification process the cask designer must demonstrate, among other things, that the cask would survive a free fall from a height of 9 meters falling onto a flat, essentially unyielding, target in the orientation most likely to damage the cask (10 CFR 71.73). The NRC's required high standards and conservative approaches for this demonstration include the use of conservative (usually minimum) material properties in analyses, allowing only small amounts of yielding, and the use of materials with high ductility. These approaches ensure that the casks not only will survive impacts at the speed created because of the 9-meter (30-foot) drop but will also survive much higher speed impacts.

In addition to the conservative designs that the certification process ensures, two additional requirements of the 9-meter drop provide safety when compared to actual accidents. The first requirement is that the impact must be onto an essentially unyielding target. This implies that the cask will absorb all of the kinetic energy of the impact and the target will absorb none. For impacts onto real surfaces, both the cask and the target absorb the kinetic energy. The second requirement is that the vertical impact must be onto a horizontal target. This requirement ensures that at some point during the impact, the velocity of the cask will be zero, and all of the kinetic energy is converted into strain energy (i.e., absorbed by the cask). Most real accidents occur at an angle, and the kinetic energy of the cask is absorbed by multiple impacts instead of one impact. In this chapter, these three aspects are discussed.

3.2 Finite Element Analyses of Casks

Previous risk studies have used generic casks. The Modal Study (Fischer et al., 1987) assumed that any accident more severe than the regulatory hypothetical impact accident would lead to a cask release. In NUREG/CR-6672 (Sprung et al., 2000), the impact limiters of the generic casks were assumed to be unable to absorb more energy than the amount from the regulatory hypothetical impact accident (i.e., a 9-meter (30-foot) free fall onto an essentially rigid target). Modeling limitations at the time of the studies required both of these assumptions. In reality, casks and impact limiters have excess capacity to resist impacts. In the current study, three NRC-certified casks were used instead of generic casks, and the actual impact resistance capability of those cask designs were included in the analyses. However, for the truck cask no new FE analyses were performed. The current study relied upon analyses performed for other studies, some of which used a generic truck cask.

The response to impacts of 48 kph, 97 kph,145 kph, and 193 kph (equal to 30 mph, 60 mph, 90 mph, and 120 mph) onto an unyielding target in the end, corner, and side orientations for the Rail-Steel and Rail-Lead spent fuel transportation casks were determined using the nonlinear transient dynamics explicit FE code PRESTO (SIERRA, 2009). PRESTO is a Lagrangian code, using a mesh that follows the deformation to analyze solids subjected to large, suddenly applied loads. The code is designed for a massively parallel computing environment and for problems with large deformations, nonlinear material behavior, and contact. PRESTO has a versatile element library that incorporates both continuum (3D) and structural elements, such as beams and shells.

In addition to the detailed analyses of rail casks performed for this study, the response of the Truck-DU spent fuel transportation cask was inferred based on the FE analyses performed for the generic casks in NUREG/CR-6672. The direction of the cask travel was perpendicular to the surface of the unyielding target in all of the analyses performed.

Figure 3-1 is a pictorial representation of the three impact orientations analyzed. In all of the analyses, the spent fuel basket and fuel elements were treated as a uniform homogenous material. The density of this material was adjusted to achieve the correct weight of the loaded basket. The overall behavior of the material was conservative (i.e., because it acts as a single entity that affects the cask all at once instead of many smaller parts that affect the cask over a longer period of time) for assessing the effect the cask contents of the cask had on the behavior of the cask. A sub-model of a single assembly was used to calculate the detailed response of the fuel assemblies.

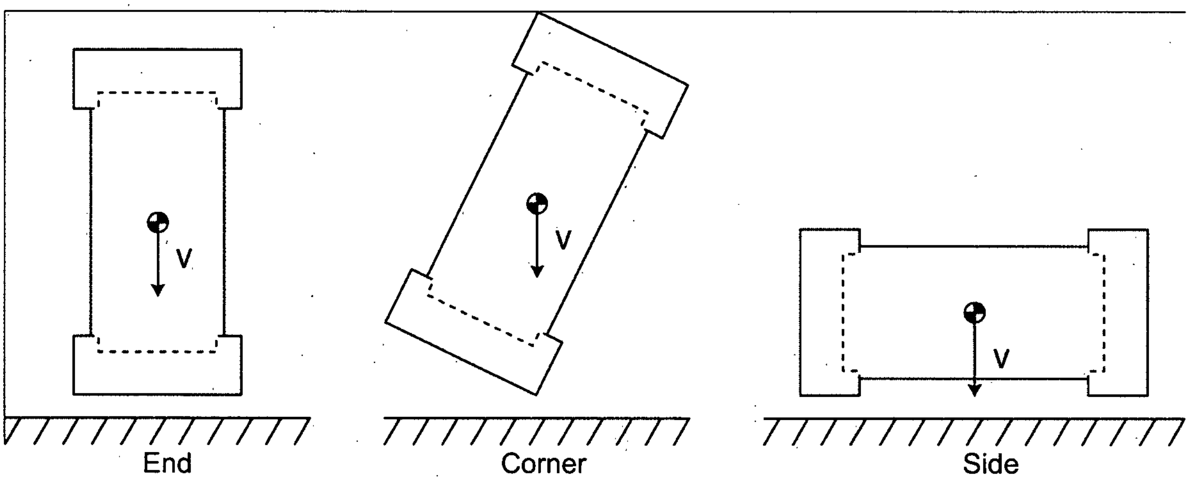


Figure 3-1 Impact orientations analyzed

3.2.1 Rail-Steel Cask

Finite Element Model

Figure 3-2 shows the overall FE model of the Rail-Steel cask depicted in Figure 1-3. This cask has steel gamma-shielding material and transports 24 PWR assemblies in a welded multipurpose canister (MPC). The impact limiters on each end of the cask are designed to absorb the kinetic energy of the cask during the regulatory hypothetical impact accident. They are made of an interior stainless steel support structure, an aluminum honeycomb energy absorber, and a stainless steel skin. Figure 3-3 shows the FE mesh of the closure end impact limiter. The one on the other end of the cask differs only in how it is attached to the cask. The aluminum honeycomb has direction-dependent properties. The strong direction of the honeycomb is oriented in the primary crush direction, requiring the FE model to include the individual blocks of honeycomb material, rather than a single material for the entire impact limiter. The cask has a single, solid steel lid attached with fifty-four 1-⅝-inch diameter bolts and sealed with dual metallic o-rings. Figure 3-4 shows the FE mesh of the closure bolts (bolts used to attach the closure end impact limiter are also shown) and the level of mesh refinement included in these important parts. Appendix III provides details of the FE models, including material properties, contact surfaces, gaps, and material failure.

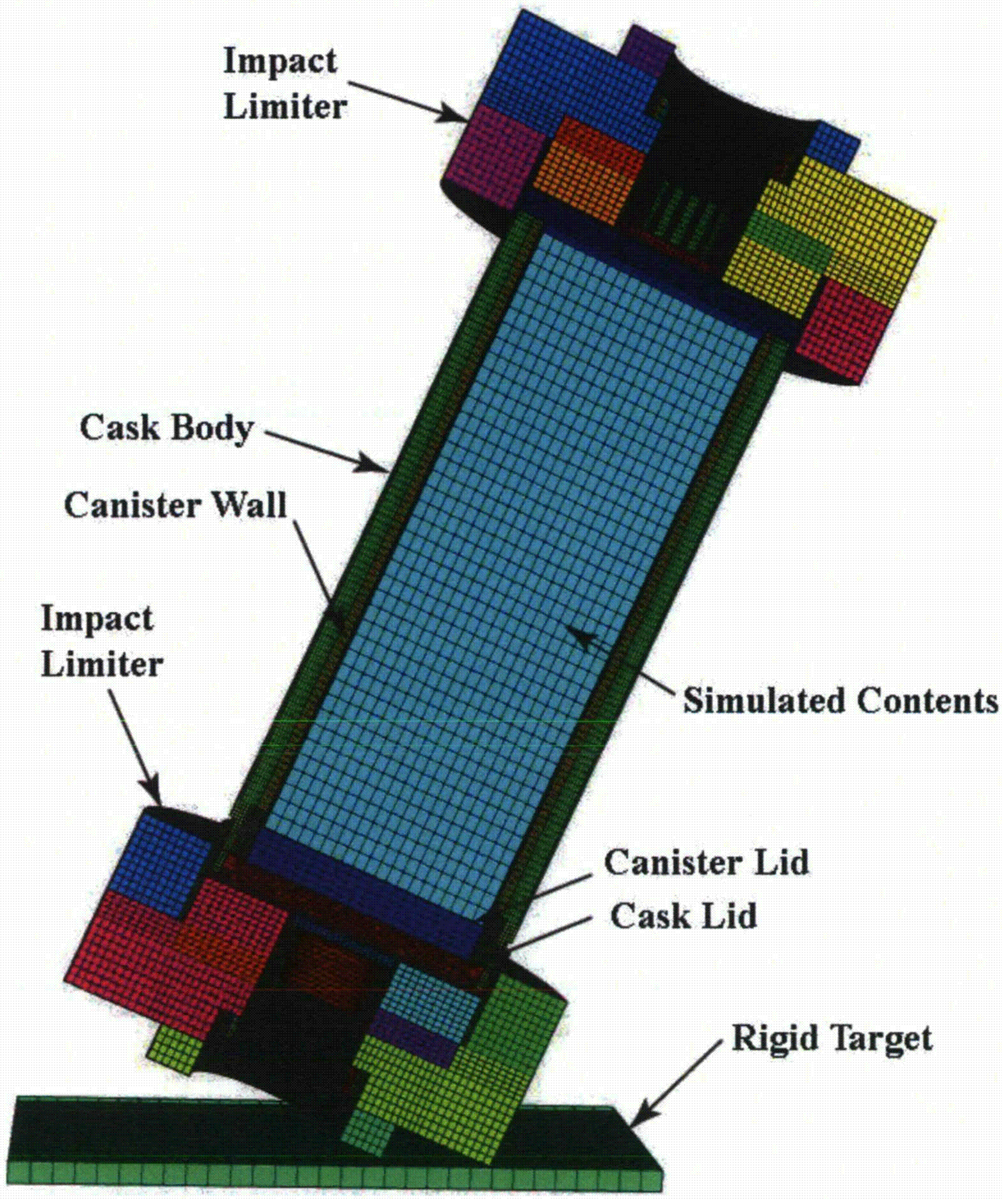
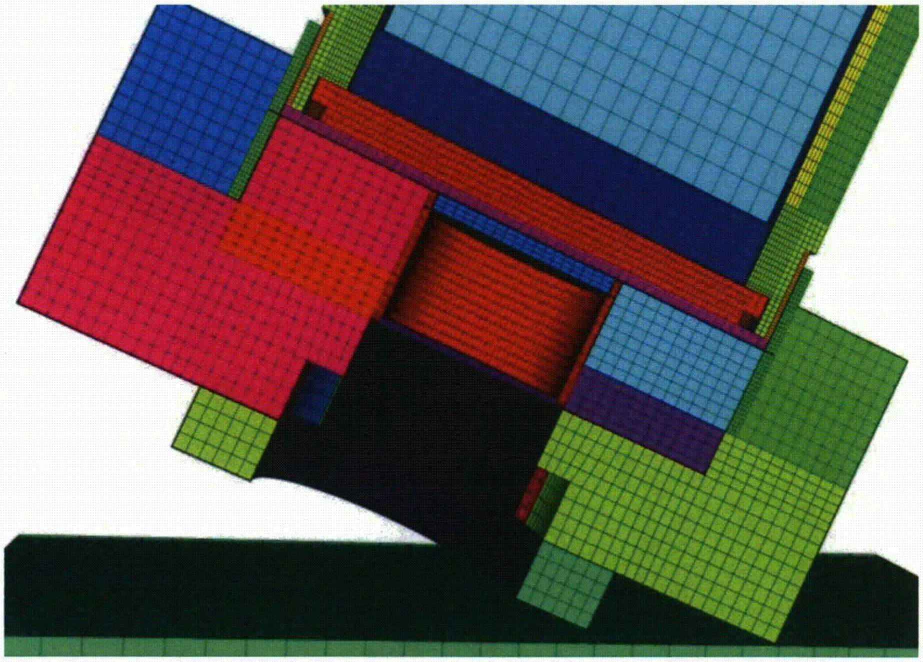
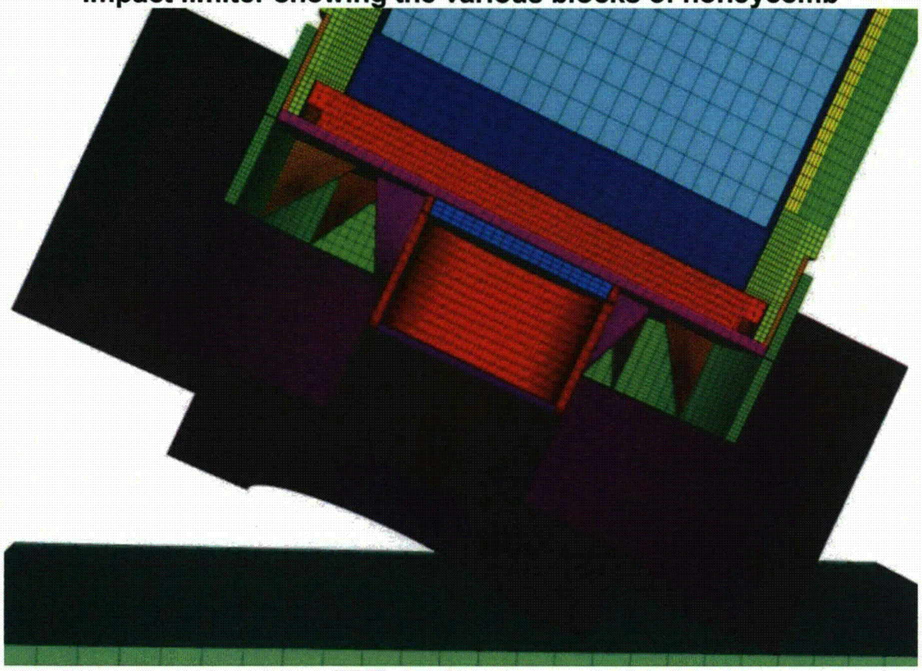


Figure 3-2 Finite element mesh of the Rail-Steel cask



Impact limiter showing the various blocks of honeycomb



Impact limiter with the honeycomb removed to reveal the inner support structure

Figure 3-3 Details of the finite element mesh for the impact limiters of the Rail-Steel cask

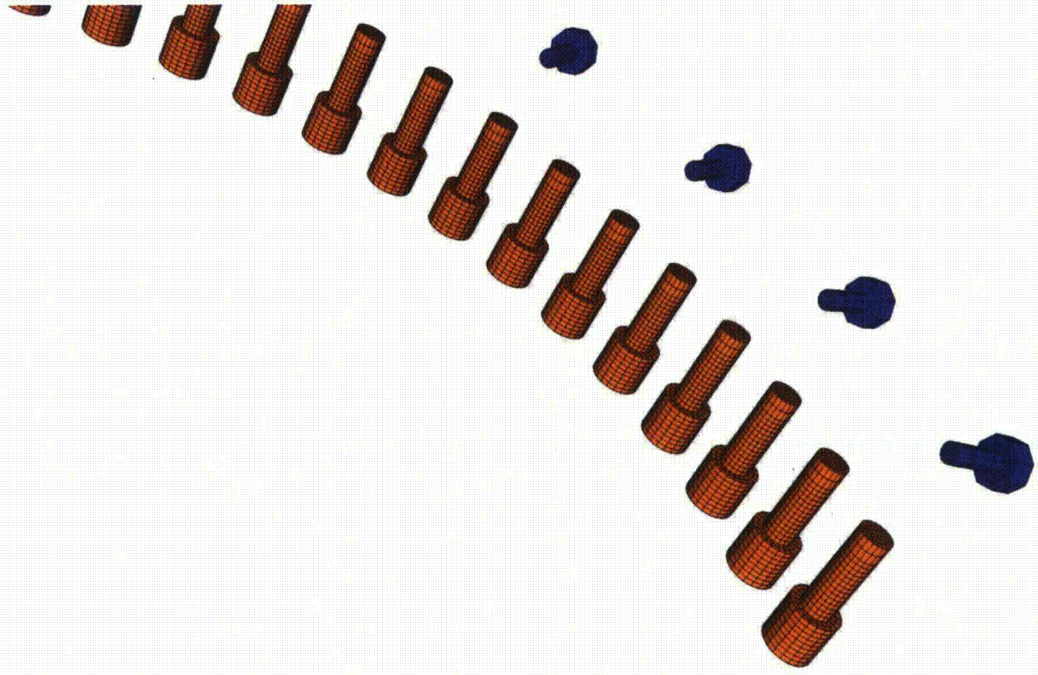


Figure 3-4 Finite element mesh of the Rail-Steel closure bolts and the closure end impact limiter attachment bolts. The highly refined mesh in these critical parts ensures an accurate assessment of the closure response.

Analysis results

As expected, for all end, corner, and side impacts of the 48 kph (30 mph) impact analyses—the impact velocity from the regulatory hypothetical impact accident—the impact limiter absorbed almost all of the cask's kinetic energy and there was no damage (i.e., permanent deformation) to the cask body or canister. As the impact velocity increases, additional damage to the impact limiter occurs for all orientations because it absorbs more kinetic energy. This shows the margin of safety in the impact limiter design. At 97 kph (60 mph) there is still no significant damage to the cask body or canister. At an impact speed of 145 kph (90 mph), damage to the cask and canister appears to begin. The impact limiter has absorbed all the kinetic energy it can, and any additional kinetic energy must be absorbed by plastic deformation in the cask body.

For the side impact at 145 kph (90 mph), several lid bolts fail in shear but the lid remains attached. At this point, the metallic seal no longer maintains the leak-tightness of the cask, but the spent fuel remains contained within the welded canister. Even at the highest impact speed of 193 kph (120 mph), the welded canister remains intact for all orientations. Figure 3-5 shows the deformed shape and plastic strain in the canister for the 193 kph (120 mph) impact in a side orientation. This case has the most plastic strain in the canister. The peak value of plastic strain in this case is 0.7. This value is specified by the equivalent plastic strain (EQPS), which is a representation of the magnitude of local permanent deformation. The canister's stainless steel material can easily withstand plastic strains greater than 1 (Blandford et al., 2007). These results demonstrate that no impact accident will lead to release of material from the Rail-Steel canister. Appendix III includes similar figures for the other orientations and speeds and criteria for the failure model.

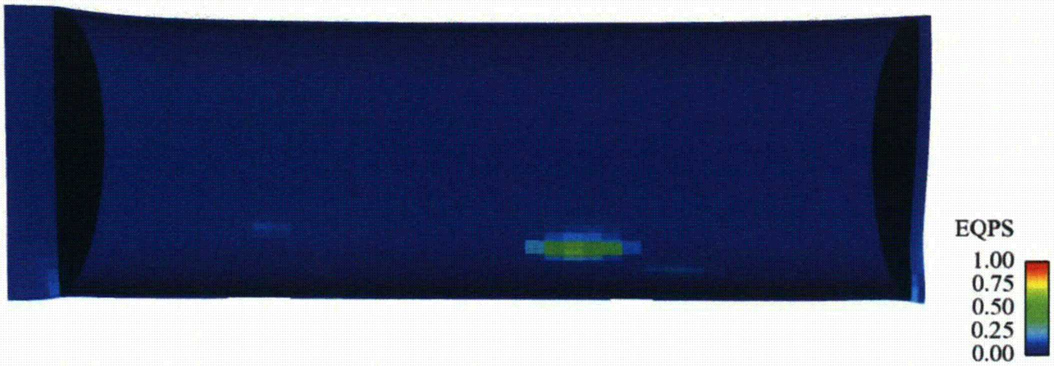


Figure 3-5 Plastic strain in the welded canister of the Rail-Steel for the 193 kph (120 mph) side impact case

3.2.2 Rail-Lead Cask

Finite Element Model

Figure 3-6 shows the overall FE model of the Rail-Lead cask depicted in Figure 1-2. This cask has lead gamma-shielding material and transports either 26 directly-loaded PWR assemblies or 24 PWR assemblies in a welded MPC. The impact limiters at each end of the cask are designed to absorb the cask's kinetic energy during the regulatory hypothetical impact accident. The impact limiters are made of redwood and balsa wood energy-absorbing material and a stainless steel skin. Figure 3-7 shows the FE mesh of the closure end impact limiter (the impact limiter on the other end of the cask is identical). The cask has a dual lid system. The inner lid is attached with 42 38 mm (1.5-inch) diameter bolts and sealed with dual elastomeric o-rings if the cask is only used for transportation and metallic o-rings if the cask is used for storage before transportation. The outer lid is attached with 36 25 mm (1-inch) diameter bolts and sealed with a single elastomeric o-ring if the cask is only used for transportation and a metallic o-ring if the cask is used for storage before transportation. Figure 3-8 shows the FE mesh of the closure bolts and the level of mesh refinement included in these important parts. Appendix III includes details of the FE models.

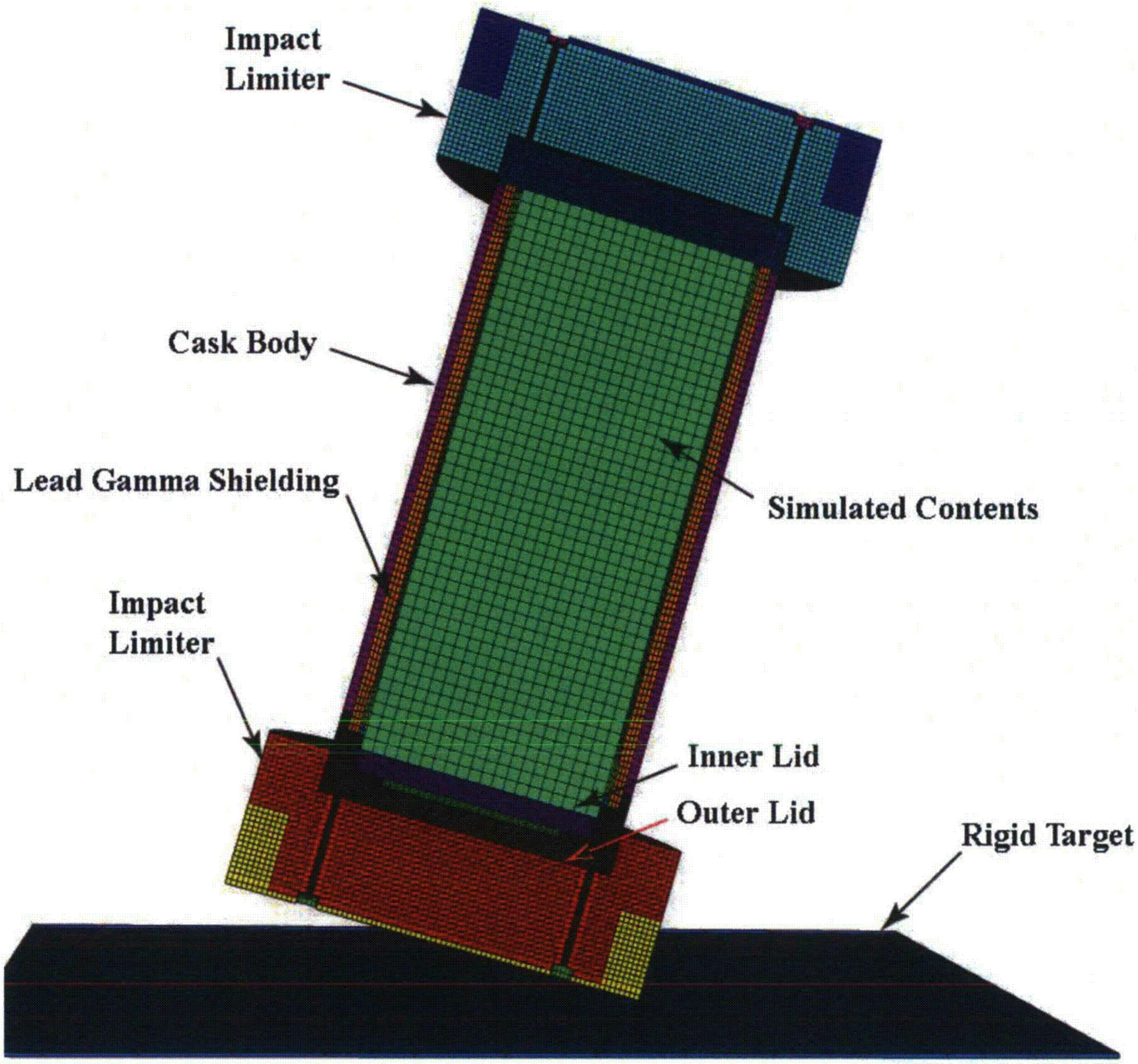
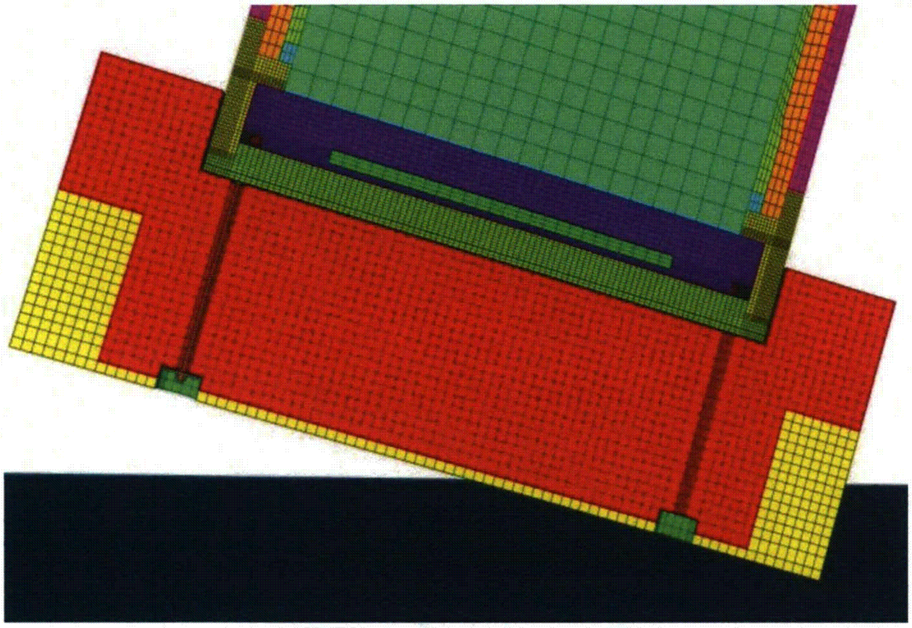
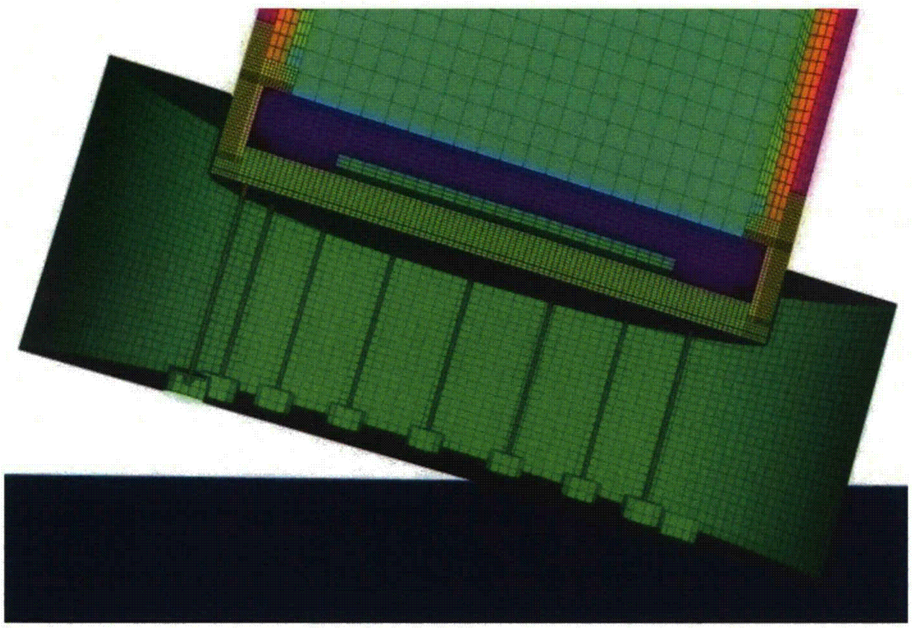


Figure 3-6 Finite element mesh of the Rail-Lead cask



Impact limiter showing the two different types of wood. The yellow is balsa and the red is redwood.



Impact limiter with the wood removed to reveal the inner attachment bolts

Figure 3-7 Details of the finite element mesh for the impact limiters of the Rail-Lead cask

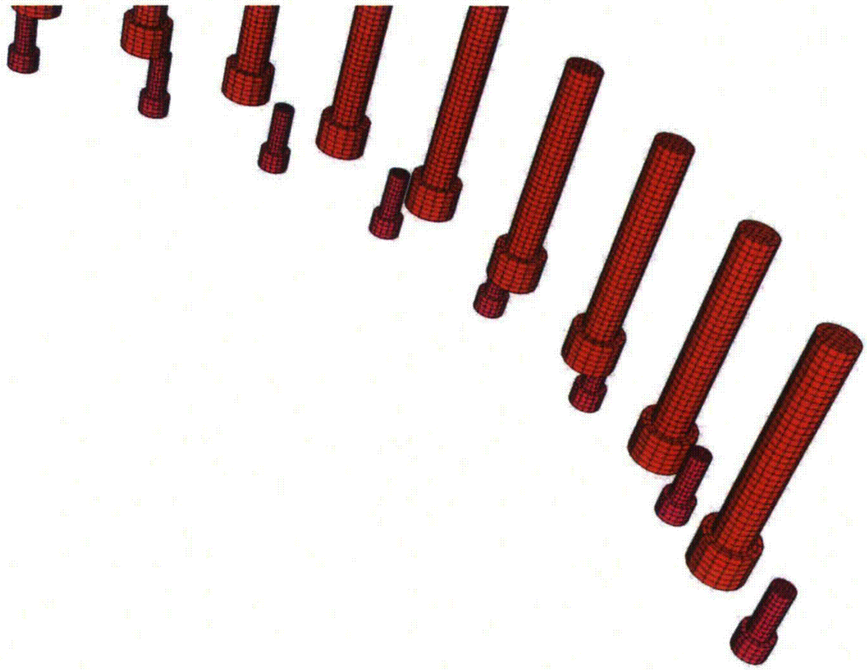


Figure 3-8 Finite element mesh of the Rail-Lead closure bolts for both the inner and outer lids. The longer bolts are for the inner lid and the shorter ones for the outer lid.

Analysis Results

The impact limiter absorbed almost all of the kinetic energy of the cask for the 48 kph impact analyses—the impact velocity from the regulatory hypothetical impact accident—and no damage to the cask body occurred. The response of the Rail-Lead cask was more complicated. For the end orientation, as the impact velocity increased, initially there was additional damage to the impact limiter because it was absorbing more kinetic energy, which shows the margin of safety in the impact limiter design. There is no significant damage to the cask body or canister at 97 kph (60 mph). At an impact speed of 145 kph (90 mph), damage to the cask and canister appears to begin. The impact limiter has absorbed all the kinetic energy it can and any additional kinetic energy is absorbed by plastic deformation in the cask body. At this speed there is significant slumping of the lead gamma shielding material, resulting in a loss of lead shielding near the end of the cask away from the impact point. As the impact velocity is increased to 193 kph (120 mph), the lead slump becomes more pronounced and there is enough plasticity in the lids and closure bolts to result in a loss of sealing capability. For the directly loaded cask (without a welded MPC) there could be some loss of radioactive contents if the cask has metallic seals. This would not be the case if the cask has elastomeric seals. A more detailed discussion of leakage is provided later in this section. Figure 3-9 shows the deformed shape of the Rail-Lead cask following the 193 kph (120 mph) impact in the end-on orientation. The amount of lead slump from this impact is 35.5 cm (14.0 in) and the area without lead shielding is visible in Figure 3-9. Table 3-1 gives the amount of lead slump in each of the analysis cases.

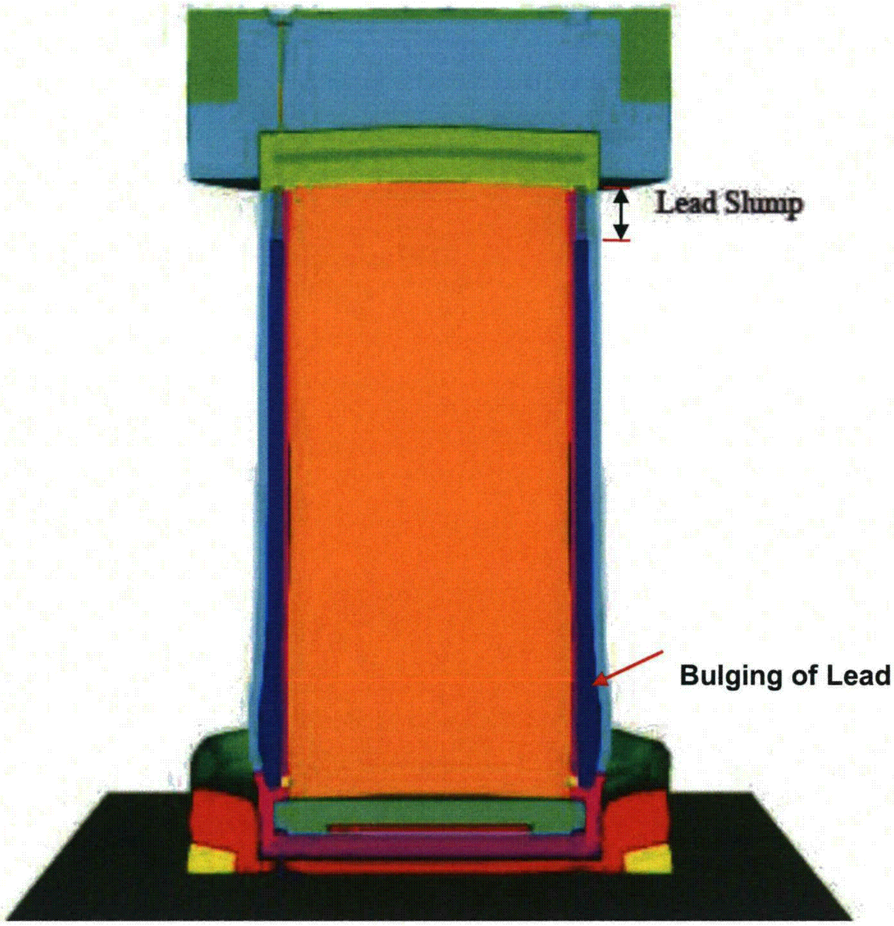


Figure 3-9 Deformed shape of the Rail-Lead cask following the 193-kph (120 mph) impact onto an unyielding target in the end-on orientation

Table 3-1 Maximum Lead Slump for the Rail-Lead Cask from Each Analysis Case[a]

Speed, kph (mph)	Max. Slump End, cm (in)	Max. Slump Corner, cm (in)	Max. Slump Side, cm (in)
48 (30)	0.64 (0.25)	0.17 (0.065)	0.01 (0.004)
97 (60)	1.83 (0.72)	2.51 (0.99)	0.14 (0.054)
145 (90)	8.32 (3.28)	11.45 (4.51)	2.09 (0.82)
193 (120)	35.55 (14.00)	31.05 (12.22)	1.55 (0.61)

[a] The measurement locations for each impact orientation are given in Appendix III.

For corner impacts at 97 kph (60 mph) and 145 kph (90 mph) , there is some damage to the cask body and deformation of the impact limiter, which results in lead slump and closure bolt deformation. The amount of closure deformation in these two cases is not sufficient to cause a leak if the cask is sealed with elastomeric o-rings, but it is enough to cause a leak if the cask is sealed with metallic o-rings. For a corner impact at 193 kph (120 mph) there is more significant deformation to the cask, more lead slump, and a larger gap between the lid and the cask body. Figure 3-10 shows the deformed shape of the cask for this impact analysis. The deformation in the seal region is sufficient to cause a leak if the cask has metallic o-rings but not if it has elastomeric o-rings. The maximum amount of lead slump is 31 cm (12 inches).

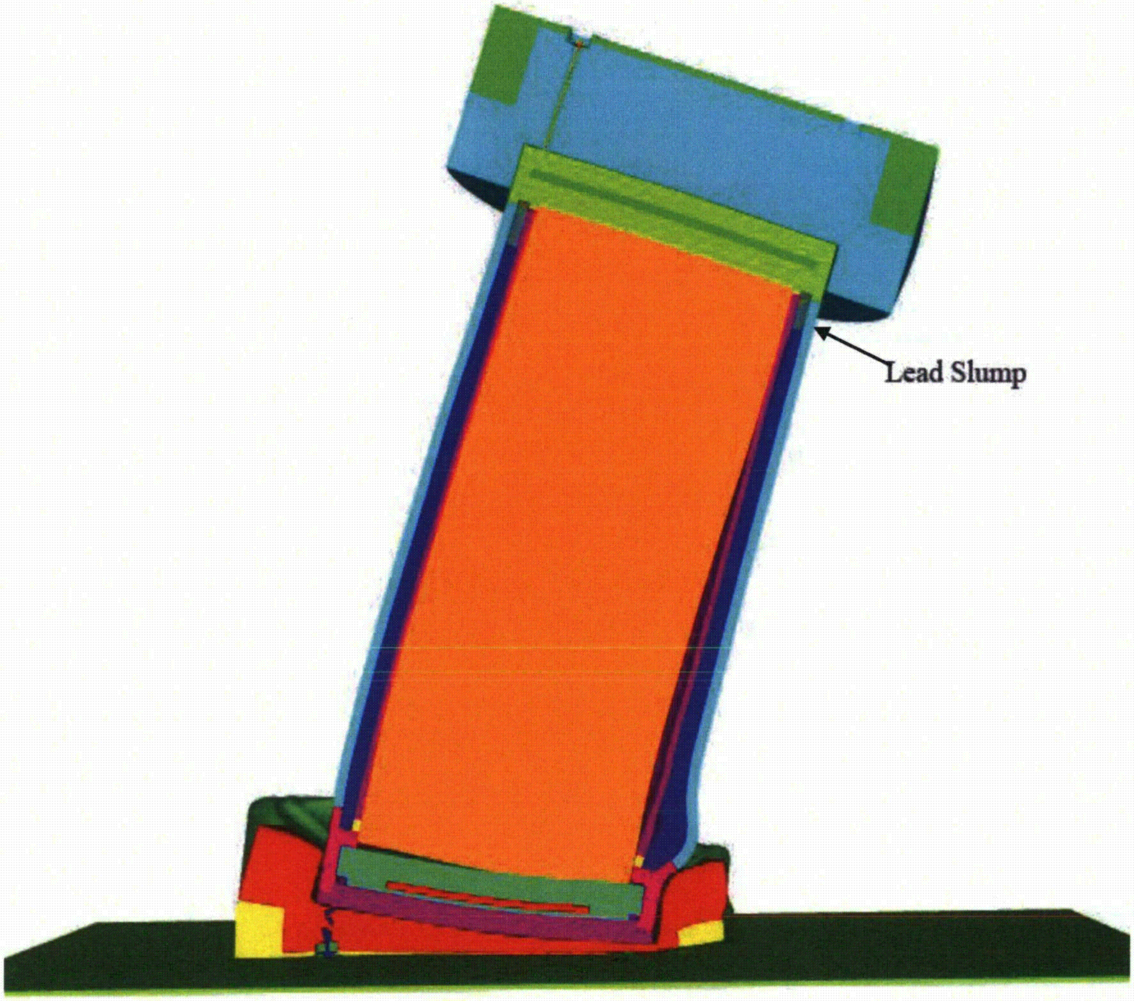


Figure 3-10 Deformed shape of the Rail-Lead cask following the 193 kph (120 mph) impact onto an unyielding target in the corner orientation

In the side impact, as the impact velocity increases from 48 kph (30 mph) to 97 kph (60 mph), the impact limiter ceases to absorb additional energy and there is permanent deformation of the cask and closure bolts. The resulting gap in between the lids and the cask body is sufficient to allow leakage if there is a metallic seal, but not if there is an elastomeric seal. This gap calculation between the cask body and lid is conservative because the clamping force applied by bolt preload was neglected in the analysis (i.e., the clamping force acts to keep the lid and cask body together). When the impact speed is increased to 145 kph (90 mph), the amount of damage to the cask increases significantly. In this case, many bolts from the inner and outer lid fail in shear and there is a gap between each of the lids and the cask. This gap is sufficient to allow leakage if the cask is sealed with either elastomeric or metallic o-rings.

Figure 3-11 shows the deformed shape of the cask following this impact. The response of the cask to the 193 kph (120 mph) impact is similar to that from the 145 kph (90 mph) impact, except that the gaps between the lids and the cask are larger. Appendix III shows the deformed shapes for all of the cases analyzed.

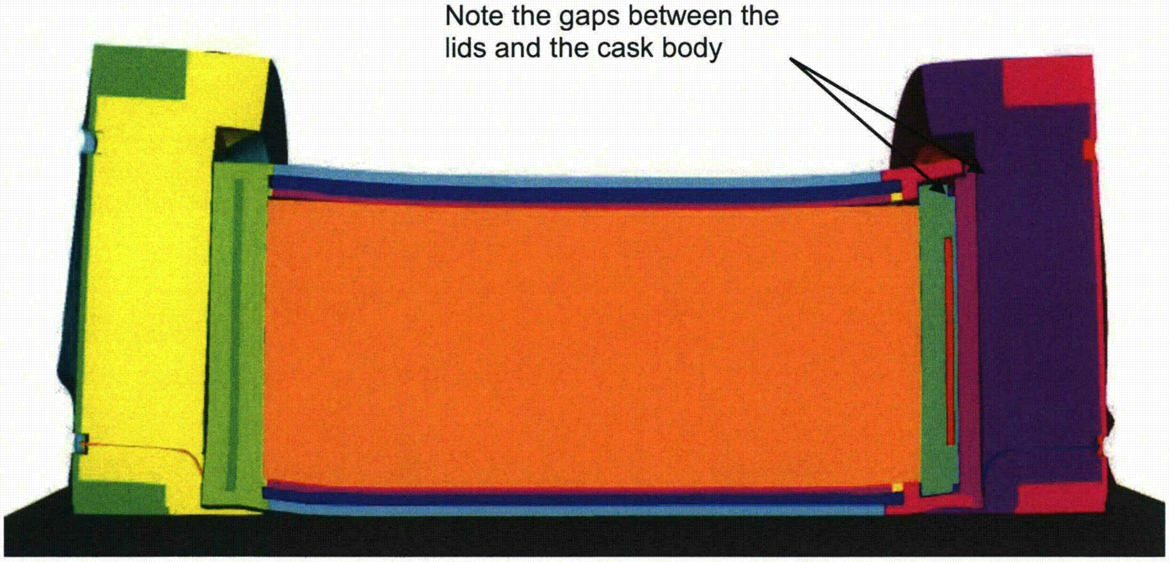


Figure 3-11 Deformed shape of the Rail-Lead cask following the 145 kph (90 mph) impact onto an unyielding target in the side orientation

Leak Area

The COC for the Rail-Lead cask allows transportation of spent fuel in three different configurations. The analyses conducted for this study were all direct-loaded fuel cases, but the results can be applied to cases with an internal canister. The impact limiter and cask body are the same for that case. The addition of the internal canister adds strength and stiffness to the cask in the closure region because it has a 203-mm (8-in) thick lid that will inhibit the rotation of the cask wall and reduce any gaps between the closure lids and the cask.

Figure 3-12 shows the deformation of the closure region for the 193 kph (120 mph) end impact. Gaps for the outer lid were measured as the shortest distance from Node A to the surface opposite it and gaps for the inner lid were measured as the shortest distance from Node B to the surface opposite it. None of the analyses show sufficient deformation into the interior volume of the cask to cause a failure of the internal welded canister. Therefore, as with the Rail-Steel cask, if the spent fuel is transported in an inner welded canister, there would be no release from any of the impacts.

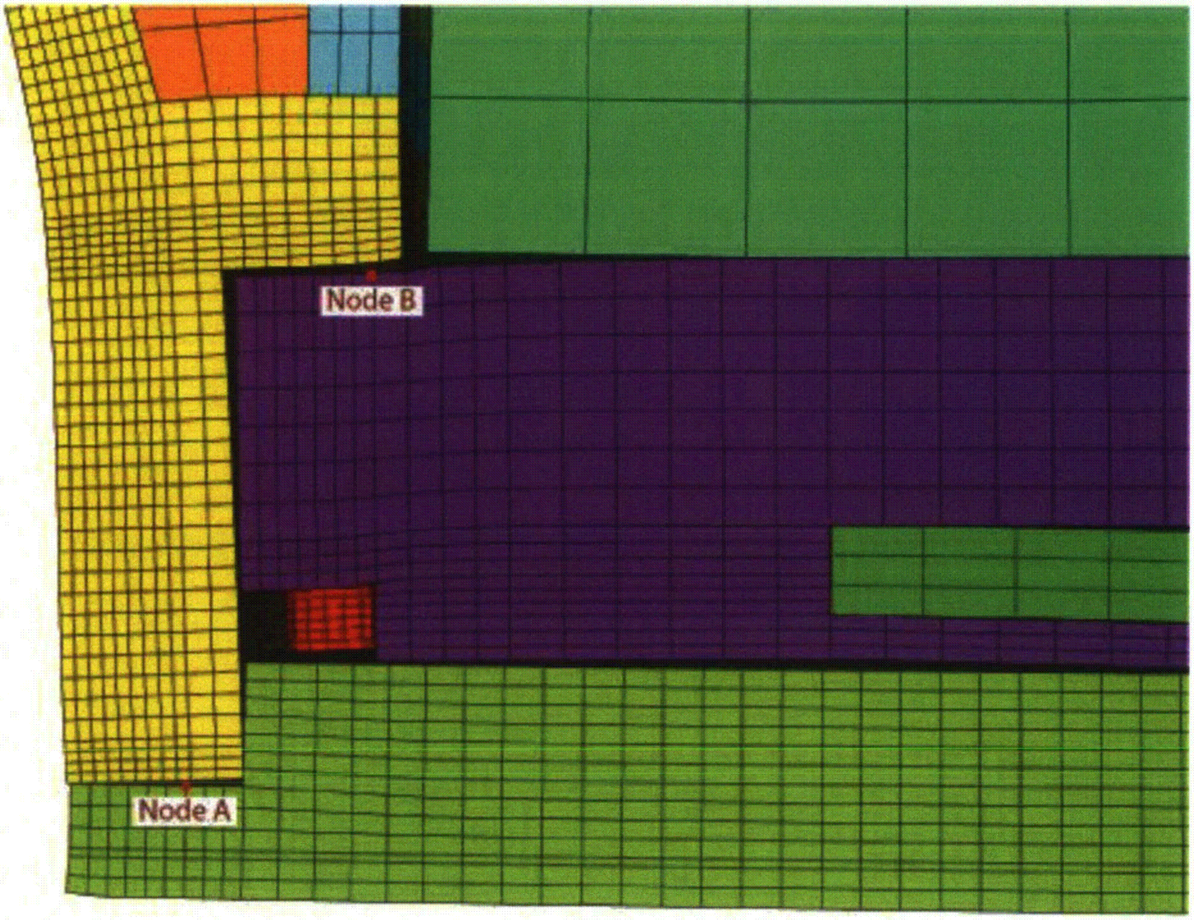


Figure 3-12 Measurement of closure gaps

In cases without an inner canister, the cask can be used for dry spent-fuel storage before shipment or to transport fuel removed from pool storage and immediately shipped. In the first of these two cases, metallic o-rings provide the seal between the lids and the cask body. This type of seal is less tolerant to movement between the lids and the cask and a closure opening greater than 0.25 mm will cause a leak. If the cask is used for direct shipment of spent fuel, elastomeric o-rings provide the seal between the lids and the cask body. While no tests of the effect of gap on leak rates for the lids of this cask have been performed, it is assumed that this type of seal can withstand closure openings of 2.5 mm (0.10 in) without leaking (Sprung et al., 2000).

Table 3-2 gives the calculated axial gap in each analysis and the corresponding leak area for both metallic and elastomeric seals. The leak areas are calculated for the lid with the smaller gap because if any leakage from the cask occurs, both lids must leak.

Table 3-2 Available Areas for Leakage from the Rail-Lead Cask

Orientation	Speed, kph (mph)	Location	Lid Gap, mm (in)	Seal Type	Hole Size, mm^2 (in^2)
End	48 (30)	Inner	0.226 (0.0089)	Metal[b]	none
		Outer	0	Elastomer	none
	97 (60)	Inner	0.056 (0.0022)	Metal	none
		Outer	0.003 (0.00012)	Elastomer	none
	145 (90)	Inner	2.311 (0.091)	Metal	none
		Outer	0.047 (0.00185)	Elastomer	none
	193 (120)	Inner	5.588 (0.220)	Metal	8796 (13.63)
		Outer	1.829 (0.072)	Elastomer	none
Corner	48 (30)	Inner	0.094 (0.0037)	Metal	none
		Outer	0.089 (0.0035)	Elastomer	none
	97 (60)	Inner	0.559 (0.022)	Metal	65 (0.10)
		Outer	0.381 (0.015)	Elastomer	none
	145 (90)	Inner	0.980 (0.0386)	Metal	599 (0.928)
		Outer	1.448 (0.057)	Elastomer	none
	193 (120)	Inner	2.464 (0.097)	Metal	1716 (2.660)
		Outer	1.803 (0.071)	Elastomer	none
Side	48 (30)	Inner	0.245 (0.0096)	Metal	none
		Outer	0.191 (0.0075)	Elastomer	none
	97 (60)	Inner	0.914 (0.036)	Metal	799 (1.24)
		Outer	1.600 (0.063)	Elastomer	none
	145 (90)	Inner	8[a] (0.3)	Metal	>10000 (>16)
		Outer	25[a] (1)	Elastomer	>10000 (>16)
	193 (120)	Inner	15[a] (0.6)	Metal	>10000 (>16)
		Outer	50[a] (2)	Elastomer	>10000 (>16)

[a] Estimated. The method used to calculate the gaps for the other cases is explained in Appendix III. For these cases, there was bolt failure and the gap was too large to measure using the standard method, but the resultant leak area is sufficiently large enough that any change to it would not change the cask-release fraction.

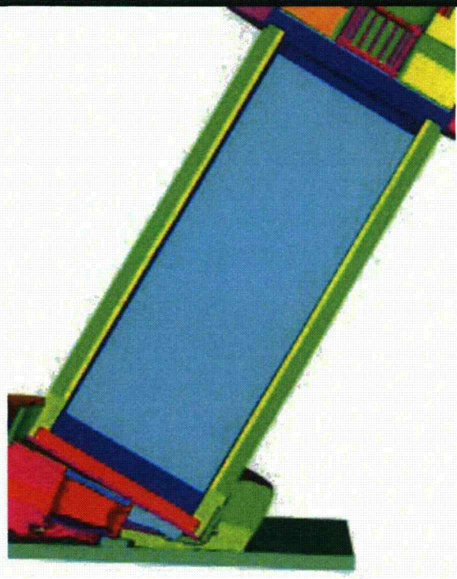
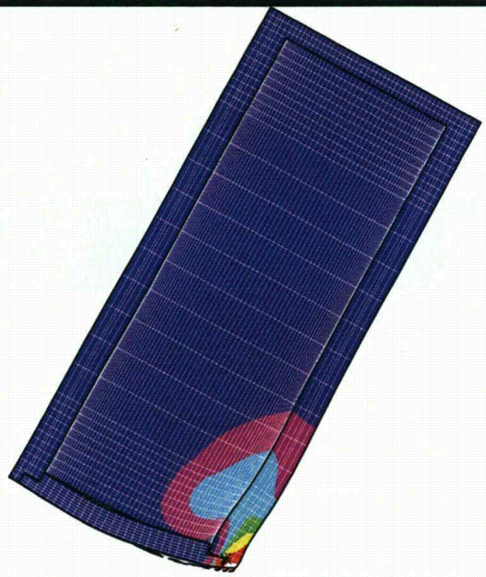
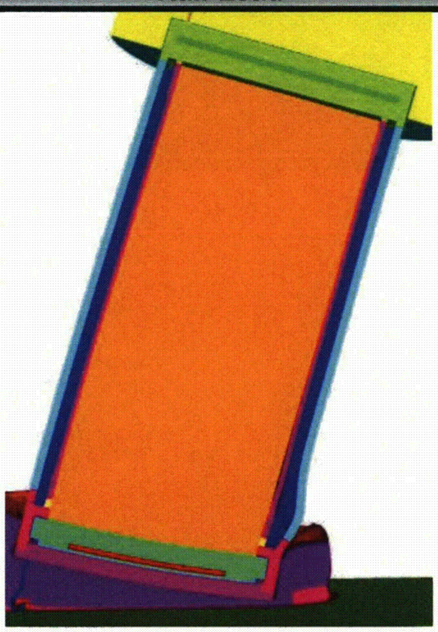
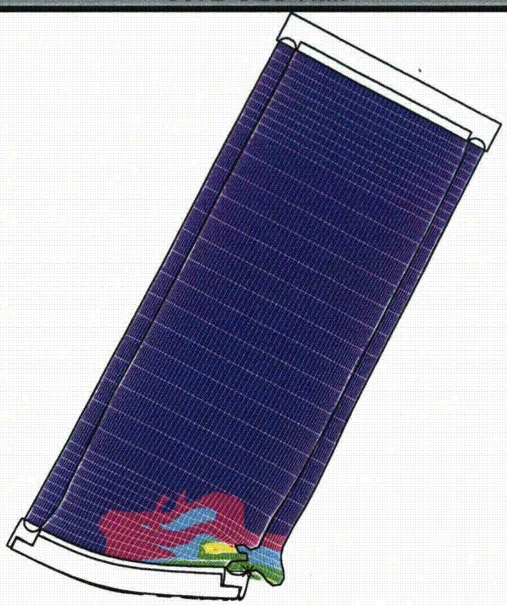
[b] The metal seal for the Rail-Lead cask is installed only when the cask has been used for dry storage prior to transportation. Currently, none of these casks are used for dry storage and there are no plans for using them that way in the future.

3.2.3 Truck-DU Cask

Detailed FE analyses of the Truck-DU cask were not performed for this study because the response of the truck casks in NUREG/CR–6672 indicated there were no gaps between the lid and the cask body at any impact speed. Therefore, the results discussed here are based on the FE analysis of the generic steel-DU-steel truck cask performed for NUREG/CR–6672. In general, results from the analyses performed for this study confirm that the analyses performed for NUREG/CR–6672 were conservative (see Table 3-3); therefore, the results discussed below are likely to be an overestimate of the damage to the Truck-DU cask from severe impacts. Figure 3-13 shows the deformed shape and plastic strain contours for the generic steel-DU-truck cask from Appendix A to NUREG/CR–6672 (Figures A-15, A-19, and A-22). None of the impacts caused strains great enough to fail the cask wall, and in all cases the deformation in the closure region was insufficient to cause seal failure.

Table 3-4 (extracted from Table 5.6 of NUREG/CR–6672) provides the deformation in the seal region for each case. There would be no release of radioactive contents in any of these cases.

Table 3-3 Comparison of Analyses between this Study and NUREG/CR-6672

Item/Cask	Rail-Steel	6672 Monolithic Steel
Deformed Shape 145 kph (90 mph)		 (Figure A-35 of NUREG/CR-6672)
Failed Bolts	No	Yes
Item/Cask	**Rail-Lead**	**6672 SLS Rail**
Deformed Shape 145 kph (90 mph)		 (Figure A-24 of NUREG/CR-6672)
Gap Size	Inner Lid - 0.980 mm (0.039 in) Outer Lid – 1.448 mm (0.057 in)	6.096 mm (0.240 in)
Failed Bolts	No	Yes

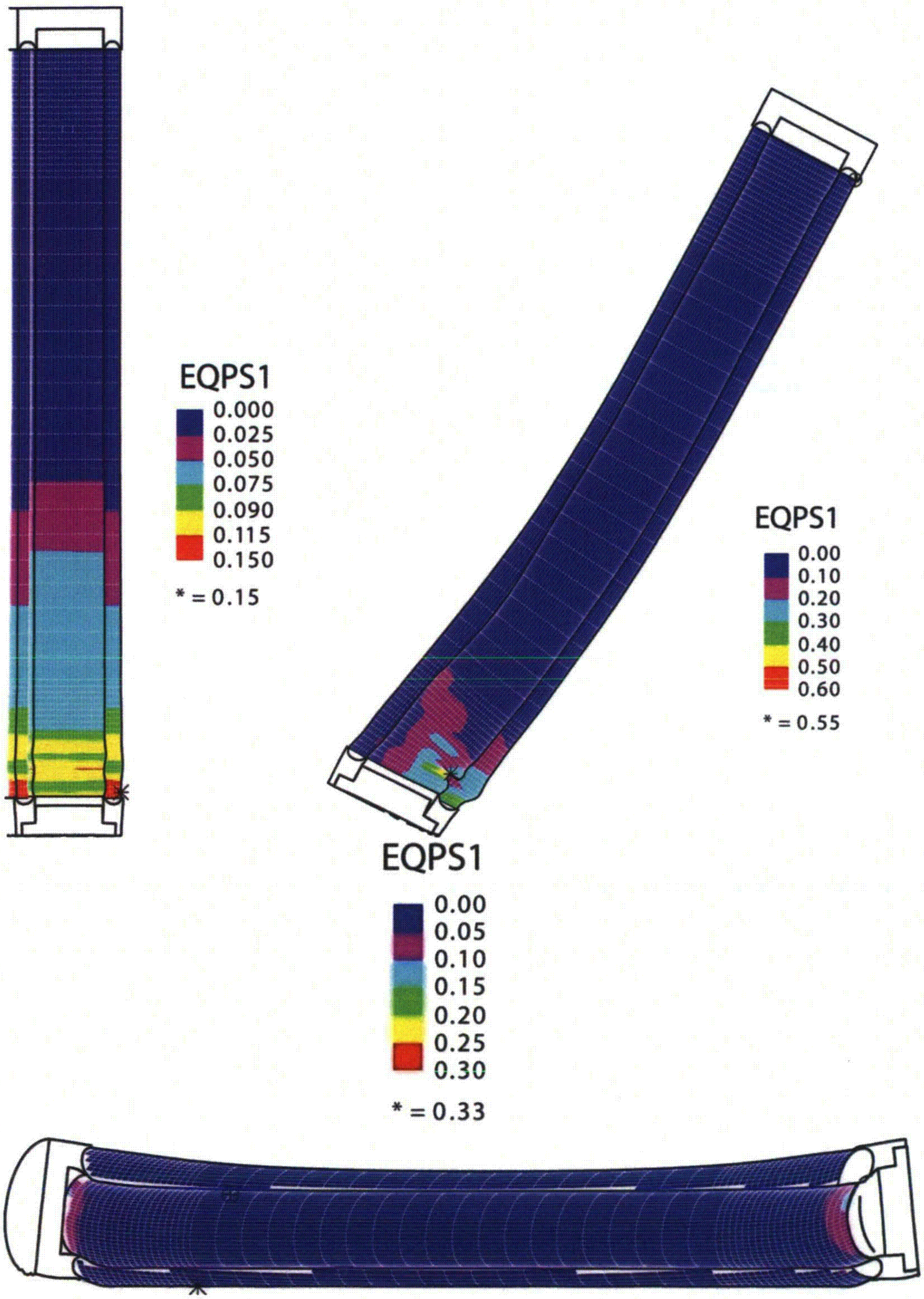


Figure 3-13 Deformed shapes and plastic strains in the generic steel-DU-steel truck cask from NUREG/CR-6672 (impact limiter removed) following 193 kph (120 mph) impacts in the (clockwise from top left) end-on, CG-over-corner, and side-on orientation

Table 3-4 Deformation of the Closure Region of the Steel-DU-Steel Truck Cask from NUREG/CR-6672, mm (in)

Cask	Analysis Velocity	Corner Impact		End Impact		Side Impact	
		Opening	Sliding	Opening	Sliding	Opening	Sliding
Steel-DU-Steel Truck	48 kph 30 mph	0.508 (0.02)	1.778 (0.07)	0.127-0.305 (0.005-0.012)	0.025-0.127 (0.001-0.005)	0.254 (0.01)	0.508 (0.002)
	97 kph 60 mph	2.032 (0.08)	1.778 (0.07)	0.254-0.508 (0.01-0.02)	0.076-0.152 (0.003-0.006)	0.254 (0.01)	0.254 (0.01)
	145 kph 90 mph	0.508 (0.02)	2.540 (0.1)	-	-	0.254 (0.01)	0.508 (0.02)
	193 kph 120 mph	0.762 (0.03)	3.810 (0.15)	0.330 (0.013)	0.762 (0.03)	0.102 (0.004)	0.508 (0.02)

3.3 Impacts onto Yielding Targets

The analysis results discussed in Section 3.2 were for impacts onto an unyielding, essentially rigid, target. All real-impact accidents involve targets yield to some extent. When a cask impacts a real target, the amount of impact energy the target and cask absorb depends on the relative strength and stiffness of the two objects. For an impact onto a real target to produce the same amount of damage as the impact onto an unyielding target, the force applied to the cask has to be the same. If the target is not capable of sustaining that level of force, it cannot produce the corresponding level of cask damage.

For the Rail-Lead cask (the only one of the three investigated in this study with any release), the peak force associated with each impact analysis performed is supplied in Table 3-5. In this table, the cases with non-zero hole sizes from Table 3-4 have bold text. It can be seen that in order to produce sufficient damage for the cask to release any material, the yielding target has to be able to apply a force to the cask greater than 146 million Newtons (MN), or 33 million pounds. Very few real targets are capable of applying this amount of force. A hard rock is the closest thing to an unyielding target. In this study, hard rock is defined as rock that requires blasting operations to remove. While not all classes of this type of rock are equally strong, all of them are assumed to absorb negligible energy during an impact; therefore, they are treated as rigid.

If the cask hits a flat target, such as the ground, roadway, or railway, it will penetrate into the surface. The greater the contact force between the cask and the ground, the greater the penetration depth. Figure 3-14 shows the relationship between penetration depth and force for the Rail-Lead cask impacting onto hard desert soil. As the cask penetrates the surface, some of its kinetic energy is absorbed by the surface. The amount of energy the target absorbs is equal to the area underneath the force versus the penetration curve seen in Figure 3-14. For example, the end impact at 97 kph (60 mph) onto an unyielding target requires a contact force of 124 MN (27.9×10^6 pounds). A penetration depth of approximately 2.2 meters (7.2 feet) will cause the soil to exert this amount of force. The soil absorbs 142 million Joules (MJ) (105×10^6 foot pounds) of energy when penetrated to this depth. Adding the energy absorbed by the soil to the 41 MJ (30×10^6 foot pounds) of energy absorbed by the cask yields a total absorbed energy of 183 MJ (135×10^6 foot pounds). For the cask to have this amount of kinetic energy, it would have to be traveling at 205 kph (127 mph). Therefore, a 205 kph (127 mph) impact onto hard desert soil causes the same amount of damage as a 97 kph (60 mph) impact onto an unyielding target. A similar calculation can be performed for other impact speeds, orientations, and target types.

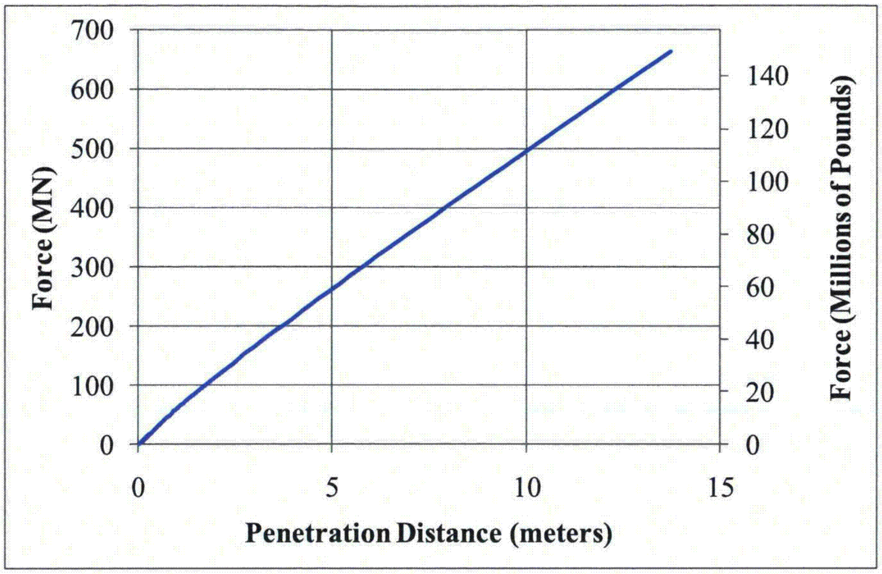


Figure 3-14 Force generated by the Rail-Lead cask penetrating hard desert soil

Table 3-6 provides the resulting equivalent velocities. Similar to Table 3-5, the cases resulting in non-zero hole sizes are identified in bold text. Where the calculated velocity is more than 250 kph (155 mph), the value in the table is listed as ">250 (>155)." No accident velocities are more than this. The concrete target used is a 23-cm-thick slab on engineered fill, which is typical of many concrete roadways and concrete retaining walls adjacent to highways. Appendix III contains details on the calculation of equivalent velocities.

Table 3-5 Peak Contact Force for the Rail-Lead Cask Impacts onto an Unyielding Target Table note: (bold numbers are for the cases where there may be seal leaks)

Orientation	Speed, kph (mph)	Accel. (g)	Contact Force (Millions of Pounds)	Contact Force (MN)
End	48 (30)	58.5	14.6	65.0
	97 (60)	111.6	27.9	123.9
	145 (90)	357.6	89.3	397.1
	193 (120)	**555.5**	**138.7**	**616.8**
Corner	48 (30)	36.8	9.2	40.9
	97 (60)	**132.2**	**33.0**	**146.8**
	145 (90)	**256.7**	**64.1**	**285.1**
	193 (120)	**375.7**	**93.8**	**417.2**
Side	48 (30)	76.1	19.0	84.5
	97 (60)	**178.1**	**44.5**	**197.8**
	145 (90)	**411.3**	**102.7**	**456.7**
	193 (120)	**601.1**	**150.0**	**667.4**

Table 3-6 Equivalent Velocities for Impacts onto Various Targets with the Rail-Lead Cask, kph (mph)

Orientation	Rigid (or hard rock)	Soil	Concrete
End	48 (30)	102 (63)	71 (44)
	97 (60)	205 (127)	136 (85)
	145 (90)	>250 (>155)	>250 (>155)
	193 (120)	**>250 (>155)**	**>250 (>155)**
Corner	48 (30)	73 (45)	70 (43)
	97 (60)	**236 (147)**	**161 (100)**
	145 (90)	**>250 (>155)**	**>250 (>155)**
	193 (120)	**>250 (>155)**	**>250 (>155)**
Side	48 (30)	103 (64)	79 (49)
	97 (60)	**246 (153)**	**185 (115)**
	145 (90)	**>250 (>155)**	**>250 (>155)**
	193 (120)	**>250 (>155)**	**>250 (>155)**

3.4 Effect of Impact Angle

The regulatory hypothetical impact accident requires the cask's velocity to be perpendicular to the impact target. All of the analyses were conducted with this type of impact. During transport, the usual scenario is that the velocity is parallel to the nearby surfaces, and therefore, most accidents that involve impact with surfaces occur at a shallow angle. This is not necessarily true, however, for impacts with structures or other vehicles.

Accident databases do not include impact angle as one of their parameters, so there is no information on the relative frequency of impacts at various angles. Given that vehicles usually travel parallel to the nearby surfaces, for this study a triangular distribution of impact angles was used. Figure 3-15 shows the assumed step-wise distribution of impact angle probabilities. For impacts onto hard targets, which are necessary to damage the cask, the component of the velocity that is parallel to the impact surface has very little effect on the amount of damage to the cask. This requires the accident speed to be higher for a shallow angle impact than a perpendicular one to achieve the same amount of damage. Figure 3-16 depicts an example of an impact at a shallow angle and the components of the velocity parallel and perpendicular to the surface.

Table 3-7 provides the cumulative probability of exceeding an impact angle range and the accident speeds required to have the velocity component in the direction perpendicular to the target.

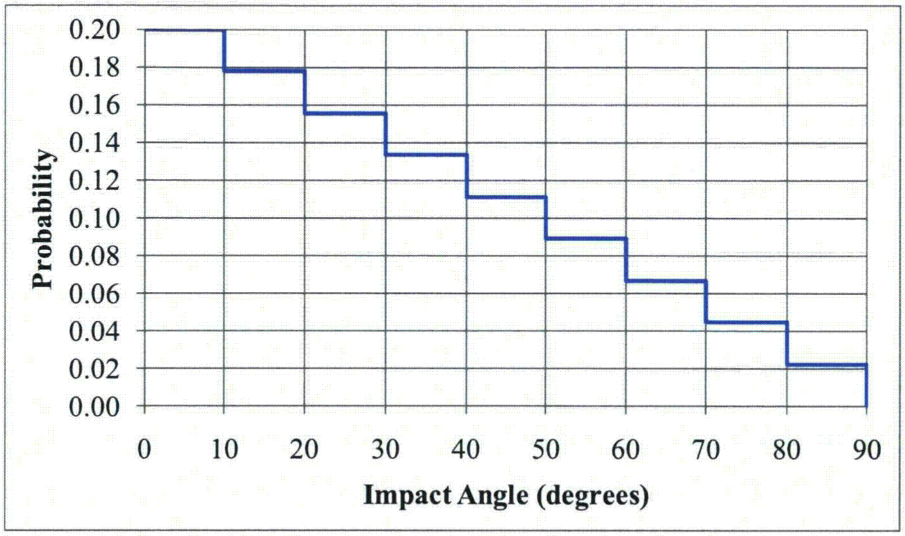


Figure 3-15 Probability distribution for impact angles

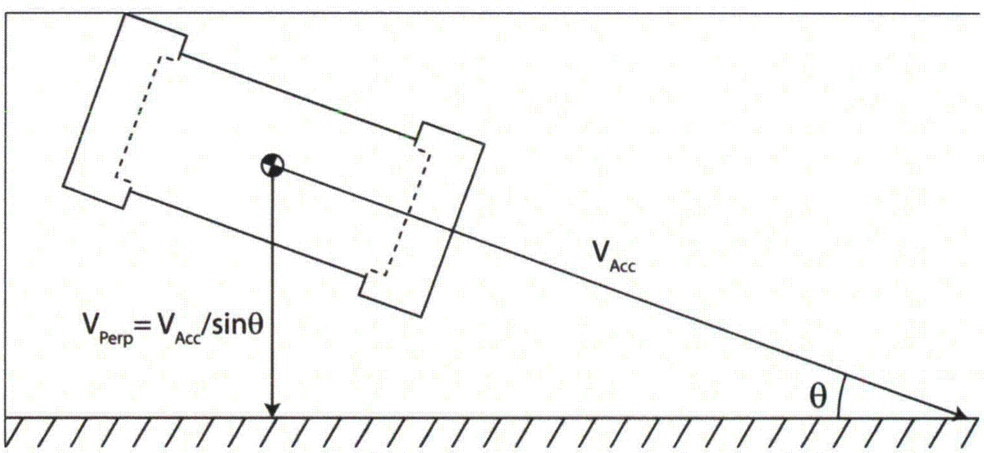


Figure 3-16 Influence of impact angle on effective velocity

Table 3-7 Accident Speeds that Result in the Same Damage as a Perpendicular Impact, kph (mph)

Angle	Prob.	Cum. Prob.	V_{Acc} so V_{Perp} = 48 kph (30mph)	V_{Acc} so V_{Perp} = 97 kph (60 mph)	V_{Acc} so V_{Perp} = 145 kph (90 mph)	V_{Acc} so V_{Perp} = 193 kph (120 mph)
0 - 10	0.2000	1.0000	278 (173)	556 (345)	834 (518)	1112 (691)
10 - 20	0.1778	0.8000	141 (88)	282 (175)	423 (263)	565 (351)
20 - 30	0.1556	0.6222	97 (60)	193 (120)	290 (180)	386 (240)
30 - 40	0.1333	0.4667	75 (47)	150 (93)	225 (140)	300 (186)
40 - 50	0.1111	0.3333	63 (39)	126 (78)	189 (117)	252 (157)
50 - 60	0.0889	0.2222	56 (35)	111 (69)	167 (104)	223 (139)
60 - 70	0.0667	0.1333	51 (32)	103 (64)	154 (96)	206 (128)
70 - 80	0.0444	0.0667	49 (30.4)	98 (61)	147 (91)	196 (122)
80 - 90	0.0222	0.0222	48 (30)	97 (60)	145 (90)	193 (120)

Using the information from Table 3-6 and Table 3-7 along with the event trees in Appendix V and the assumptions that half of the impacts into tunnels are hard rock surfaces and half are concrete leads to the result that 99.95% of all rail impact accidents are less severe than the regulatory hypothetical accident of 10 CFR 71.73.

3.5 Impacts with Objects

The preceding sections dealt with impacts onto flat surfaces, but a large number of impacts occur on surfaces that are not flat. These include impacts into columns and other structures, impacts by other vehicles, and, more rarely, impacts by collapsing structures. These types of impacts were not explicitly included in this study, but recent work by Sandia National Laboratories (NRC, 2003a; Ammerman and Gwinn, 2004; Ammerman et al., 2005) has shown the GA-4 cask response to some of these impacts. The result of an impact into a large, semi-circular, rigid column is shown in Figure 3-17 (NRC, 2003a). While this impact led to significant permanent deformation of the cask, the level of strain was not high enough to cause tearing of the containment boundary and there was no permanent deformation in the closure region and no loss of containment.

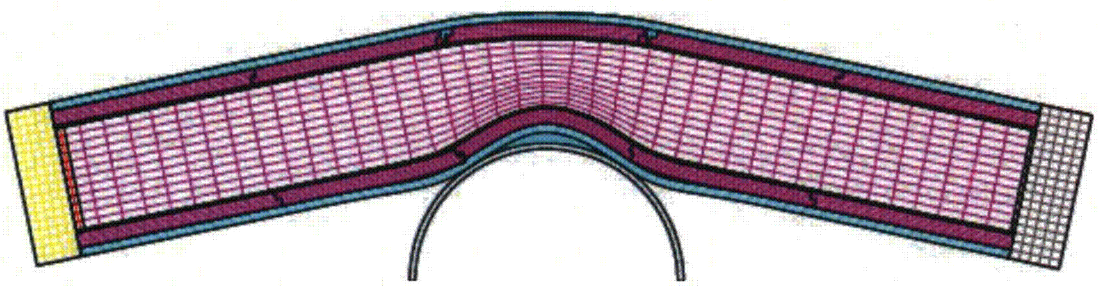


Figure 3-17 Deformations to the GA-4 truck cask after a 97 kph (60 mph) side impact onto a rigid semi-circular column
Figure source: (from NRC, 2003b)

Collision by a railroad locomotive could potentially cause cask damage and is probably the most severe type of collision with another vehicle that could occur. Ammerman et al. (2005) investigated several different scenarios of this type of collision. The overall configuration of the general analysis case is shown in Figure 3-18. Most trains involve more locomotives and trailing cars than used in this analysis, but additional train mass has little effect on the force acting on the cask. The impact duration is short and the coupling between the cars is flexible, so the impact is over before the inertia of more cars can influence it. Variations on the general configuration included the most common locomotive scenarios: 1) having a level crossing where the truck tires and locomotive wheels are at the same elevation, 2) having a raised crossing where the bottom of the trailer's main beams are at the same elevation as the top of the tracks, and 3) having a skewed crossing so the impact is at 67 degrees instead of at 90 degrees. For all analyses, the truck was assumed to be stopped and train velocities were considered to be 113 kph (70 mph) and 129 kph (80 mph).

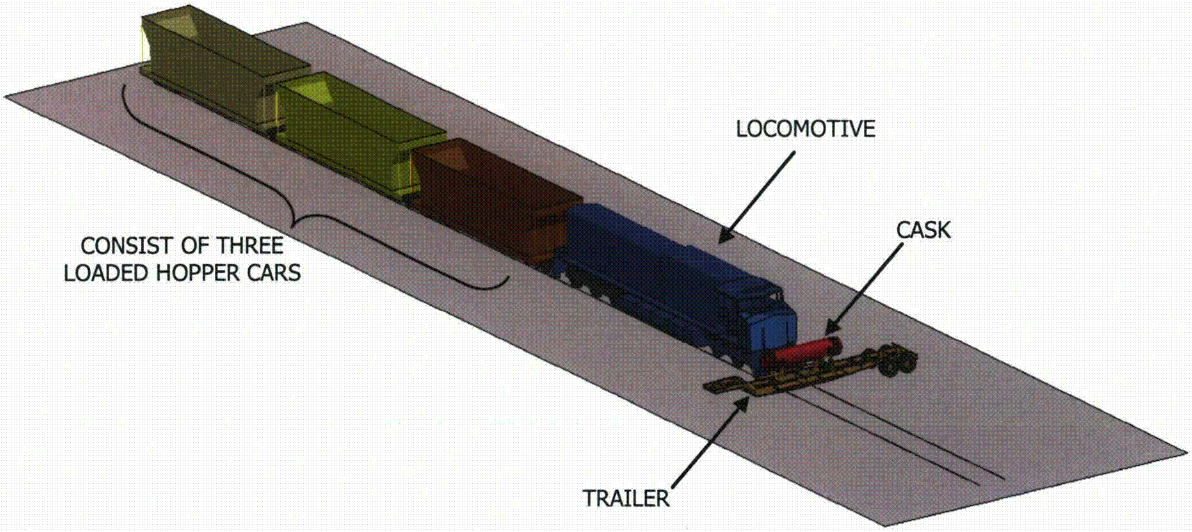


Figure 3-18 Configuration of locomotive impact analysis
Figure source: (Ammerman et al., 2005)

None of the analyses led to deformations that would cause a release of radioactive material from the cask or resulted in cask accelerations high enough for the fuel rod cladding to fail. Figure 3-19 shows a sequence of the impact. The front of the locomotive is severely damaged and the trailer is totally destroyed, but there is very little deformation of the cask—only minor denting where the collision posts of the locomotive hit the cask.

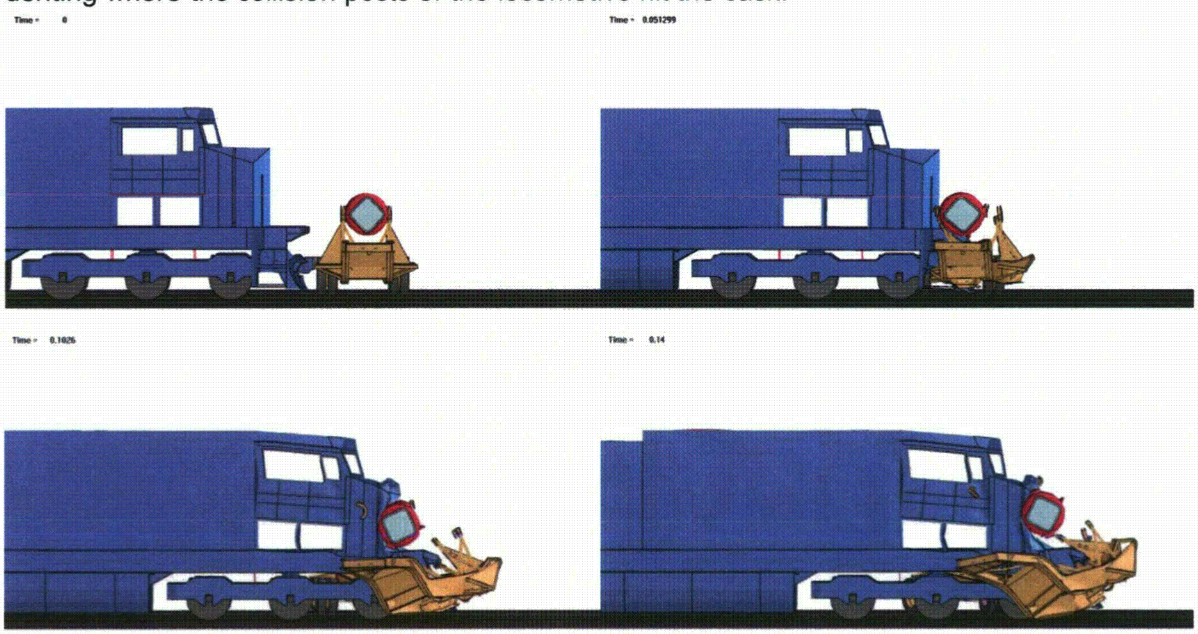


Figure 3-19 Sequential views of a 129 kph (80 mph) impact of a locomotive into a GA-4 truck cask
Figure source: (Ammerman et al., 2005)

The collapse of a bridge onto a cask occurs less frequently, but it also has the potential to damage a cask. This type of accident occurred when an elevated portion of the Nimitz Freeway collapsed during the Loma Prieta earthquake near San Francisco on October 17, 1989. This scenario was analyzed to determine if it would cause a release of spent fuel from the GA-4 truck cask (Ammerman and Gwinn, 2004). The analysis assumed that the cask was lying directly on the roadway (negating the cushioning effect of the trailer and impact limiters) and a main beam of the elevated freeway fell and hit the middle of the cask. Stresses in the cask and damage to the beam are shown in Figure 3-20. As in the other analyses for impacts with objects, no loss of containment would occur from this accident.

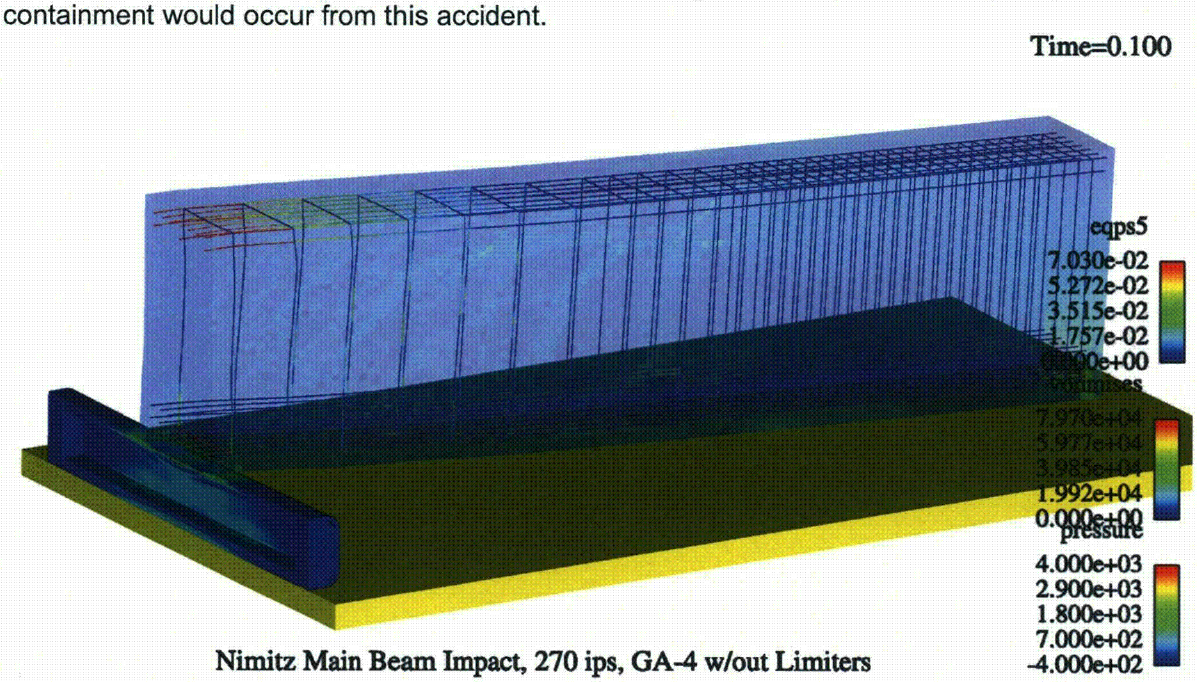


Figure 3-20 Results of a finite element simulation of an elevated freeway collapse onto a GA-4 spent fuel cask
Figure source: (Ammerman and Gwinn, 2004), 270 ips = 15.3 mph = 24.7 kph

3.6 Response of Spent Fuel Assemblies

The FE analyses of the casks in this study did not include the individual components of the spent fuel assemblies. Instead, the total mass of the fuel and its support structure were combined into an average material. A detailed model of a spent fuel assembly was developed to determine the response of individual components (Kalan et al., 2005). Figure 3-21 shows this model. In the figure, the fuel rods are shown in yellow, the guide tubes in green, the spacer grids in red, the end plates in light blue, and the impact surface in dark blue. The loads associated with a 100 g[16] cask impact in a side orientation were then applied to this detailed model. Kalan et al., 2005, only analyzed the side impact of spent fuel assemblies because the strains associated with the rods buckling during an end impact are limited by the constrained lateral deformations the basket provides. The side impact results in forces in each fuel rod at

[16] g refers to the acceleration due to gravity. A 100 g impact results in a deceleration of the cask equal to 100 times the acceleration due to gravity.

their supports and in many of the fuel rods midway between the supports where they impact on the rods above or below them. A detailed FE model determined the response of the rod with the highest loads is shown in Figure 3-22. There is slight yielding of the rod at each support location and slightly more yielding where the rods impact each other.

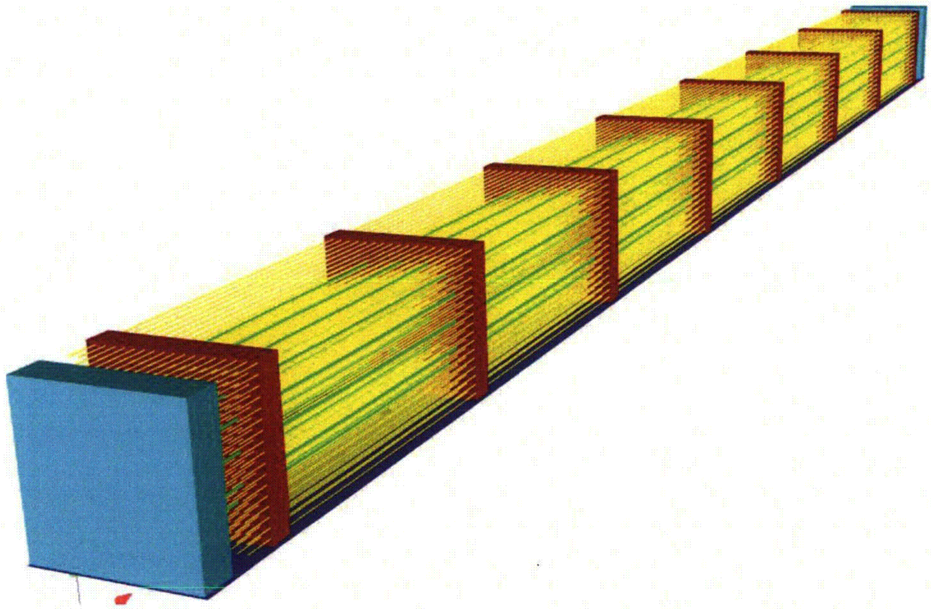


Figure 3-21 Finite element model of a PWR fuel assembly

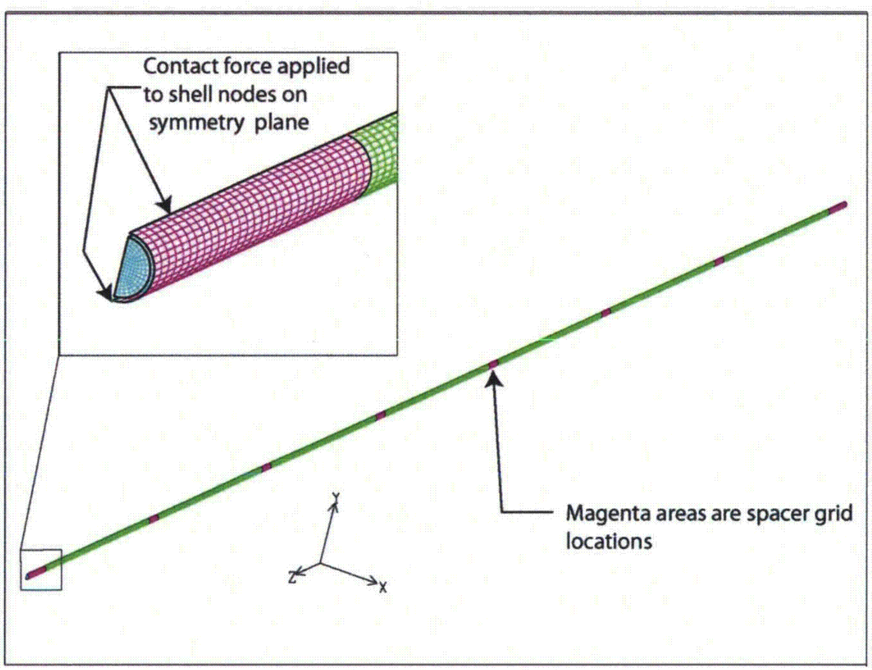


Figure 3-22 Detailed finite element model of a single fuel rod

Figure 3-23 shows the maximum plastic strain at each location. The largest of these strains is slightly below 2 percent, which is half the plastic strain capacity of irradiated zircaloy at the maximum burnup allowed in the Rail-Lead cask (45,000 MWD/MTU) (Sanders et al., 1992); therefore, the fuel rods will not crack. The peak acceleration of the cask would have to be above 200 g for the cladding to fail. The only impacts severe enough to crack the rods are those with impact speeds onto an essentially unyielding target of 145 kph (90 mph) or higher. Appendix III includes a detailed description of the fuel assembly modeling.

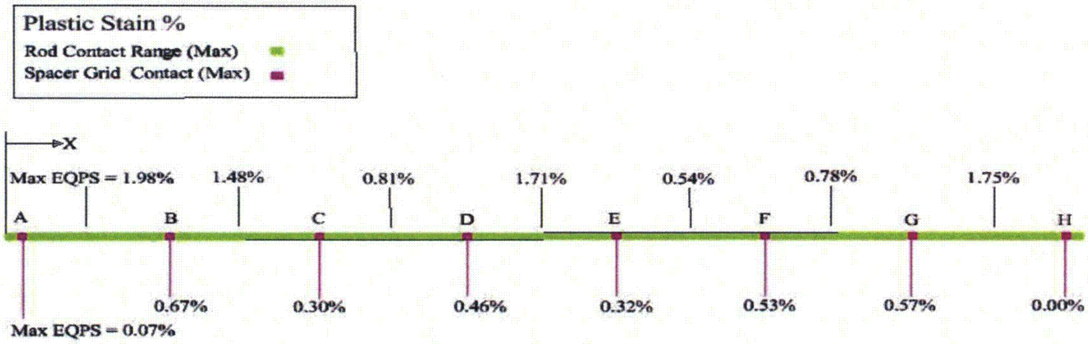


Figure 3-23 Maximum strains in the rod with the highest loads

3.7 Chapter Summary

Detailed FE analyses performed for two spent fuel transportation rail casks indicate that casks are very robust structures capable of withstanding almost all impact accidents without release of radioactive material. In fact, when spent fuel is transported within an inner welded canister or in a truck cask, no impacts result in release. Even the rail cask without an inner welded canister can withstand impacts much more severe than the regulatory impact without releasing any material.

The analyses in this chapter and the event trees in Chapter 5 combine to show that 99.95% of the impact accidents are less severe than the regulatory hypothetical accident of 10 CFR 71.73.

In the worst orientation (i.e., side impact), an impact speed onto a rigid target at more than 97 kph is required to cause seal failure in a rail cask. If the cask has an inner welded canister, even this impact will not lead to a release of radioactive material. A 97 kph (60 mph) side impact onto a rigid target produces a force of approximately 200 MN (45 million pounds) and is equivalent to a 185 kph (115 mph) impact onto a concrete roadway or abutment, or a 246 kph (153 mph) impact onto hard soil. For impacts onto hard rock, which may be able to resist these large forces, impacts at angles less than 30 degrees require a speed of more than 193 kph (120 mph) to be equivalent.

Assessment of previous analyses performed for spent fuel truck transportation casks, including impacts onto flat rigid targets, into cylindrical rigid targets, by locomotives, and by falling bridge structures, indicate that truck casks will not release their contents in any impact accidents.

In summary, the sequence of events necessary for there to be the possibility of any release is a rail transport cask with no welded canister travelling at an impact velocity greater than 97 kph (60 mph). This cask would have to impact in a side orientation and the surface would have to be hard rock with an impact angle greater than 30 degrees.

4. CASK RESPONSE TO FIRE ACCIDENTS

4.1 Introduction

Certified Type B casks are designed to withstand a fully-engulfing fire for 30 minutes while maintaining critical functions, including protecting the public from doses of radiation exceeding regulatory limits. Certification analyses of the hypothetical accident condition (HAC) fire specified in 10 CFR 71.73, "Hypothetical Accident Conditions," generally impose a thermal environment on the cask similar to or more severe than most thermal environments a cask may be exposed to in actual transportation accidents involving a fire (Fischer et al., 1987). Large open-pool fires can burn at temperatures higher than the average temperature of 800 degrees Celsius (C) (1,475 degrees Fahrenheit (F)) specified in HAC fire regulations. Actual fire plumes have location- and time-varying temperature distributions that vary from about 600 degrees C (1,112 degrees F) to more than 1,200 degrees C (2,192 degrees F) (Koski, 2000; Lopez et al., 1998). Therefore, an evenly-applied 800 degrees C (1,475 degrees F) fire environment used in a certification analysis could be more severe for cask seals and fuel rod response than exposure to an actual fire.

This risk study used computer codes capable of modeling both fire behavior and the thermal responses of objects engulfed in those fires in a realistic way[17] to analyze the response of the Rail-Steel and the Rail-Lead casks to three different fire configurations. This chapter describes these configurations and discusses the casks' temperature responses. An analysis of the thermal performance of the Truck-DU cask when exposed to a severe fire scenario is also presented.

The thermal response of each cask is compared to two characteristic temperature limits: the rated seal temperature (350 degrees C (662 degrees F) for elastomeric seals used in the Rail-Lead cask and the Truck-DU and 649 degrees C (1,200 degrees F) for the metallic seal used in the Rail-Steel cask) and the fuel rod burst rupture temperature (750 degrees C (1,382 degrees F) for all casks (Lorenz, 1980)). These temperature limit values are the same as those used in NUREG/CR-6672 for the elastomeric seal and fuel rod burst temperature. The Rail-Steel cask seal temperature limit is obtained from Table 2.1.2 and Table 4.1.1 in the HI-STAR 100 SAR (Holtec International, 2000). Section 7.2.5.2 in NUREG/CR-6672 explains that 350 degrees C (662 degrees F) is a conservative temperature limit the SNF transportation industry typically uses for elastomeric seals. Section 7.2.5.2 of NUREG/CR-6672 also provides the rationale for the use of 750 degrees C (1,382 degrees F) as the fuel rod burst rupture temperature. These temperature limits are used in this study to determine if the cask seals or fuel rods would be compromised under any of the accident scenarios analyzed. If only the seals are compromised, a CRUD-only release ensues. If the fuel rods and seals are both compromised, a release of CRUD and spent fuel constituents would ensue. In either case, the consequences the release would have to be evaluated.

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[17] Computational fluid dynamics fire codes are capable of modeling flame behavior, soot formation, flow of hot gasses, and other physical phenomena found in actual fires.

4.2 Description of Accident Scenarios

4.2.1 Pool size

Three fire accident scenarios are analyzed for each rail cask and one for the truck cask. A hydrocarbon fuel pool that conforms to the HAC fire described in 10 CFR 71.73 is used as the basis for each scenario. This regulation specifies a hydrocarbon fuel pool that extends between 1 and 3 meters (3.3 and 10 feet) horizontally beyond the external surface of a cask. To ensure that the fire fully engulfed the large casks analyzed in this study, all fuel pools extended 3 meters (10 feet) from the sides of the cask.

4.2.2 Fire Duration

The fire duration postulated for the rail cask analyses is based on the capacity of a large rail tank car. Typical large rail tank cars can carry about 113,562 liters (30,000 gallons) of flammable or combustible liquids (i.e., hydrocarbon-based liquids). To estimate the duration of the fires, all of the fuel in the tank car is released and assumed to form a pool with the dimensions of a regulatory pool fire for the rail casks analyzed. That is, fuel pools extending horizontally 3 meters (10 feet) beyond the surfaces of the casks are used in the fire models. Provided that relatively small differences exist between the overall dimensions of the Rail-Steel cask and the Rail-Lead cask, these fuel pools are similar in size and are nominally 14 m×9 m (46 feet×29.5 feet). A pool of this size would have to be 0.9 meters (3 feet) deep to pool 113,562 liters (30,000 gallons) of liquid fuel, a condition extremely unlikely to occur in any accident scenario. If all of the fuel in this pool were to ignite and burn (i.e., none of the fuel runs off or soaks into the ground), the pool fire would burn for approximately 3 hours. This fire duration is estimated using a nominal hydrocarbon fuel recession (evaporation) rate of 5 mm (0.2 inches) per minute, which is typical of large pool fires (SFPE, 2002; Lopez et al., 1998; Quintiere, 1998). This large pool area could burn for up to 3 hours—although it would be even less likely—if the liquid fuel flows at exactly the right rate to feed and maintain the pool area for the duration of the fire. Since these pooling conditions are very difficult to obtain, the fire duration presented here is considered conservative. NUREG/CR-7034 corroborates that it is very difficult for a rail cask to be subjected to long duration, large fires (Adams et al., 2011). Nonetheless, a 3-hour fire that does not move over time, and is capable of engulfing a rail cask over the duration of the fire, is conservatively used for the analysis of the two rail casks in this study.

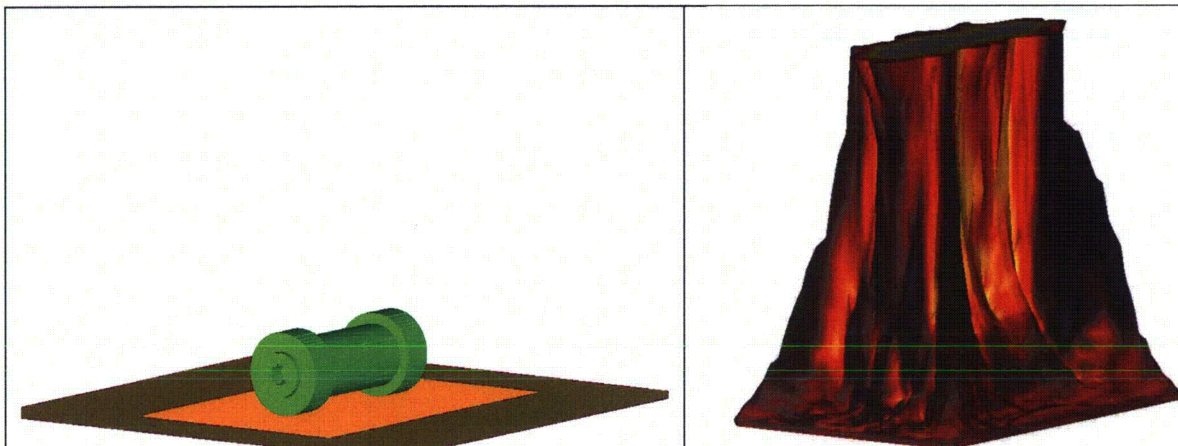
In the case of the Truck-DU cask, fire duration is based on the fuel capacity of a typical petroleum tank truck. One of these tank trucks can transport approximately 34,070 liters (9,000 gallons) of gasoline on the road. Provided that the overall dimensions of the Truck-DU cask are 2.3 meters×6 meters (7.5 feet×19.7 feet), a regulatory pool that extends horizontally 3 meters (10 feet) beyond the outer surface of the cask would be 8.3 meters×12 meters (27.2 feet×39.4 feet). To pool 34,070 liters (9,000 gallons) of gasoline in this area, the pool would have to be 0.3 meter (1 foot) deep, a configuration difficult to obtain in an accident scenario and therefore unlikely to occur. This type of pool fire would burn for a little more than 1 hour. As discussed for the rail cask pool fire, the other possibility of maintaining an engulfing fire which can burn for that duration is if, for example, gasoline flowed at the right rate to maintain the necessary fuel pool conditions. This scenario is also very unlikely. NUREG/CR-7035 corroborates the assertion that it is very difficult for a truck cask to be subjected to long duration, large fires (Adams and Mintz., 2011). Nevertheless, 1 hour is used as the duration of a fire not moving over time for the conservative analysis of the Truck-DU cask.

4.2.3 Hypothetical Accident Configurations for the Rail Casks

Three fire accident scenarios that differ from the regulatory HAC fire configuration are analyzed in this study for the rail casks. These are:

(1) Cask lying on the ground in the middle of (concentric with) a pool of flammable liquid (such as gasoline) as depicted in

(2) Figure 4-1. This scenario represents the case in which the liquid fuel spilled because of an accident flows to the location where the cask comes to rest following the accident and forms a large pool under (and concentric with) the cask.



Cask in the middle of flammable liquid fuel pool region(shown in orange)	Fire engulfing the cask

Figure 4-1 Cask lying on ground concentric with fuel pool

(3) Cask lying on the ground 3 meters (10 feet) away from the pool of flammable liquid (with the side of the cask aligned with the long side of the fuel pool) as depicted in Figure 4-2. This scenario represents the hypothetical case in which the fuel pool and the cask are separated by the width of one rail car. This could be the case in an accident in which the rail cars derail in an “accordion” fashion.

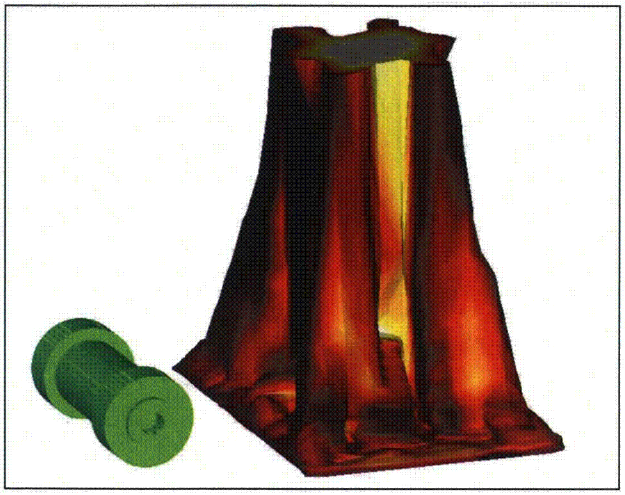


Figure 4-2 Cask lying on ground 3 meters (10 feet) from pool fire

(4) Cask lying on the ground 18 meters (60 feet) from the pool of flammable liquid (with the side of the package aligned with the long side of the fuel pool) as depicted in Figure 4-3. This scenario represents the hypothetical case in which the pool of flammable liquid and the cask are separated by the length of one rail car. This represents an accident in which the separation between a tank car carrying flammable liquid and the railcar carrying the SNF package is maintained (the distance of a buffer rail car, which is always required when radioactive and flammable/hazardous liquids are transported on the same train[18]) after the accident. For this scenario, the most damaging cask position is assumed (i.e., the side of the cask is assumed to face the fire).

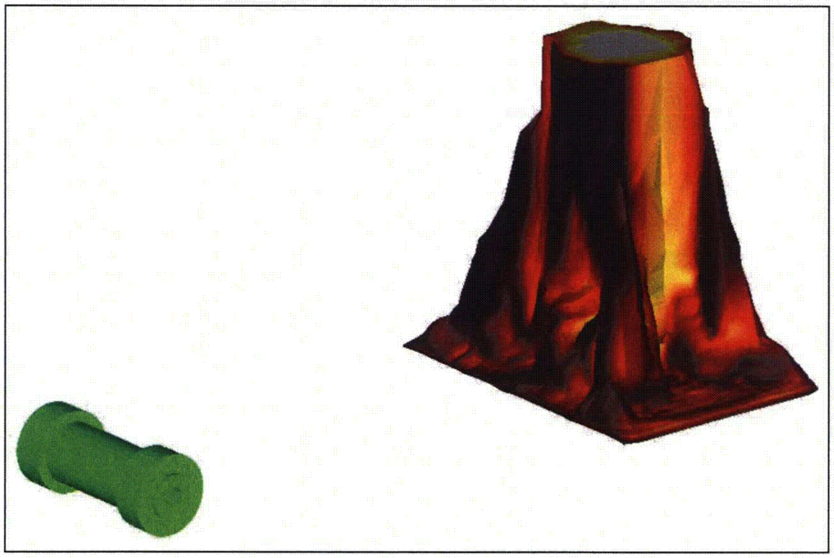


Figure 4-3 Cask lying on ground 18 meters (60 feet) from pool fire

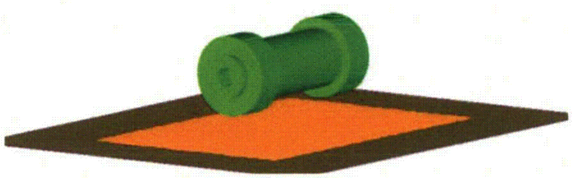
[18] 49 CFR 174.85

For each scenario, calm wind conditions leading to a vertical fire are assumed. Only the cask and the fuel pool are represented for the analysis. For conservatism, objects that would be present and could shield or protect the cask from the fire (i.e., such as the conveyance or other rail cars) are not included. All analyses include decay heat from the cask content.

Before the accident scenarios were analyzed, two additional 30-minute regulatory HAC fire analyses were performed for each rail cask based on conditions described in 10 CFR 71.73. In the first analysis, a commercially-available FE heat transfer code is used to apply an 800 degrees C (1,475 degrees F) uniform-heating fire condition to the casks. In the second analysis, a benchmarked computational fluid dynamics (CFD) computer model with radiation heat transfer is used.

In the computer model, each cask is positioned 1 meter above the fuel pool (as described in 10 CFR 71.73) and a realistic fire fully engulfs the cask as shown in

Figure 4-4. The FE uniform heating analyses results were compared to those in the SARs to ensure that the cask models used in these analyses were representative. The CFD fire analyses results are compared to the results obtained from the uniform-heating FE analyses to demonstrate that the realistic CFD fire imposes conditions similar to uniform heating.



Cask elevated 1 m (3.3 feet) above flammable liquid fuel pool region (shown in orange)

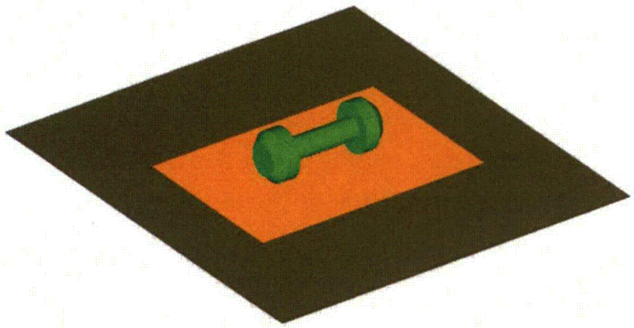
Regulatory fire engulfing the cask

Figure 4-4 Regulatory pool fire configuration

4.2.4 Hypothetical Accident Configuration for the Truck Cask

In the case of the truck cask, only the most severe hypothetical accident configuration (i.e., the cask is assumed to be concentric with a flammable fuel pool and is fully engulfed by fire) is analyzed because none of the temperature limits were reached and the offset fire scenarios would be less severe.

Figure 4-5 presents this hypothetical accident configuration.



Cask in the middle of flammable liquid fuel pool region (shown in orange)

Fire engulfing the cask

Figure 4-5 Truck-DU cask lying on ground concentric with fuel pool

4.3 Analysis of Fire Scenarios Involving Rail Casks

Advanced computational tools generated the data necessary for this risk study. Heat transfer from the fire to the cask body was simulated for hypothetical fire accidents. Two computer codes, including all the relevant heat transfer and fire physics, were used in a coupled manner. This allows for the simultaneous detailed modeling of realistic external fire environments and heat transfer within the cask's complex geometry. This section contains brief descriptions of the models and detailed information on the computer models, including material properties, geometry, and boundary conditions. Appendix IV presents the assumptions used for model generation and subsequent analyses.

This section presents the results from the fire and heat transfer analyses performed on the Rail-Steel and Rail-Lead casks. The scale in the temperature distribution plots of all the Rail-Steel cask analysis results are the same to make comparisons easier. The same is done for the Rail-Lead cask plots.

Results are presented in the following order:

(1) 800 degrees C (1,475 degrees F) uniform heating exposure for 30 minutes (based on 10 CFR 71.73)

(2) 30-minute CFD pool fire using the container analysis fire environment (CAFE) code (based on 10 CFR 71.73)

(3) 3-hour container analysis fire analysis (CAFE) pool fire (cask on ground concentric with pool)

(4) 3-hour CAFE pool fire (cask on ground 3 meters from pool)

(5) 3-hour CAFE pool fire (cask on ground 18 meters from pool)

4.3.1 Simulations of the Fires

Fire simulations are performed with the CAFE code (Suo-Anttila et al., 2005). CAFE is a CFD and radiation heat transfer computer code capable of realistically modeling fires that is coupled to a commercially-available FE analysis computer code to examine the effects of fires on objects. CAFE has been benchmarked against large-scale fire tests specifically designed to obtain data for calibration of fire codes (del Valle, 2008; del Valle et al., 2007; Are et al., 2005; Lopez et al., 2003). Appendix IV contains details on the benchmark exercises performed to ensure that proper input parameters are used to realistically represent the engulfing and offset fires assumed in this study.

4.3.2 Simulations of the Rail Casks

The heat transfer within the Rail-Steel and the Rail-Lead casks is modeled with the computer code MSC PATRAN-Thermal (P-Thermal) (MSC, 2008). This code is commercially available and may be used to solve a variety of heat transfer problems. P-Thermal has been coupled with CAFE, allowing for a refined heat transfer calculation within complex objects, such as spent fuel casks, with realistic external fire boundary conditions.

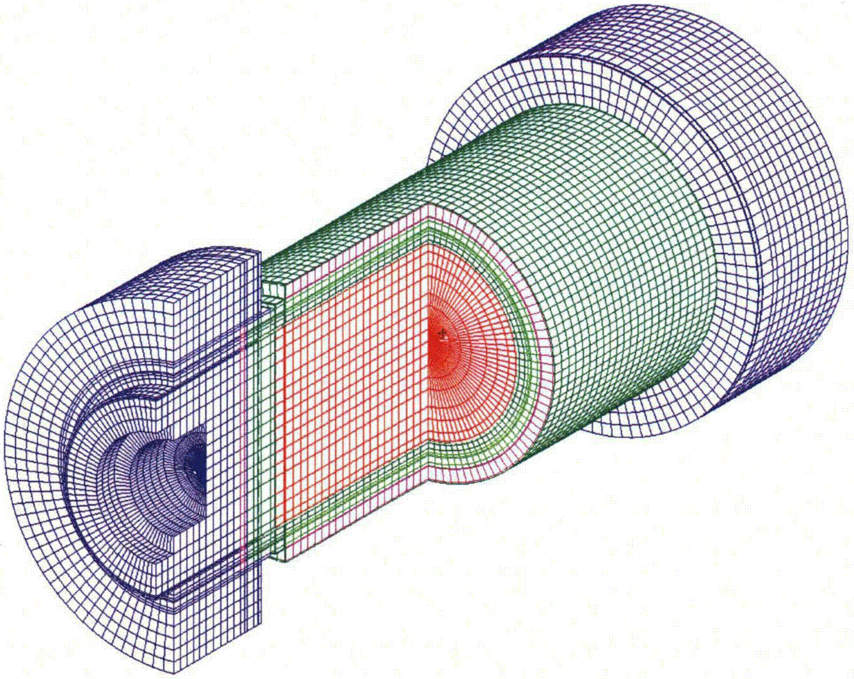
Both the Rail-Steel and Rail-Lead casks have a polymeric neutron shield that is assumed to melt completely and be replaced by air at its operational temperature limit (see Appendix IV).

The Rail-Lead cask has a lead gamma shield that can change phase upon reaching its melting temperature. Unlike the neutron shield, the thermal energy absorbed in the process of melting the gamma shield is included in the analyses. The thermal expansion effects of the lead are not included in the heat transfer calculations but are considered in the estimation of the gamma shielding reduction. Thick multilayered carbon steel walls provide the gamma shielding in the Rail-Steel cask. Therefore, melting is not a consideration for this cask under any condition to which it is exposed.

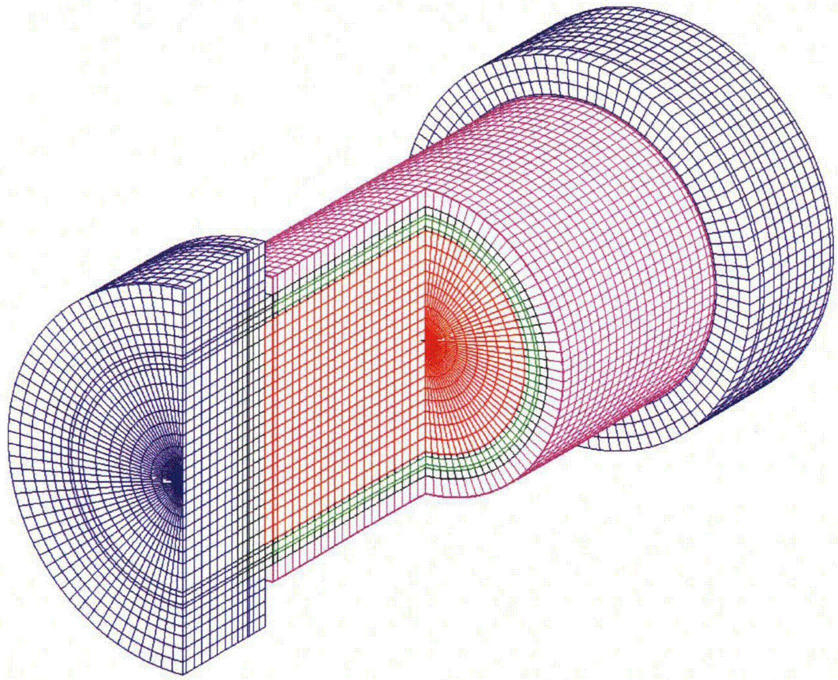
Impact limiters are modeled as undamaged (not deformed). The Rail-Steel cask has aluminum honeycomb impact limiters and the Rail-Lead cask has wood impact limiters. Spaces between components are explicitly modeled in both casks because they could have a significant effect on the cask's thermal response. FE models of the two casks are shown in Figure 4-6 and Appendix IV presents details on cask modeling.

4.3.3 Simulation of the Spent Nuclear Fuel Region

The interior of the package comprising the fuel basket and the fuel assemblies is not modeled explicitly. A homogenized SNF region, comprised of all materials and geometric features of the fuel basket and fuel assemblies, is represented as a solid cylinder inside the cask. The thermal response of the homogenized SNF region is similar to the overall response for the more detailed fuel basket model and assemblies reported in NUREG/CR-6886 (Adkins et al., 2006) and provides enough resolution for the purposes of this study. Appendix IV presents details on how the effective properties of the homogenized SNF region are determined and applied to the models.



Rail-Steel cask



Rail-Lead cask

Figure 4-6 Finite element models (cut views) of the two rail casks analyzed

4.3.4 Rail-Steel Cask Results

Results for the Rail-Steel cask are presented in the order specified at the beginning of Section 4.3 in Figure 4-7 through Figure 4-21. Figure 4-7 through Figure 4-10 contain the temperature distribution and transient temperature response of key cask regions for the regulatory 800 degrees C uniform heating and regulatory CAFE fire.

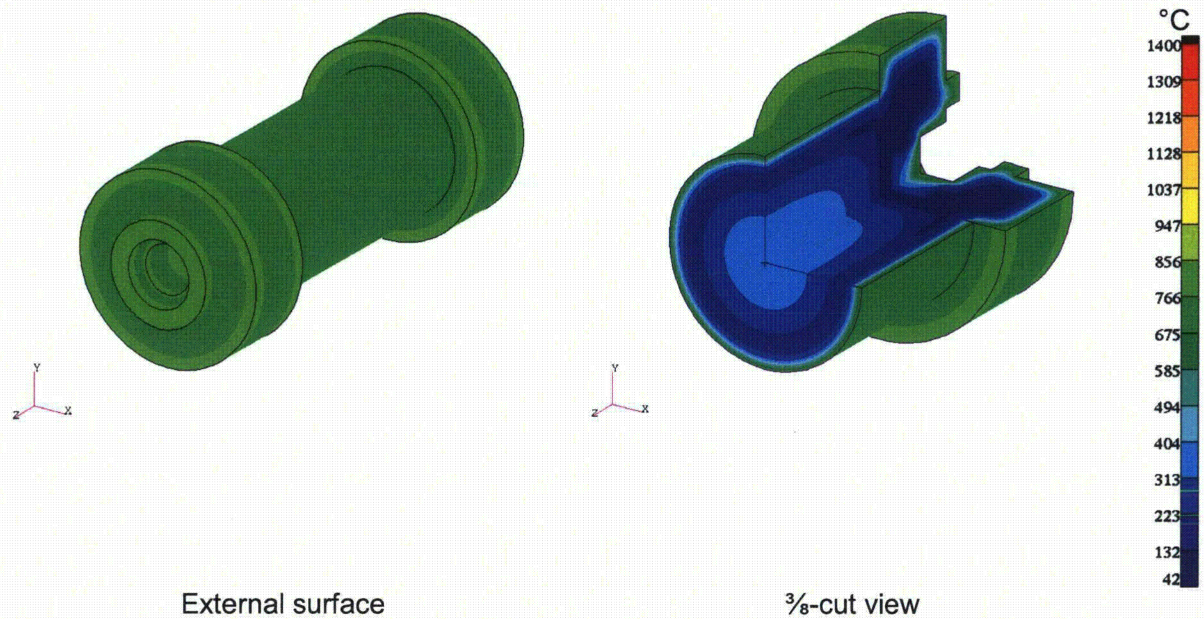


Figure 4-7 Temperature distribution of the Rail-Steel cask at the end of the 30-minute 800°C (1472°F) regulatory uniform heating

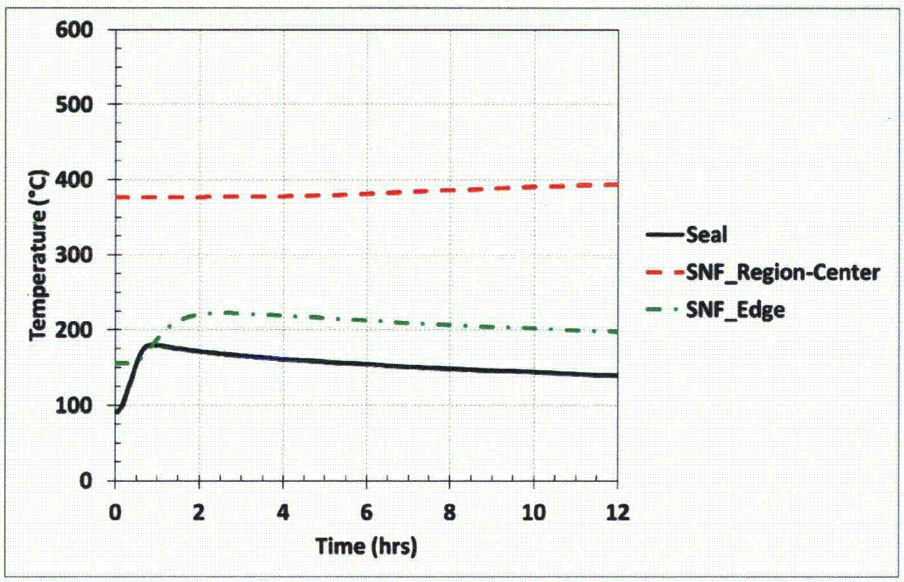


Figure 4-8 Temperature of key cask regions, Rail-Steel cask undergoing regulatory uniform heating

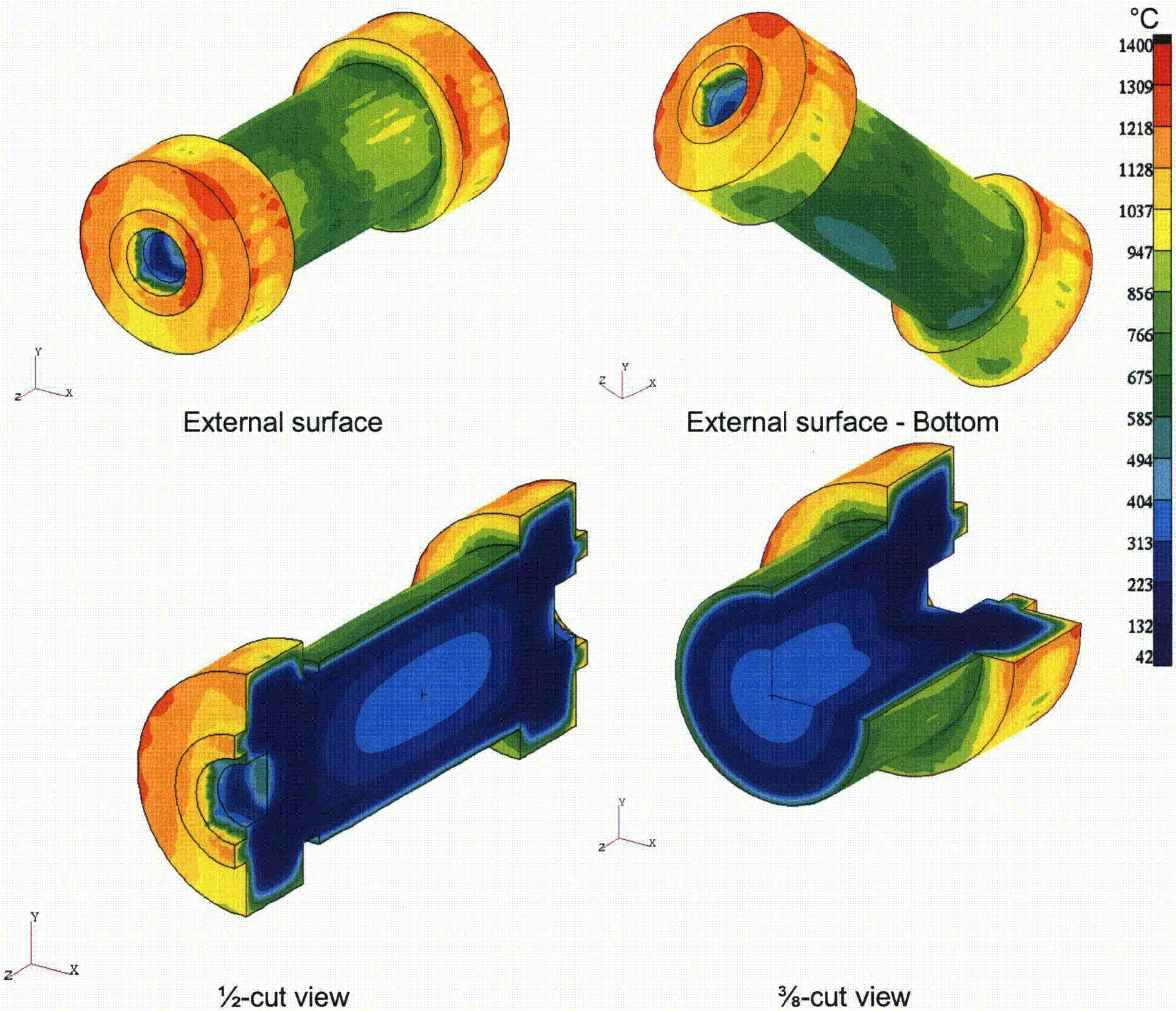


Figure 4-9 Temperature distribution of the Rail-Steel cask at the end of the 30-minute regulatory CAFE fire

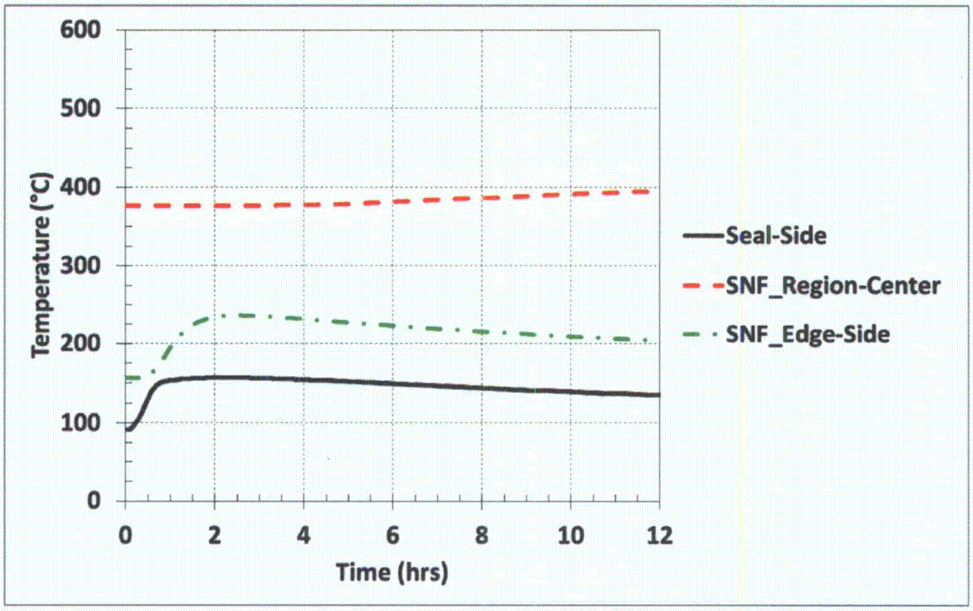


Figure 4-10 Temperature of key cask regions, Rail-Steel cask undergoing regulatory CAFE fire

As modeled using FE, the uniform external heating produces an even temperature response around the circumference of the cask. However, the realistic uneven fire heating of the exterior, as modeled using CAFE, produces temperatures that vary around the circumference. For comparison, results from the uniform (FE) regulatory fire simulation are plotted against the hottest regional temperatures obtained from the regulatory CAFE (nonuniform) fire simulation.

Figure 4-11 presents this thermal response comparison and illustrates that the uniform heating thermal environment described in 10 CFR 71.73 heats up the seal region of the Rail-Steel cask more than a real fire, even though a real fire can heat the cask to a temporary and localized thermal environment greater than 800 degrees C. A real fire applies a time- and space-varying thermal load to an object that it engulfs. In particular, large fires have an internal region where fuel exists in the form of gas, but not enough oxygen is available for that fuel to burn. That region is typically called the "vapor dome." The lack of oxygen in the vapor dome is attributed to poor air entrainment in larger diameter pool fires, where most of the oxygen is consumed in the plume region's perimeter. Since combustion is inefficient inside the vapor dome, this region remains cooler than the rest of the fire envelope. Thus, the presence of regions cooler than 800 degrees C within a real fire makes it possible for fires with peak flame temperatures above 800 degrees C to have an overall effect on internal temperatures of a thermally massive object that is similar to those obtained by applying a simpler heating condition, such as the one specified in 10 CFR 71.73.

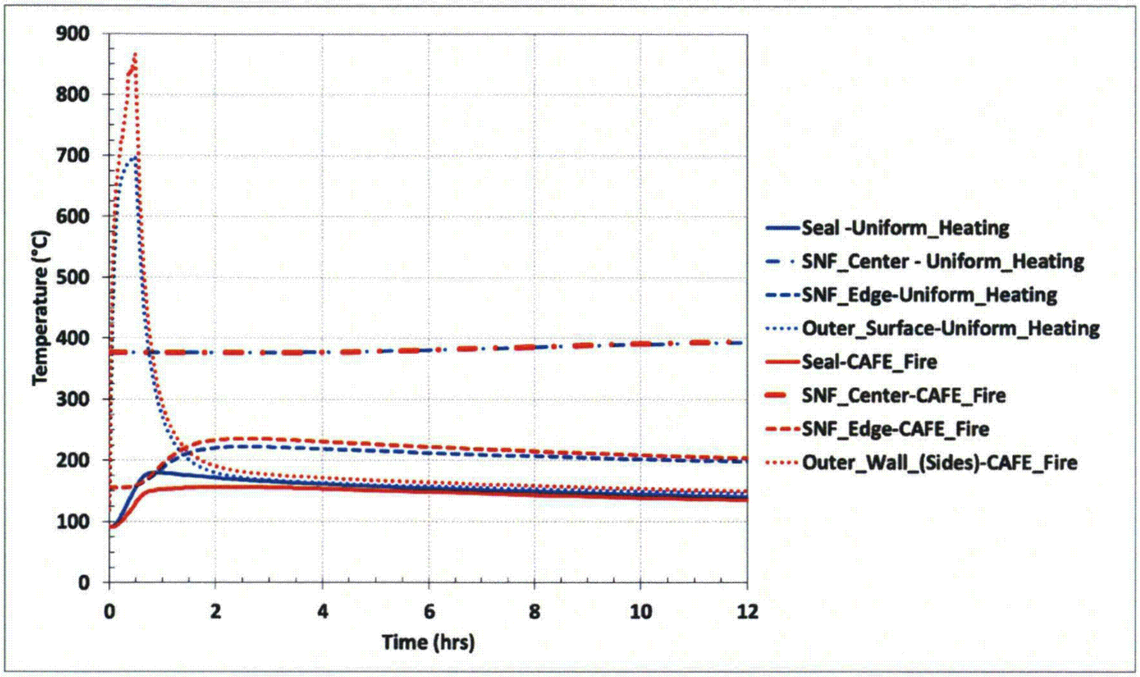
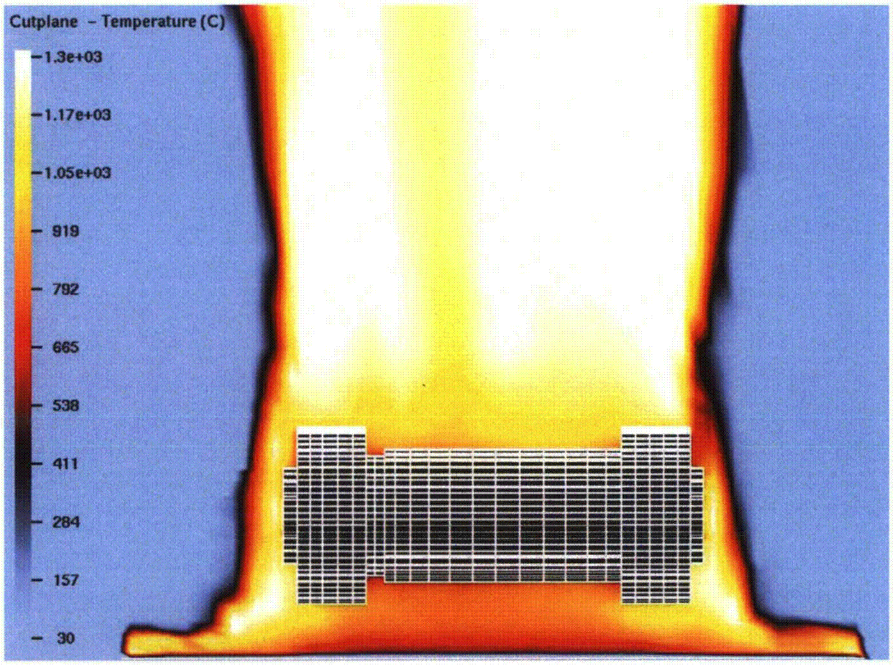
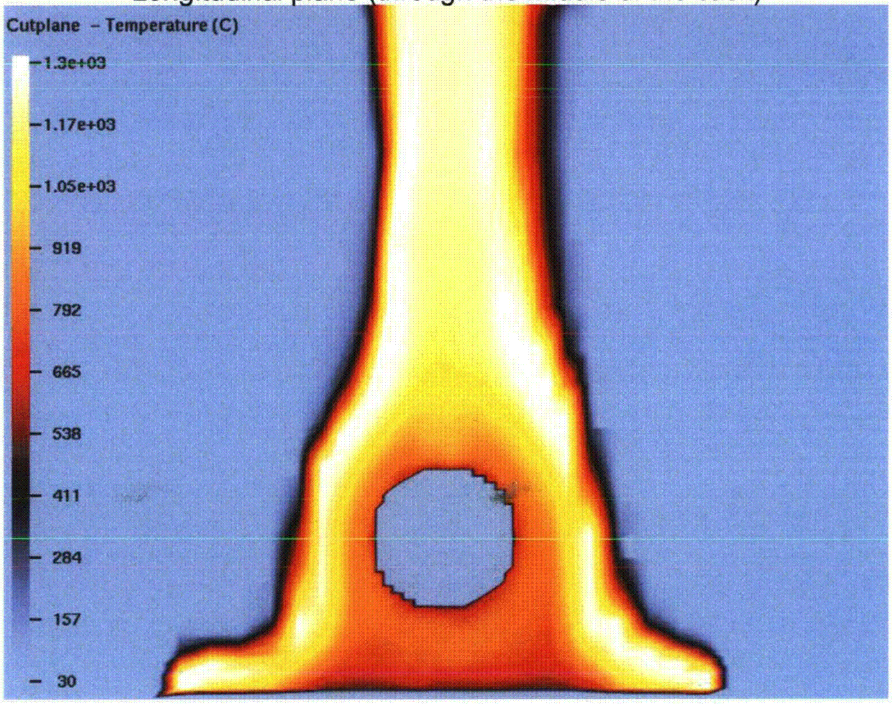


Figure 4-11 Comparison of regulatory fire analysis for Rail-Steel cask: Uniform heating vs. CAFE fire. The "Outer Wall" CAFE curve is the average of the two "Outer Surface" CAFE curves for the sides of the cask as presented in Appendix IV, Figure IV-11.

The vapor dome effects on the temperature distribution within a fire and the concentration of unburned fuel available in the vapor dome for the CAFE regulatory analysis is illustrated in Figure 4-12 and Figure 4-13.



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

Figure 4-12 Gas temperature plots from the regulatory CAFE fire analysis

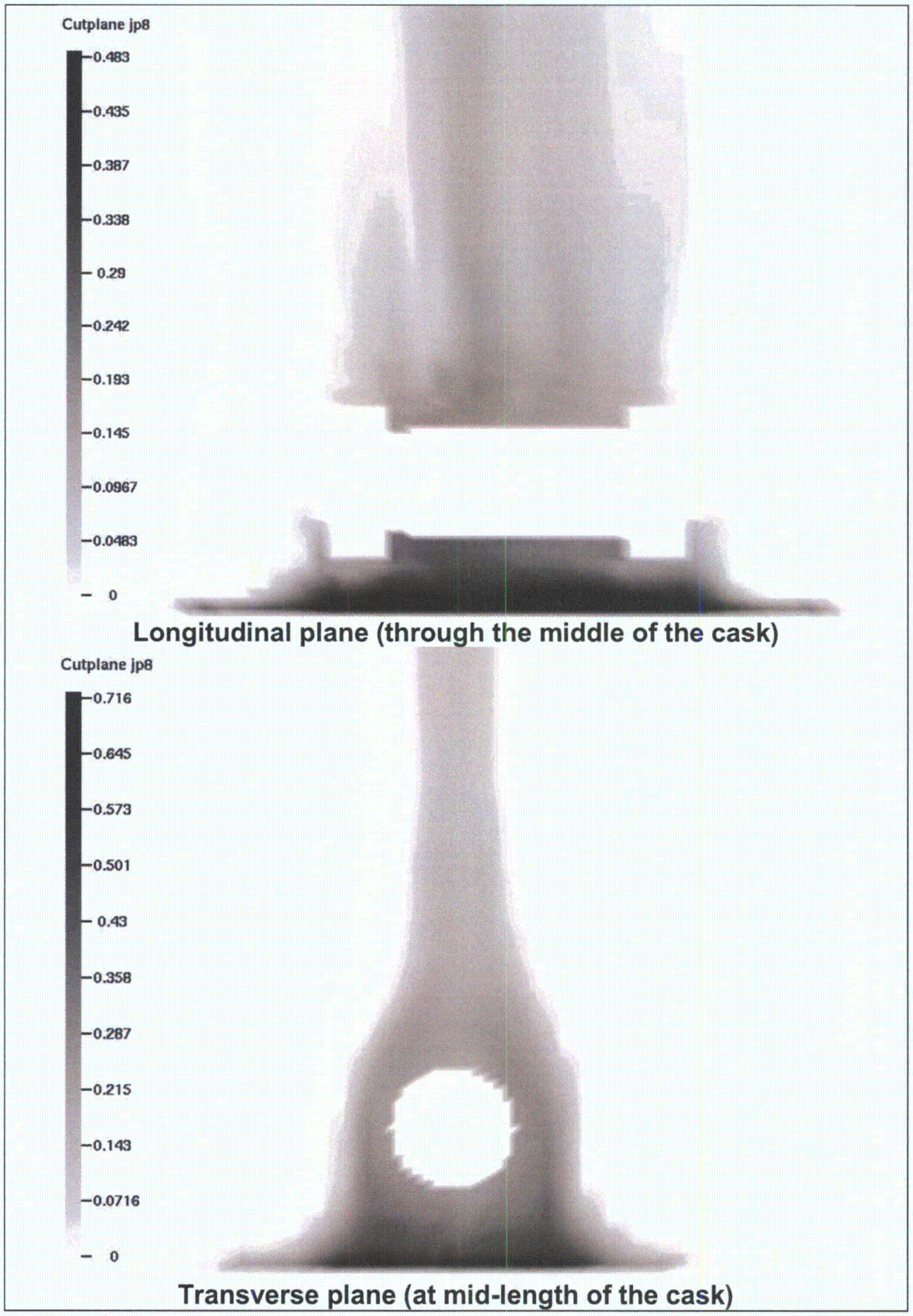


Figure 4-13 Fuel concentration plots from the regulatory CAFE fire analysis

Note that the plots in Figure 4-12 and Figure 4-13 are snapshots of the distributions at an arbitrary time during fire simulation. In reality, the fire moves slightly throughout the simulation, causing these distributions to vary over time. Nevertheless, these plots show representative distributions for the cask and fire configuration shown.

Appendix IV provides additional plots with more information about temperature distributions at different locations in the cask.

Results from the analysis of the cask lying on the ground and concentric with a pool fire that burns for 3 hours are presented in Figure 4-14 and Figure 4-15. As in the regulatory configuration, in which the cask is elevated 1 meter above the hydrocarbon fuel pool, the vapor dome affected the temperature distribution of the cask. This is evident by the cooler temperatures observed at the bottom of the cask. In this scenario, even after 3 hours in the fire, temperatures at the bottom of the package are cooler than temperatures observed in the regulatory configuration. However, the top of the cask in this configuration heats up more than the rest of the cask. This differs from what is observed in the regulatory configuration, in which the hotter regions are found on the sides of the cask.

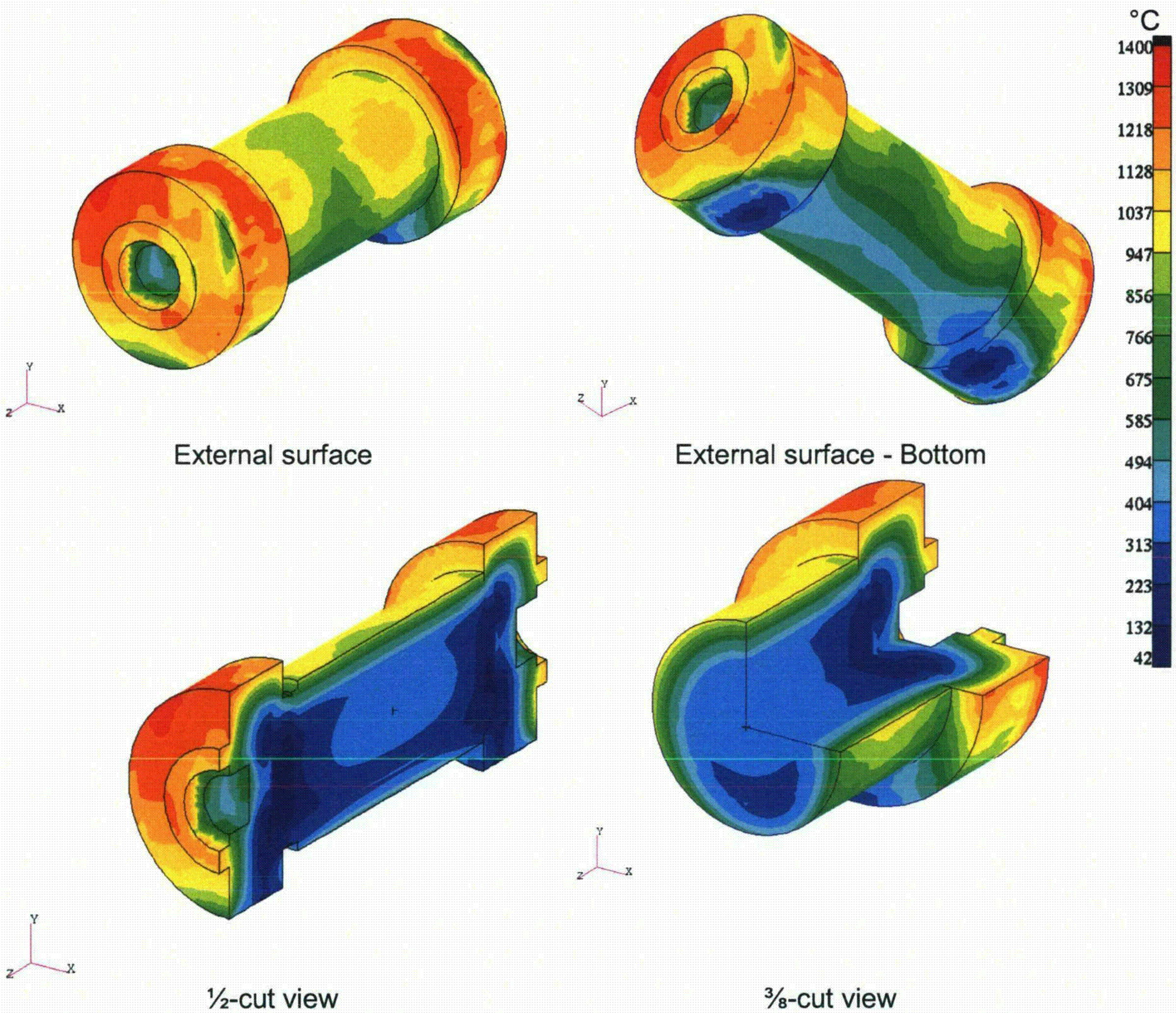


Figure 4-14 Temperature distribution of the Rail-Steel cask at the end of the 3-hour concentric CAFE fire with cask on ground

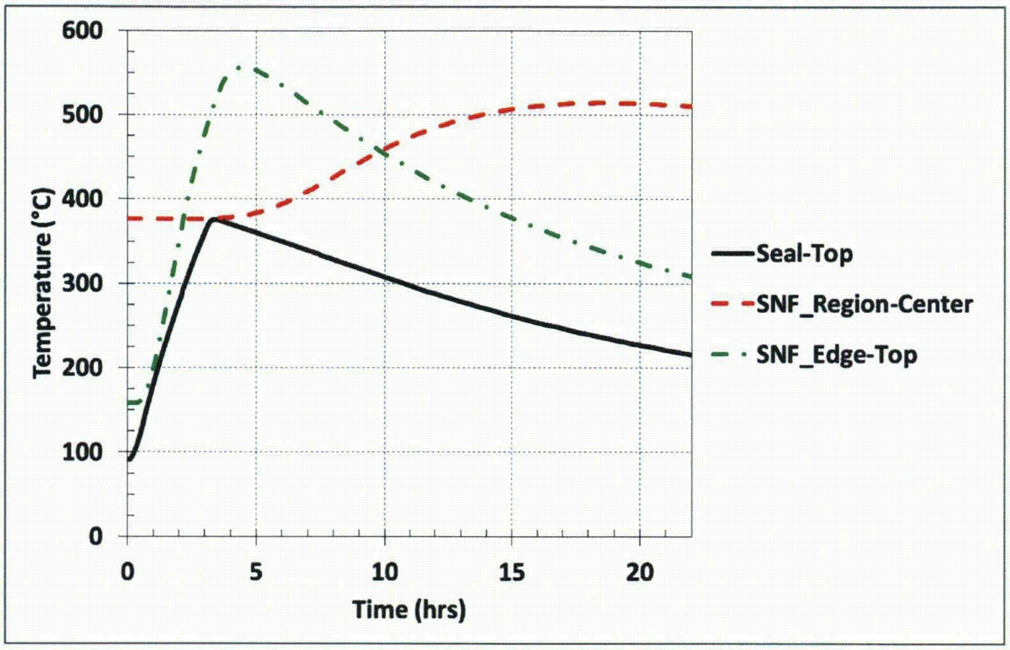
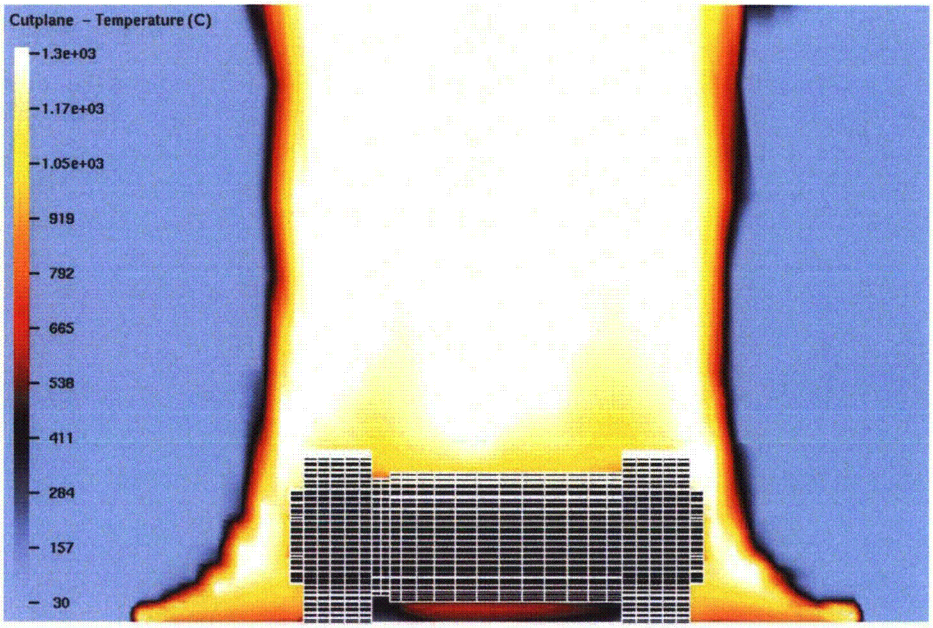
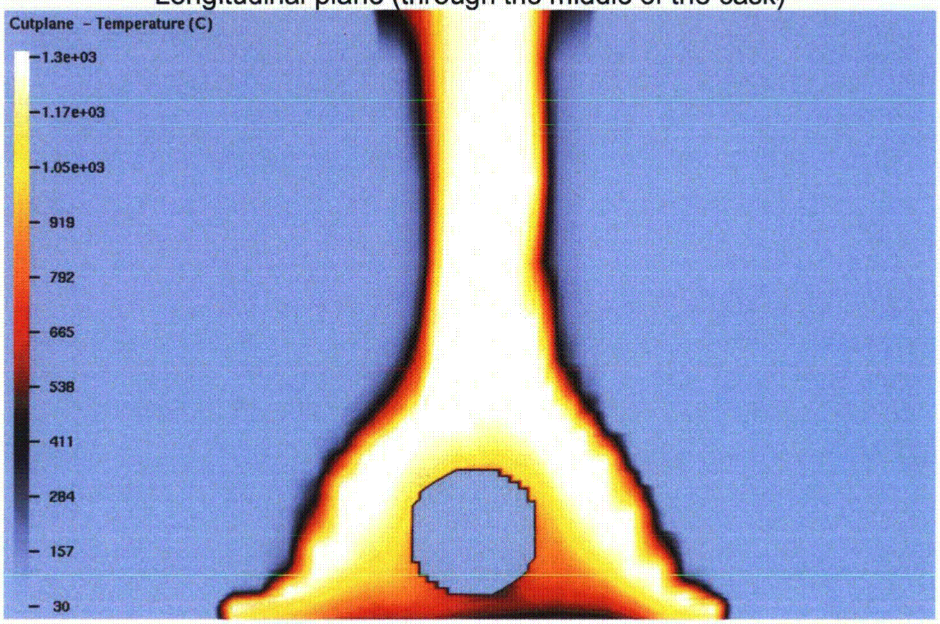


Figure 4-15 Temperature of key cask regions, Rail-Steel cask with cask on ground, concentric fire

Figure 4-16 and Figure 4-17 are the fire temperature distribution and fuel concentration plots at an arbitrary time during the CAFE fire simulation. In this case, the concentration of unburned fuel under the cask is high; therefore, the fire temperature under the cask is lower than what is observed in the regulatory configuration.

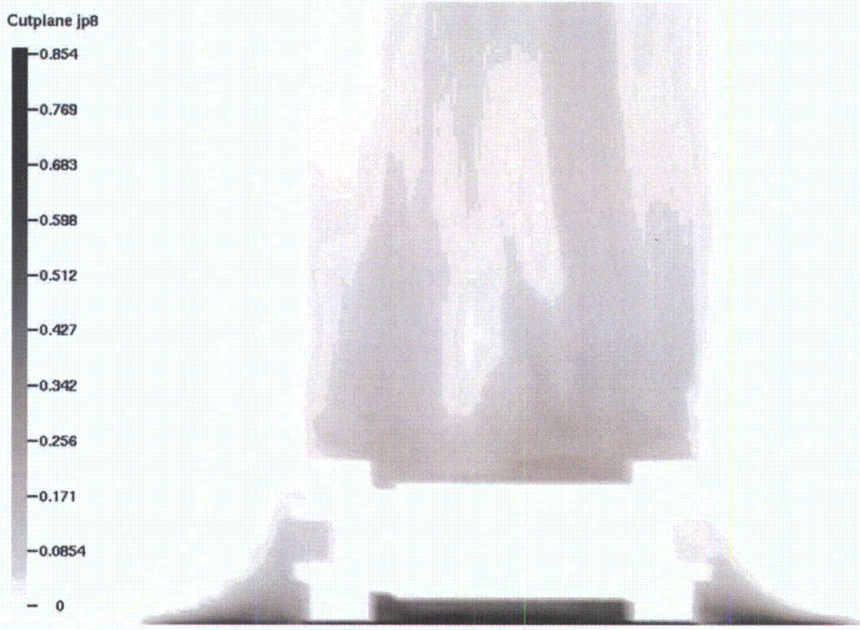


Longitudinal plane (through the middle of the cask)

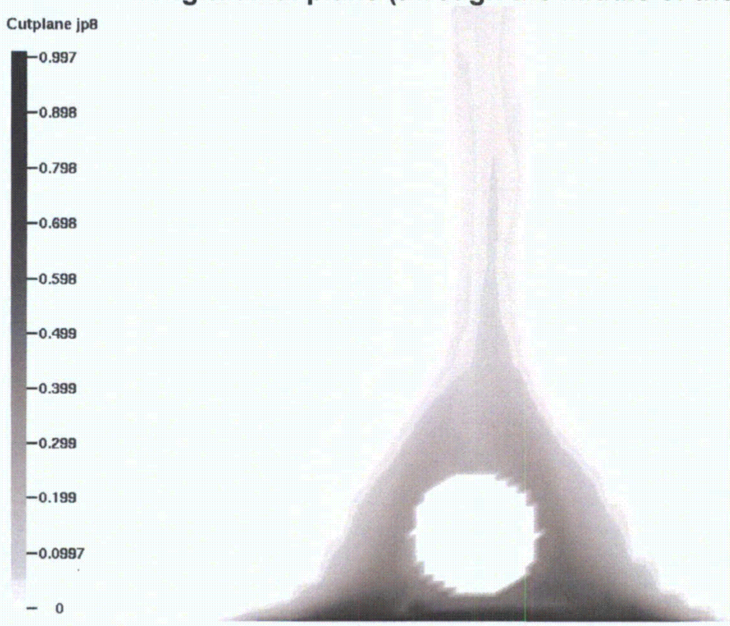


Transverse plane (at mid-length of the cask)

Figure 4-16 Gas temperature plots from the CAFE fire analysis of the cask on ground



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

Figure 4-17 Fuel concentration plots from the CAFE fire analysis of the cask on ground

Results of the offset fire analyses are summarized in Figure 4-18 through Figure 4-21. In the case of the 3-meter offset, the side of the cask facing the fire received heat by thermal radiation. The heat that the cask absorbed during the 3-hour exposure caused the cask temperature to rise, as depicted in Figure 4-18 and Figure 4-19. Similarly, the 18-meter offset fire caused the cask temperature to rise as illustrated in Figure 4-20 and Figure 4-21. These results show that offset fires, even as close to the cask as 3 meters, do not represent a threat to this thermally massive SNF transportation cask. The maximum temperatures observed in the seal and in the

SNF region did not reach their temperature limits. Therefore, offset fire scenarios will not cause this package to release radioactive material.

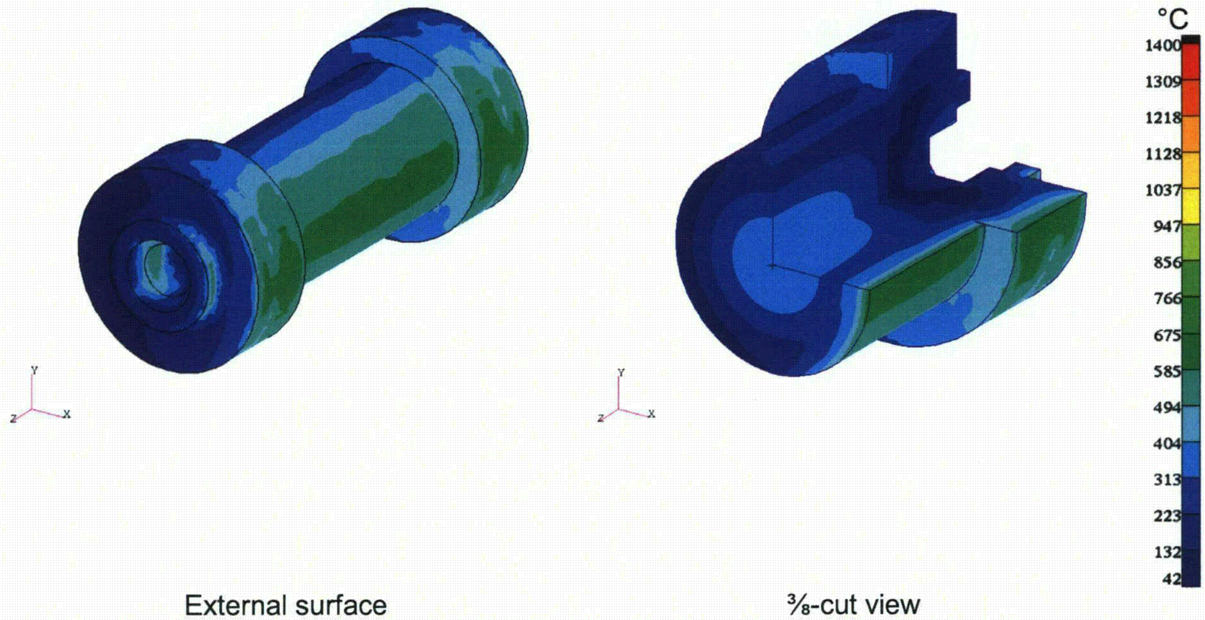


Figure 4-18 Temperature distribution of the Rail-Steel cask at the end of the 3-hour, 3-meter (10-foot) offset CAFE fire with cask on ground

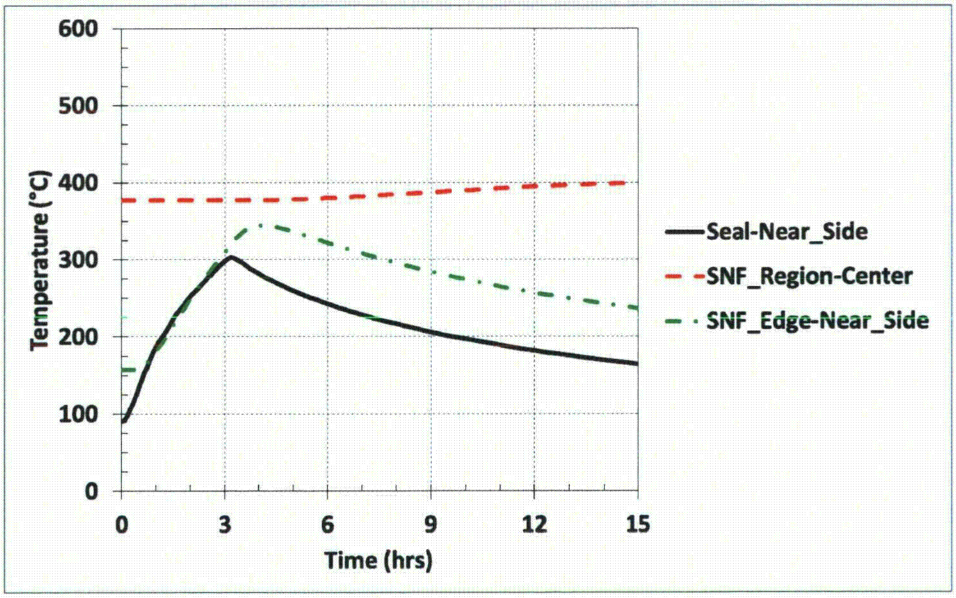


Figure 4-19 Temperature of key cask regions, Rail-Steel cask with Cask on ground, 3-meter (10-foot) offset fire

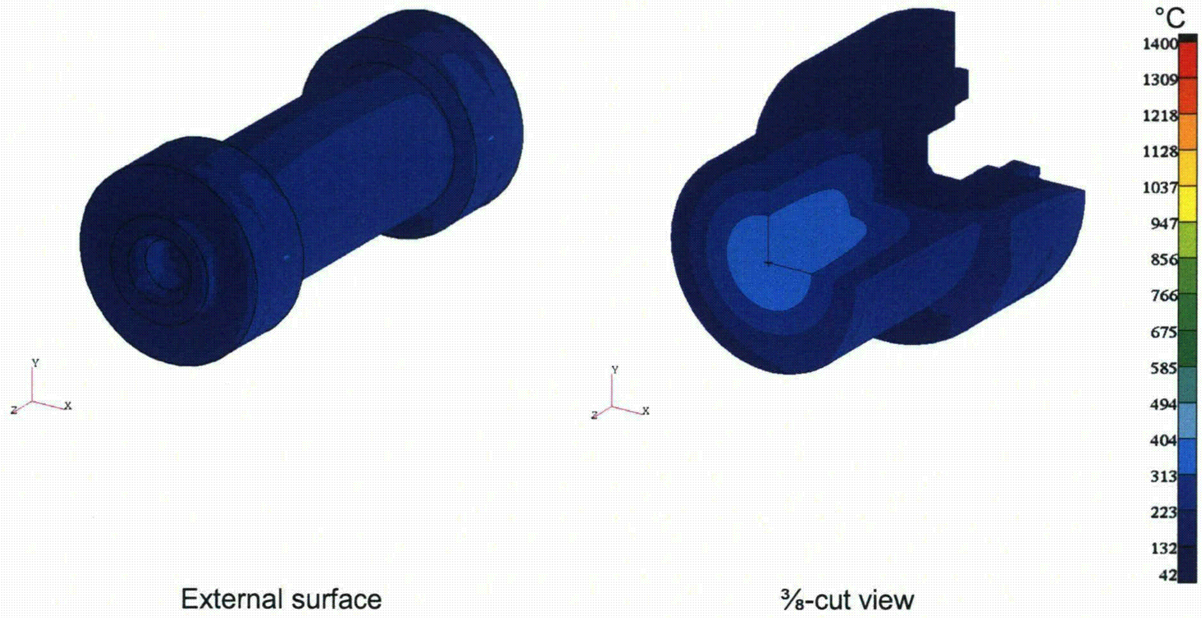


Figure 4-20 Temperature distribution of the Rail-Steel cask at the end of the 3-hour 18-meter (60-foot) offset CAFE fire with cask on ground

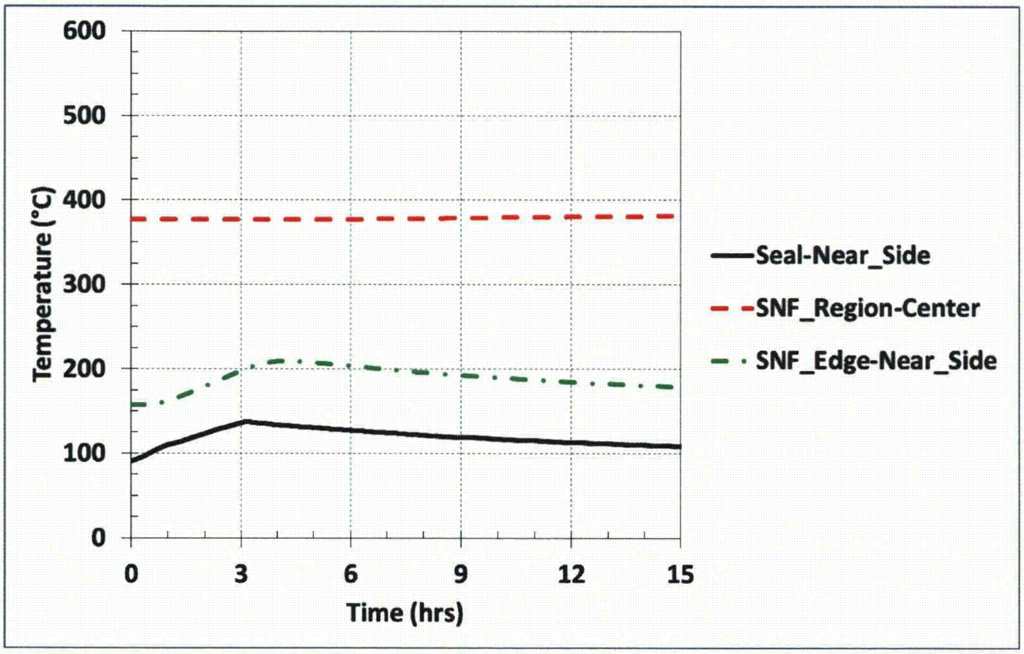


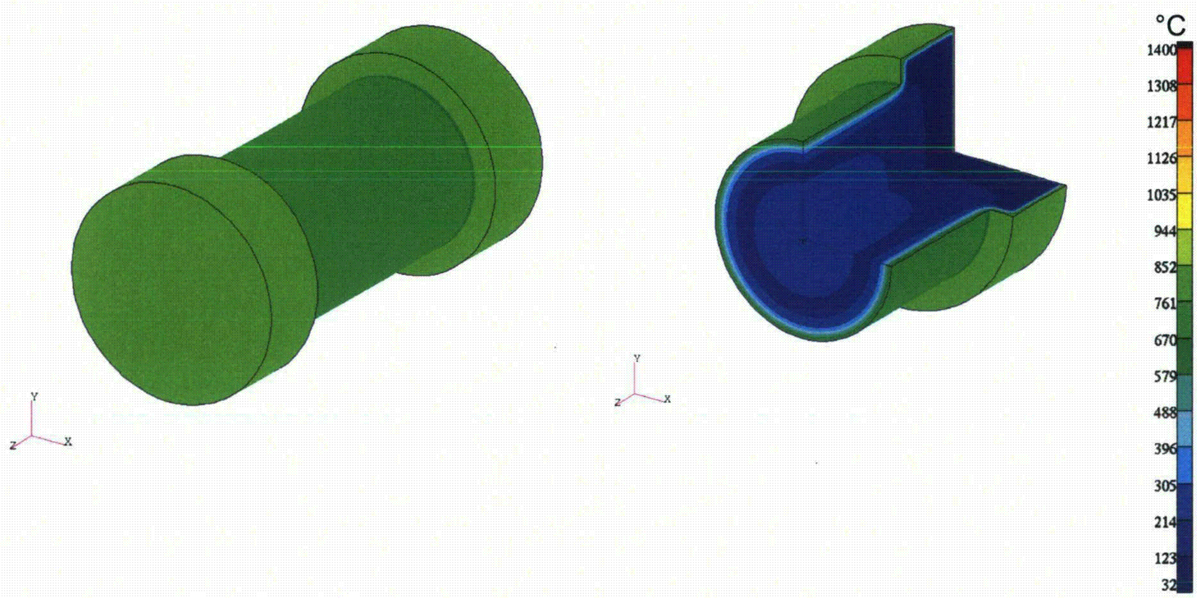
Figure 4-21 Temperature of key cask regions, Rail-Steel cask with cask on ground, 18-meter (60-foot) offset fire

Summary of Rail-Steel Cask Analysis Results

The results show that the Rail-Steel cask is capable of protecting fuel rods from burst rupture and of maintaining containment when exposed to the severe fire environments analyzed as part of this study. That is, while the neutron shield material is conservatively assumed to be absent during the fire accident, the SNF region stays below 750 degrees C (1,382 degrees F) and the seal region stayed under 649 degrees C (1,200 degrees F) for all the scenarios considered. Furthermore, this cask uses a welded canister that will not be compromised under these thermal loads. This cask will not experience loss of gamma shielding because the shielding is a thick multilayered carbon steel wall, which is not affected in a way that could reduce its ability to provide shielding.

4.3.5 Rail-Lead Cask Results

The thermal response of the Rail-Lead cask to the same fire environments discussed for the Rail-Steel cask is presented in this section. The 30-minute regulatory fire results are summarized in Figure 4-22 through Figure 4-26.



External surface ⅜-cut view

Figure 4-22 Temperature distribution of the Rail-Lead cask at the end of the 30-minute 800°C (1472°F) regulatory uniform heating

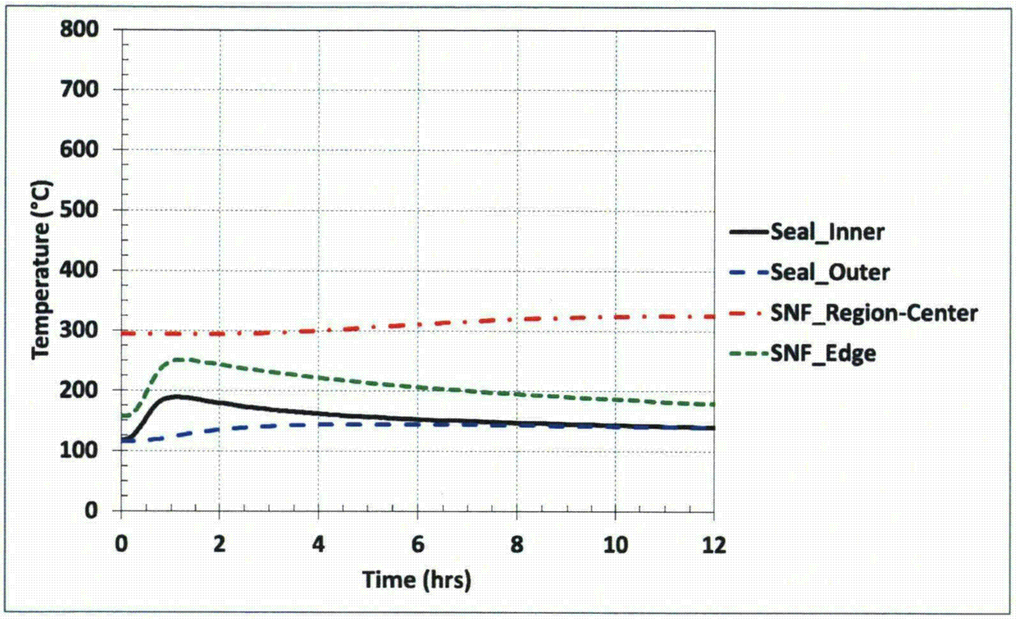


Figure 4-23 Temperature of key cask regions, Rail-Lead cask undergoing regulatory uniform heating

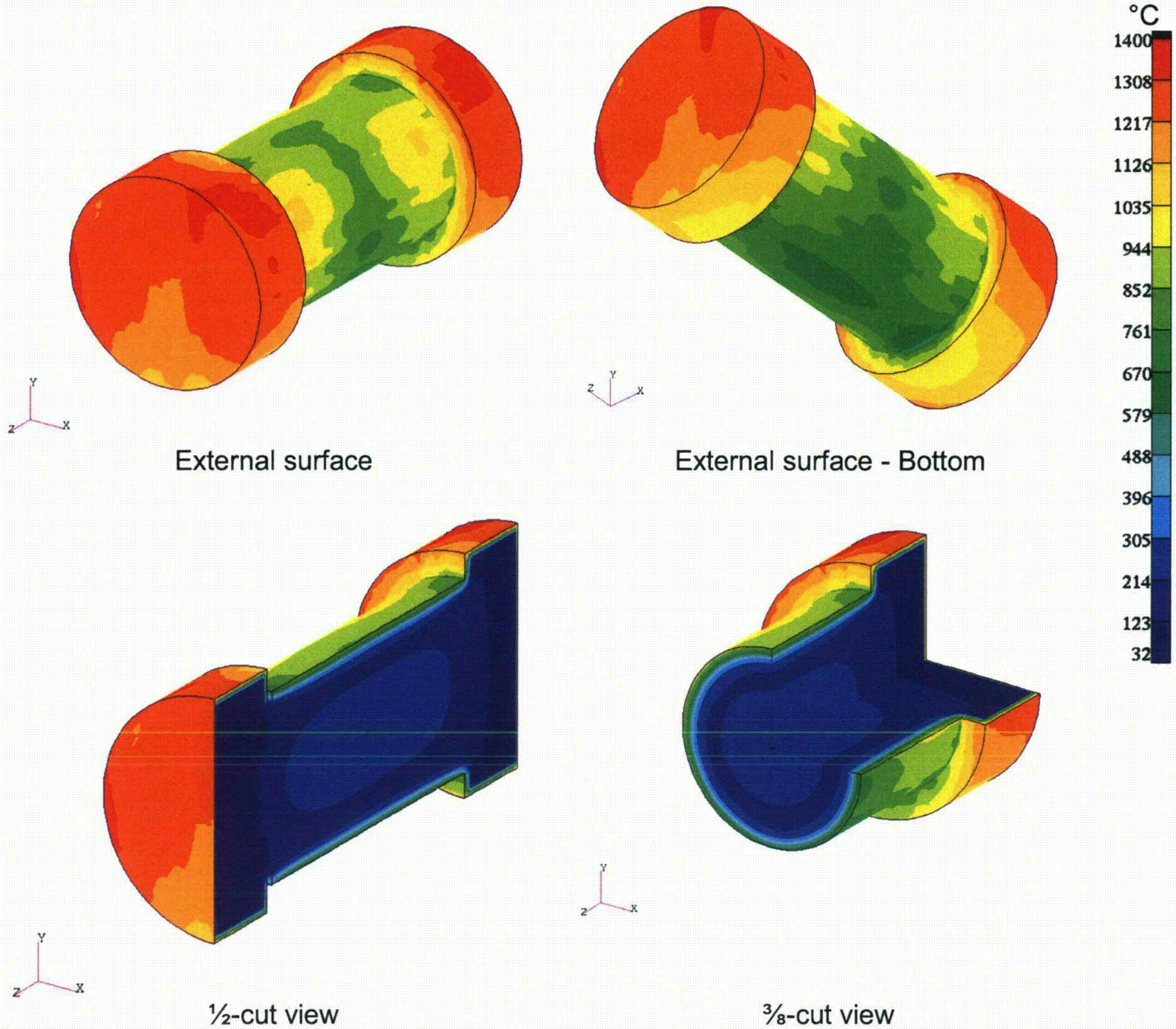


Figure 4-24 Temperature distribution of the Rail-Lead cask at the end of the 30-minute regulatory CAFE fire

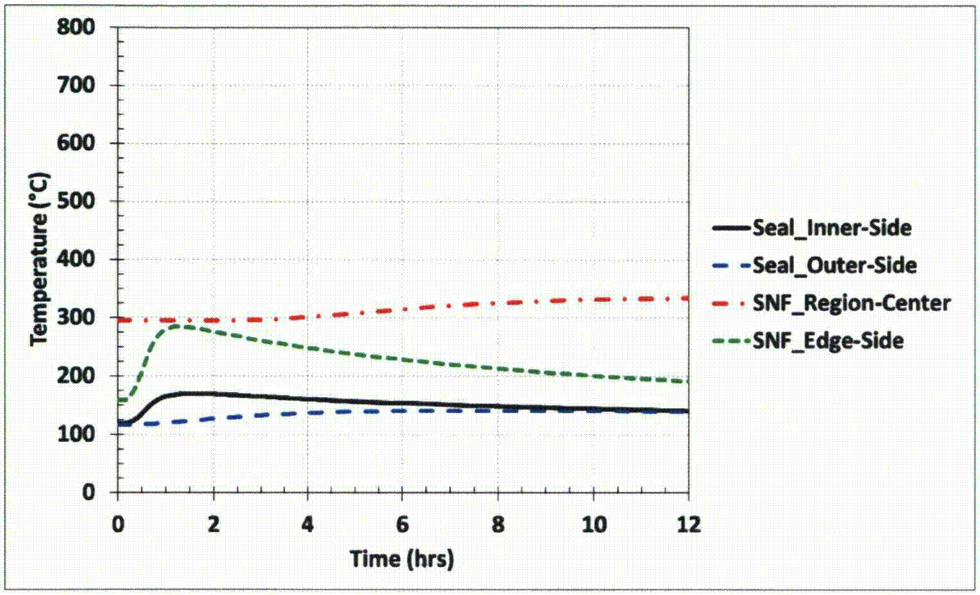


Figure 4-25 Temperature of key cask regions, Rail-Lead cask in regulatory CAFE fire

Results from the uniform regulatory fire simulation are plotted against the hottest regional temperatures from the CAFE (nonuniform) regulatory fire simulation. This plot is shown in Figure 4-26. As with the Rail-Steel cask, this figure illustrates that the uniform heating thermal environment described in 10 CFR 71.73 heats the seal region of the Rail-Lead cask more than a nonuniform real fire may, even though a real fire may impart to the cask a localized thermal environment greater than 800 degrees C (1,472 degrees F).

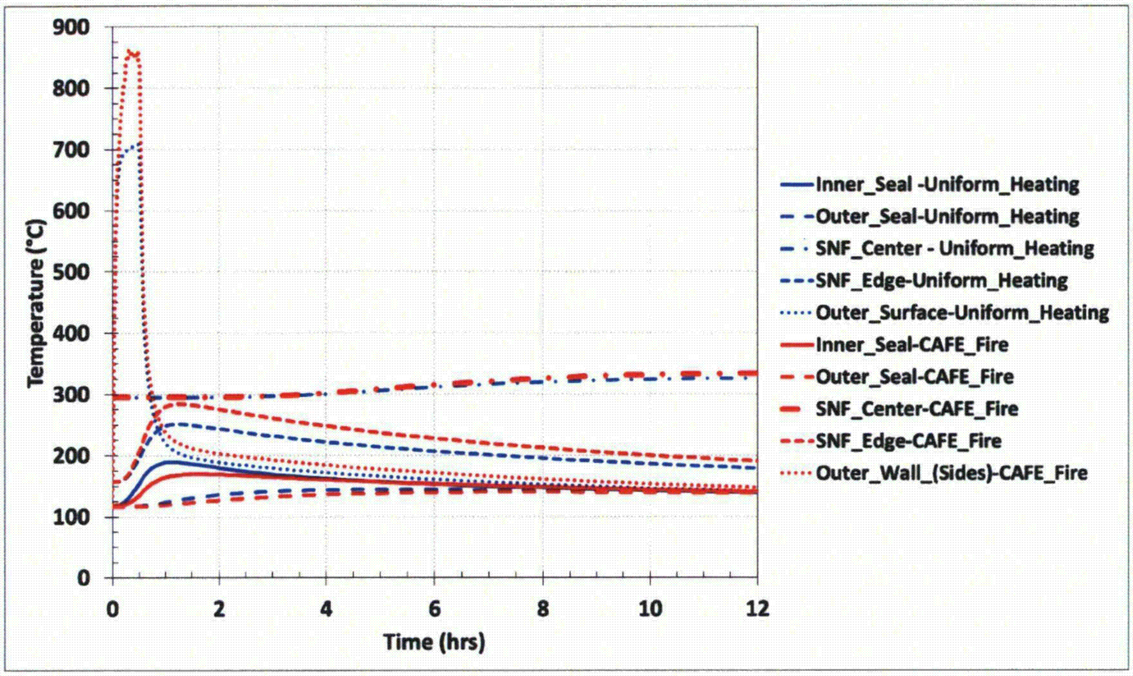


Figure 4-26 Comparison of regulatory fire analysis for Rail-Lead cask: Uniform heating vs. CAFE fire. The "Outer Wall" CAFE curve is the average of the two "Outer Surface" CAFE curves for the sides of the cask as presented in Appendix IV, Figure IV-21.

Analyses results of the cask lying on the ground heated by the concentric and offset fires are summarized in Figure 4-27 through Figure 4-32. These plots show similar trends to those observed in the Rail-Steel cask for the same configurations.

Two of the scenarios analyzed show melting of the lead gamma shield in the Rail-Lead cask. Lead melts at 328 degrees C (622 degrees F). During that process, it absorbs (stores) heat while maintaining its temperature relatively constant at 328 degrees C. As a result, the heatup rate of parts of the cask slows down while the lead melts. This is why the curve of the region inward from the gamma shield region (i.e., the edge of the SNF region) in Figure 4-28 and Figure 4-30 shows a change in slope at about 328 degrees C. This effect is seen more clearly in the slower heating case shown in Figure 4-30. Once the lead melting process is complete, the cask resumes heating up if the external source is still at a higher temperature. Note that a similar effect is observed when the lead solidifies at 328 degrees C during the postfire cooling period. In this case, the cooling rate of portions of the cask slows down while the lead solidifies. This can also be clearly seen in Figure 4-30.

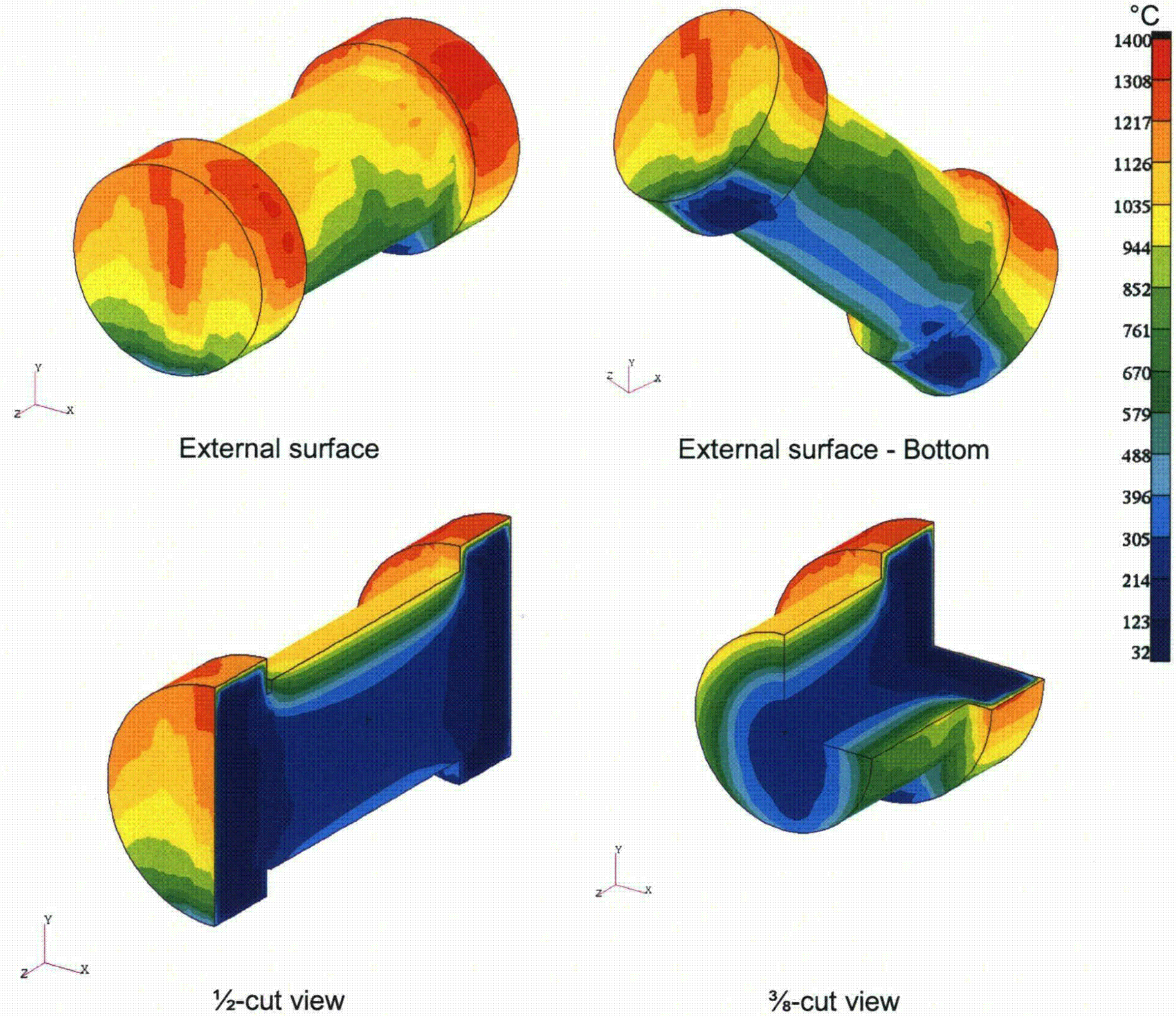


Figure 4-27 Temperature distribution of the Rail-Lead cask at the end of the 3-hour concentric CAFE fire with cask on ground

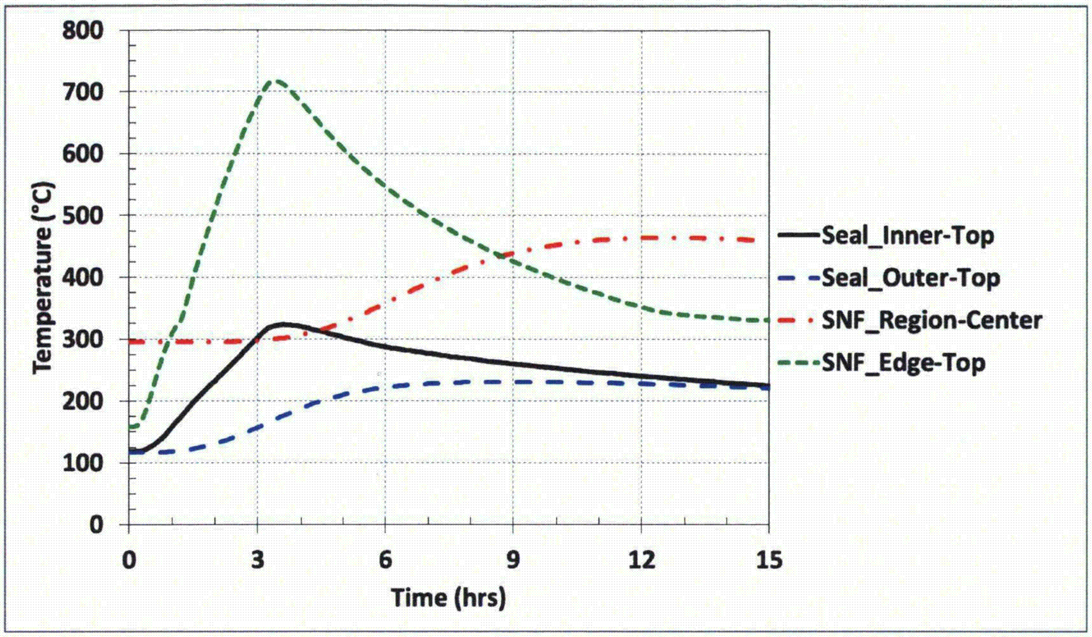


Figure 4-28 Temperature of key cask regions, Rail-Lead cask with cask on ground, concentric fire

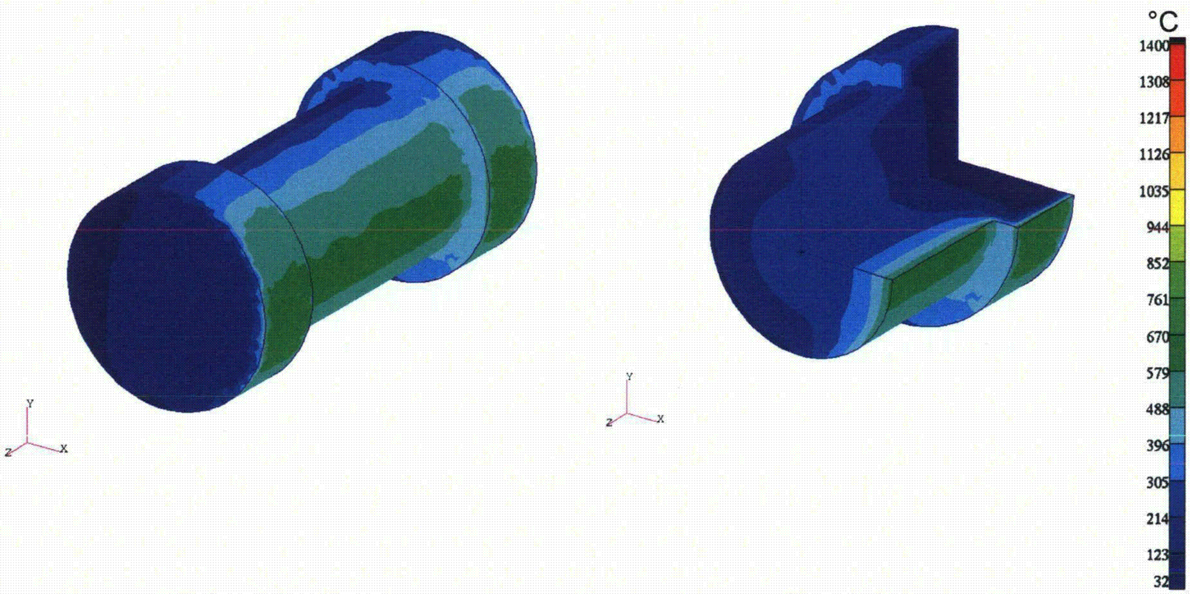


Figure 4-29 Temperature distribution of the Rail-Lead cask at the end of the 3-hour 3-meter (10-foot) offset CAFE fire with cask on ground

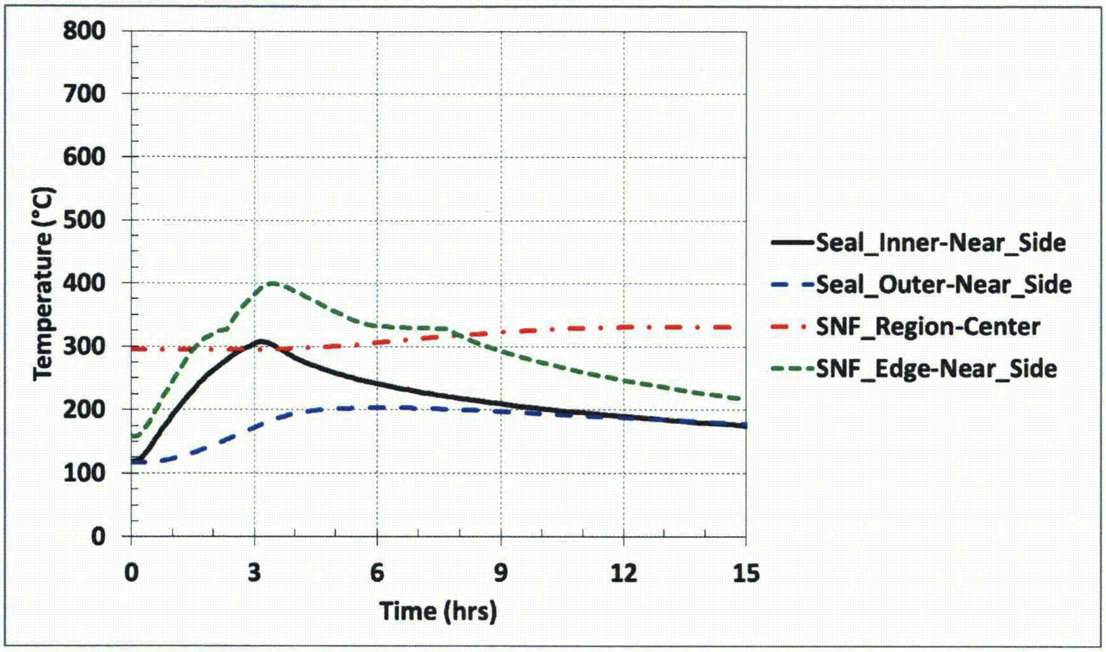


Figure 4-30 Temperature of key cask regions, Rail-Lead cask with Cask on ground, 3-meter (10-foot) offset fire

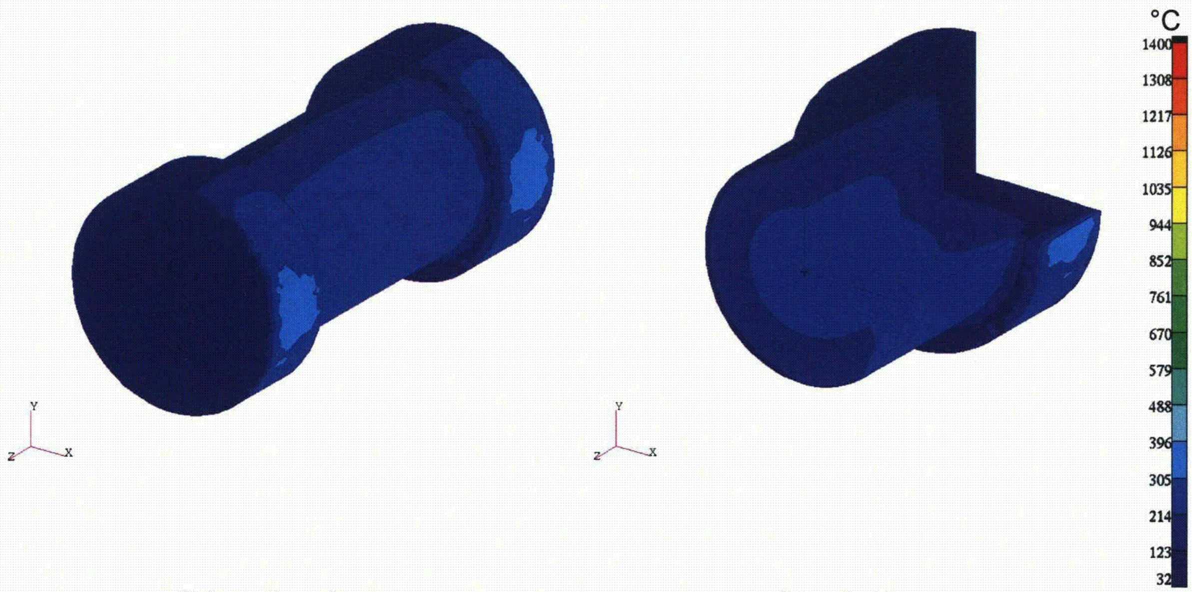


Figure 4-31 Temperature distribution of the Rail-Lead cask at the end of the 3-hour 18-meter (60-foot) offset CAFE fire with cask on ground

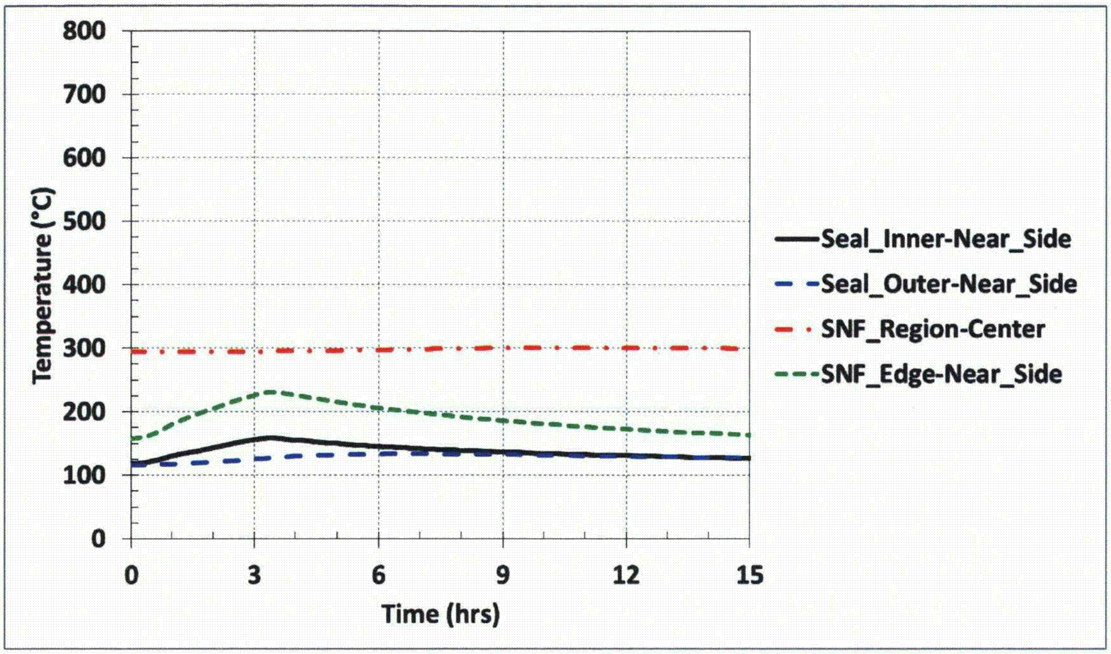


Figure 4-32 Temperature of key cask regions, Rail-Lead cask with cask on ground, 18-meter (60-foot) offset fire

Appendix IV contains plots with additional information on temperature distributions at more cask locations. The gradual thermal expansion and contraction of the gamma shield region during cask heating and cooling is another effect considered in cases where lead melted. This effect is discussed in the next subsection.

Melting of the Lead Gamma Shield

There are two cases in which a portion of the lead gamma shield melts. These are the 3-hour concentric fire and the 3-hour, 3-meter (10-foot) offset fire. The lead gamma shield region that melted for each case is shown in red in Figure 4-33 and Figure 4-34. These two figures only show the lead portion of the cask wall. As these figures show, approximately 88 percent of the lead melts in the case of the 3-hour concentric fire, whereas only about 30 percent of the lead melts in the 3-hour, 3-meter (10-foot) offset fire. Because of melting and thermal expansion of some of the lead gamma shield, some loss of lead shielding is observed, which translates to an increase in gamma radiation exposure. The width of the streaming path (i.e., the gap created because of lead melt, expansion, and subsequent contraction as it solidifies) is estimated. For this estimate, it is assumed that the thermal expansion of the lead permanently deforms (buckles) the interior wall of the cask, enabling calculation of the gap in the lead gamma shield.

The lead region gap that the concentric fire case causes is assumed to appear on the top portion of the cask. That is, after the lead melts and buckles the interior wall of the cask because of its thermal expansion, molten lead is assumed to flow to the lower portions of the cask's gamma shield region, which allows a gap to form on the top portion. From a geometric analysis that considered the expansion and contraction of the lead and a conservative cask wall deformation, this gap is estimated to be about 0.5 m (20 inches), which translates to an

8.1 percent loss of lead shielding. In the 3-meter offset fire, the gap is assumed to form on the top portion of the molten lead region shown in Figure 4-34. In this case, the gap is estimated to be about 0.127 m (5 inches), which translates to a 2 percent loss of lead shielding. These gaps are estimated using geometric information and temperature-dependent density values of lead (i.e., 11.35 g/cm^3 (0.41 lb/in^3) for solid lead and 10.6 g/cm^3 and 10.3 g/cm^3 (0.38 lb/in^3 and 0.37 lb/in^3) for molten lead at temperatures of 384 degrees C and 577 degrees C (723 degrees F and 1071 degrees F), respectively). The loss-of-shielding fractions reported in this section are used in Chapter 5 to estimate the consequences.

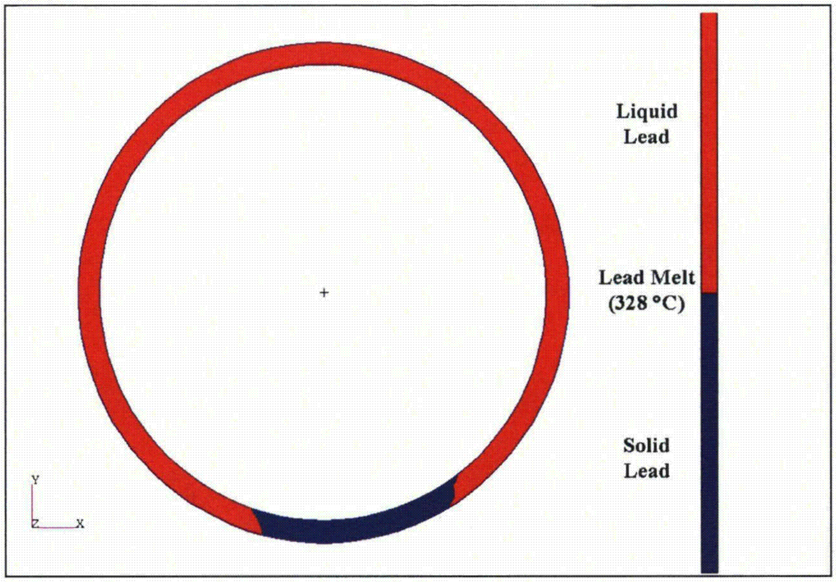


Figure 4-33 Rail-Lead cask lead gamma shield region – maximum lead melt at the middle of the cask – Scenario: Cask on ground, 3-hour concentric pool fire

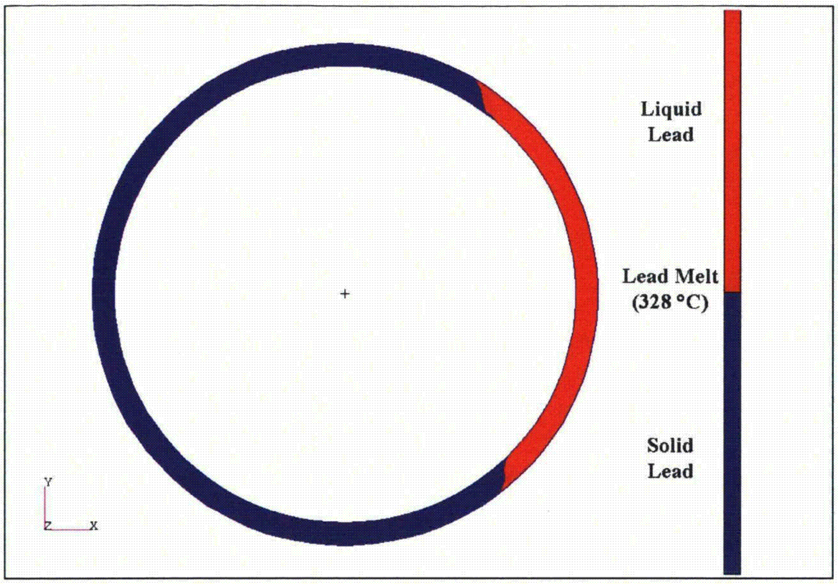


Figure 4-34 Rail-Lead cask lead gamma shield region – maximum lead melt at the middle of the cask – Scenario: Cask lying on ground, 3-hour 3-meter (10-foot) offset pool fire

Summary of Rail-Lead Cask Analysis Results

The results presented here show that the Rail-Lead cask is also capable of protecting the fuel rods from burst rupture and of maintaining containment when exposed to the severe fire environments analyzed, even when the neutron shield material is conservatively assumed to be absent during the fire accident. However, some reduction of gamma shielding is estimated to occur in two cases. Partial loss of lead shielding is expected when the cask is exposed to an engulfing fire that burns for longer than 65 minutes and for casks that receive heat from a fire offset by 3 meters (10 feet) and that burns for longer than 2 hours and 15 minutes. Nevertheless, no release of radioactive material is expected if this cask was exposed to any of these severe thermal environments because the elastomeric seals did not reach their temperature limit. This ensures the cask is capable of maintaining containment (i.e., preventing any radioactive material from getting out of the package) under any of the fire environments analyzed.

4.4 Truck Cask Analysis

A 3D analysis of the Truck-DU cask engulfed in a large fire is performed for this study. The cask is assumed to lie on the ground concentric with the hydrocarbon fuel pool fire. As explained in Section 4.2.2, the fire is assumed to last 1 hour. Results from the fire and heat transfer analyses performed on the Truck-DU cask are presented in this section.

4.4.1 Simulation of the Truck Cask

The heat transfer to and within the Truck-DU cask is modeled using P-Thermal/CAFE. The cask has a hydrogenous neutron shield that is assumed to disappear completely and replaced by air at its operational temperature limit (see Appendix IV). In this cask, a layer of DU within the cask wall provides the gamma shielding. Melting of the DU is not a concern for this cask under any of the conditions to which it is exposed. The aluminum honeycomb Impact limiters are modeled as undamaged (not deformed). Decay heat was included in the analysis. The FE model of the cask is shown in Figure 4-35. Appendix IV presents cask modeling details.

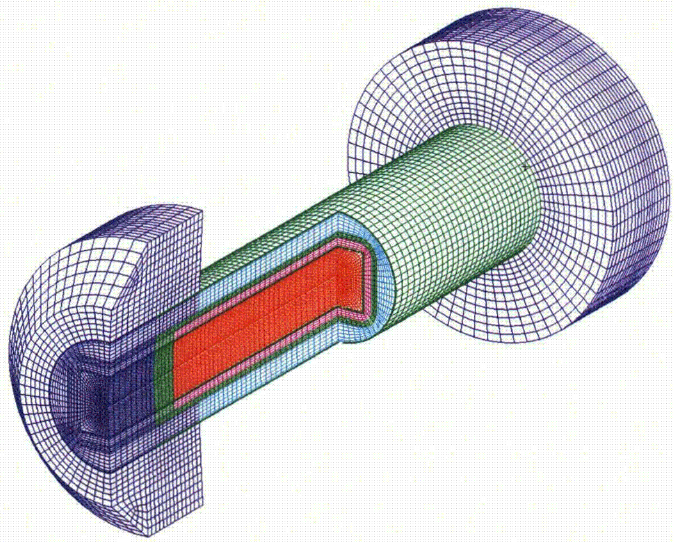


Figure 4-35 Finite element model (cut view) of the Truck-DU cask

4.4.2 Simulation of the Spent Nuclear Fuel Region

As with the rail casks, the SNF region comprising the fuel basket and the fuel assemblies is not modeled explicitly for the Truck-DU cask. Instead, a homogenized SNF region is used. All materials and geometric features of the fuel basket and fuel assemblies are represented as a single solid inside the cask. Appendix IV presents the effective properties of the homogenized SNF region.

4.4.3 Truck-DU Cask Results

The results from the analysis of the cask lying on the ground and concentric with a pool fire that burns for 1 hour are presented in Figure 4-36 and Figure 4-37.

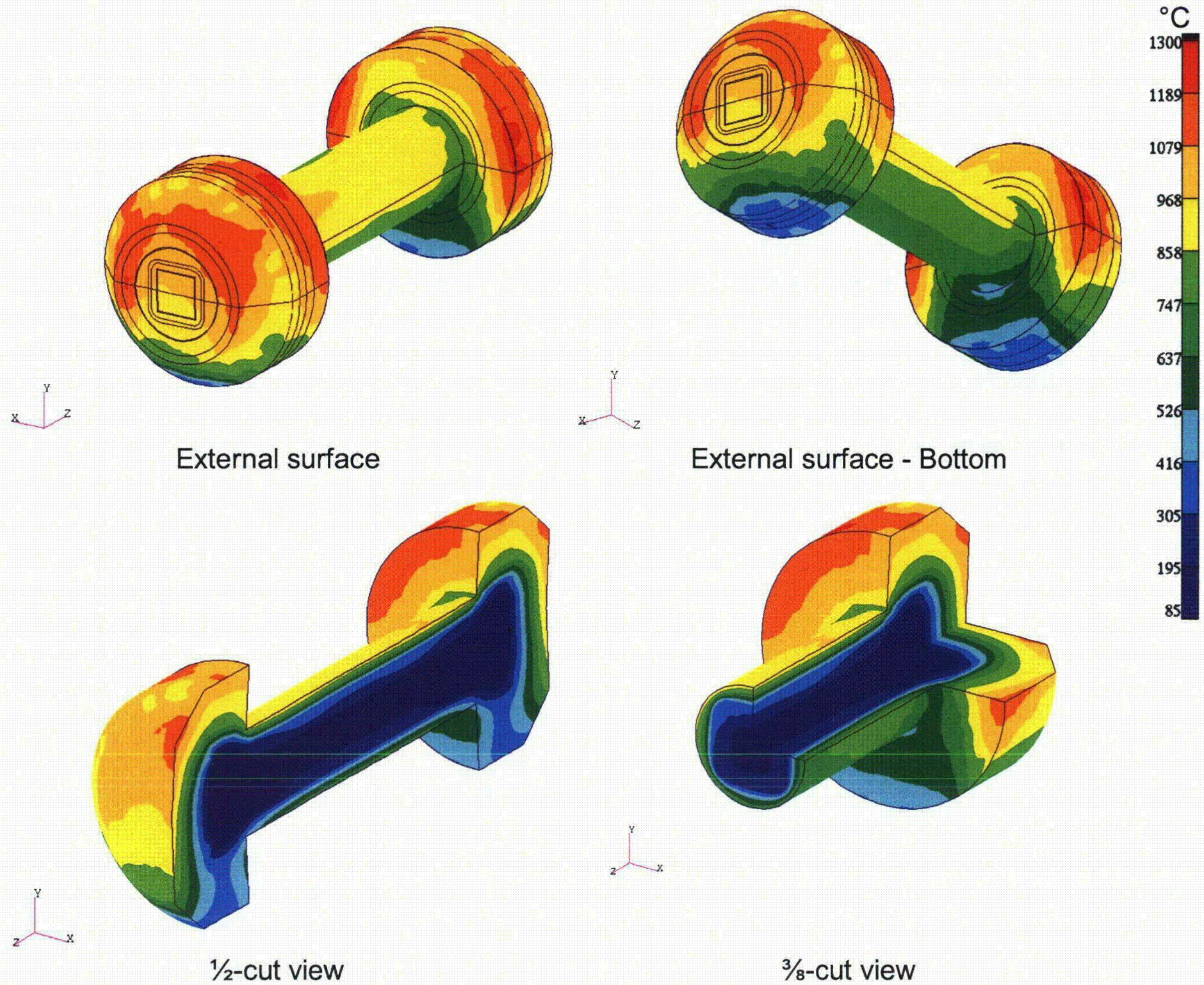


Figure 4-36 Temperature distribution of the Truck-DU cask at the end of the 1-hour concentric CAFE fire with cask on ground

As observed with the rail casks, the vapor dome affected the temperature distribution of the truck cask. This is evident by the cooler temperatures observed at the bottom of the cask. Even after 1 hour in the fire, the temperatures at the bottom of the cask are lowest and the temperatures at the top are highest.

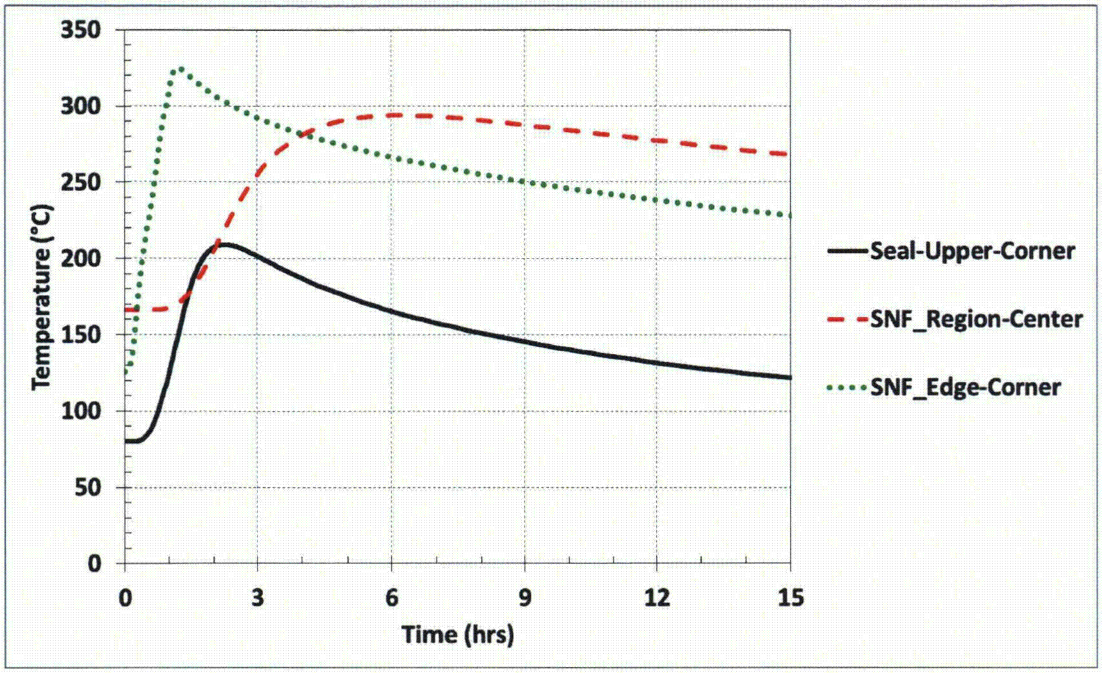
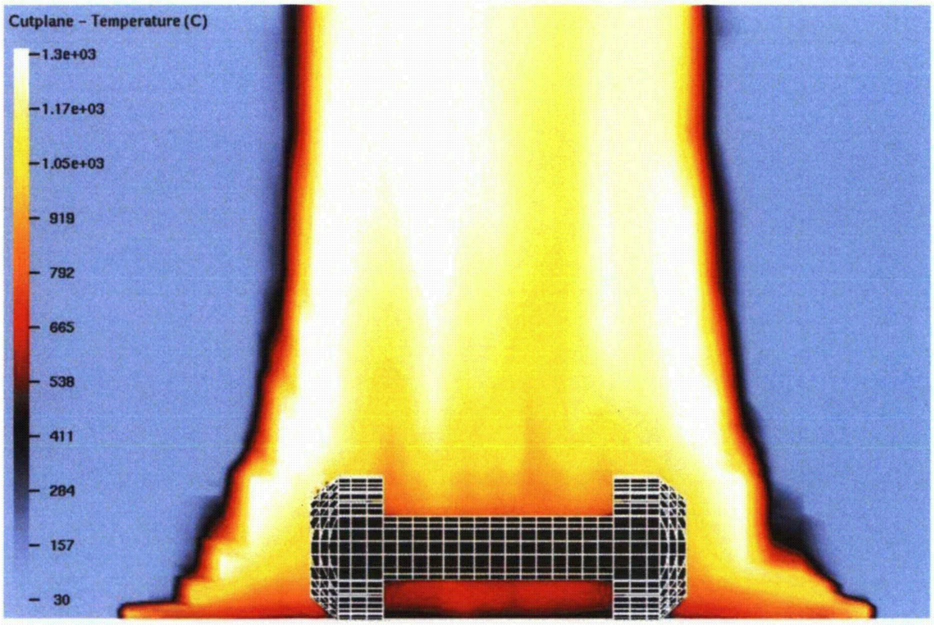
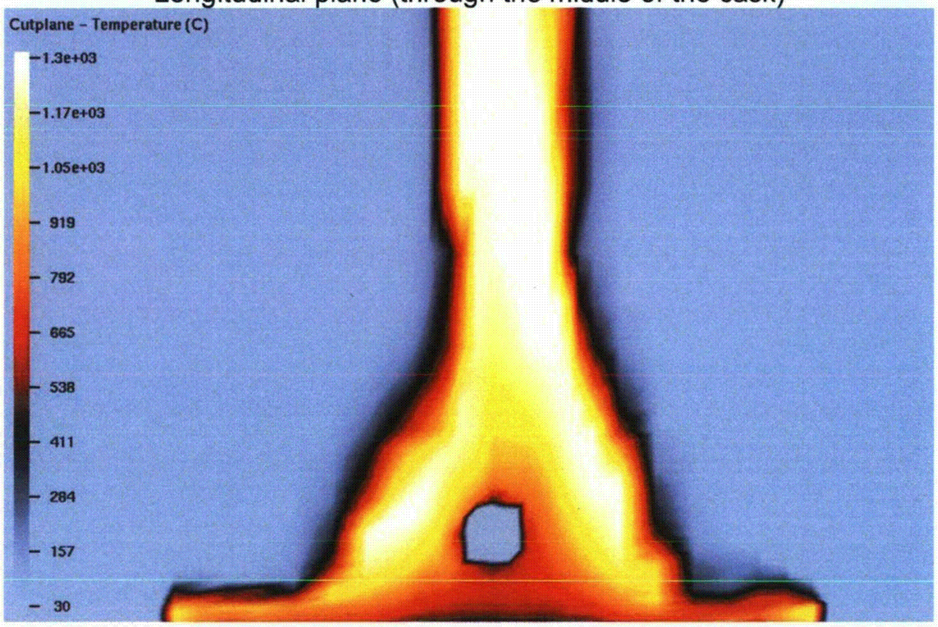


Figure 4-37 Temperature of key cask regions, Truck-DU cask with cask on ground, concentric fire

Figure 4-38 and Figure 4-39 are the fire temperature distribution and fuel concentration plots at an arbitrary time during the CAFE fire simulation. Note that the concentration of unburned fuel under the cask is high. This means that poor combustion is occurring in that zone, leading to cooler temperatures of the cask's lower region.

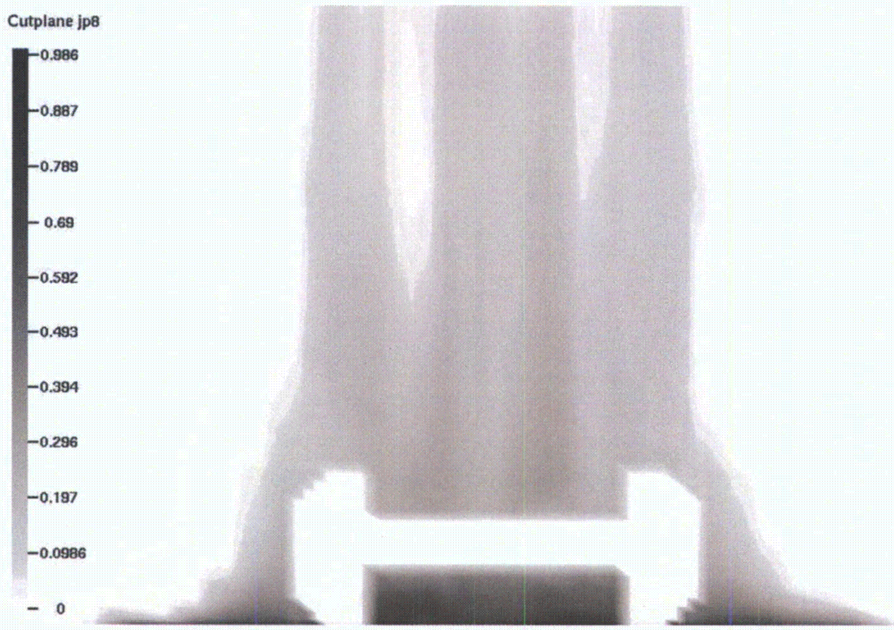


Longitudinal plane (through the middle of the cask)

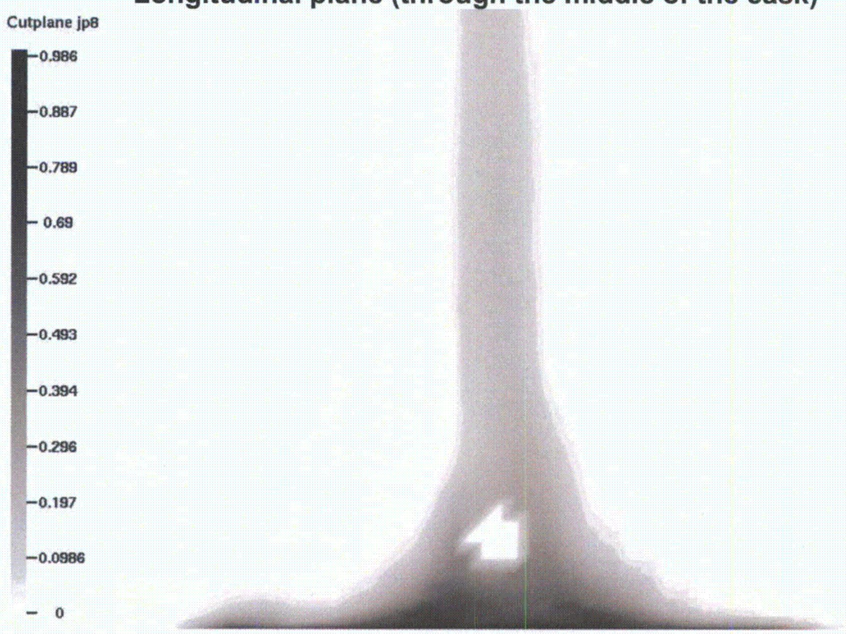


Transverse plane (at mid-length of the cask)

Figure 4-38 Gas temperature plots. CAFE fire analysis of the truck cask on ground.



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

Figure 4-39 Fuel concentration plots. CAFE fire analysis of the Truck-DU cask lying on ground.

<u>Summary of Truck-DU Cask Analysis Results</u>

The results presented here show that the Truck-DU cask is capable of protecting the SNF rods from burst rupture and of maintaining containment when exposed to the severe fire environment analyzed in this study. That is, while the neutron shield material is conservatively assumed to be absent during the fire accident, the SNF region stays below 750 degrees C (1,382 degrees F) and the seal region stayed under 350 degrees C (662 degrees F). This cask will not experience gamma shielding loss because a thick steel-DU wall provides the shielding, which is not affected in a way that could reduce its ability to provide shielding.

4.5 Chapter Summary

This chapter presents the realistic analyses of four fire accident scenarios. These accident scenarios are identified below:

- the HAC fire described in 10 CFR 71.73,
- a cask on the ground concentric with a fuel pool sufficiently large to engulf the cask,
- a cask on the ground with a pool fire offset by the width of a rail car (3 meters), and
- a cask on the ground with a pool fire offset by the length of a rail car (18 meters).

Analyses are performed for the Rail-Steel and the Rail-Lead casks for these four fire accident scenarios. An analysis of a Truck-DU cask on the ground concentric with a hydrocarbon fuel pool sufficiently large enough to engulf the cask is also performed. Probable worst-case fire accident scenarios for a rail cask transported by railway and for a truck cask transported by roadway were represented within the cases analyzed. The neutron shield material of each cask analyzed was assumed to melt and flow out of the cask instantly at the beginning of the fire.

Results show that neither the Rail-Steel cask nor the Rail-Lead cask would lose the containment boundary seal in any of the accidents considered in this study. In addition, the SNF rods did not reach burst rupture temperature. However, some loss of gamma shielding is expected with the Rail-Lead cask in the event of a 3-hour engulfing fire and a 3-hour, 3-meter (10-foot) offset fire. Nevertheless, no release of radioactive material is expected to occur as a result of these hypothetical fire accidents because containment is not lost in any of the cases studied. In the case of the Truck-DU cask, containment would be maintained in the 1-hour fire accident. These results demonstrate the adequacy of current regulations to ensure the safe transport of SNF. Furthermore, the results demonstrate that SNF casks designed to meet current regulations will prevent the loss of radioactive material in realistic severe fire accidents.

5. TRANSPORTATION ACCIDENTS

5.1 Types of Accidents and Incidents

The different types of accidents that can interfere with routine transportation of SNF are listed below.

- Accidents in which the spent fuel cask is not damaged or affected.
  - Minor traffic accidents ("fender-benders," flat tires) resulting in minor damage to the vehicle. These usually are called "incidents."[19]
  - Accidents that damage the vehicle or trailer enough so that the vehicle cannot move from the scene of the accident under its own power, but do not result in damage to the spent fuel cask.
  - Accidents involving a death or injury, or both, but no damage to the spent fuel cask.
- Accidents in which the spent fuel cask is affected.
  - Accidents resulting in the loss of lead gamma shielding or neutron shielding (or both), but no radioactive material is released.
  - Accidents in which radioactive material is released.

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

When an accident happens at a particular spot along the route, the vehicle carrying the spent fuel cask stops. Therefore, there can only be one accident for a shipment; resumption of the shipment essentially is a new shipment. Accidents can result in damage to spent fuel in the cask even if no radioactive material is released. While this would not result in additional exposure to members of the public, workers engaged in accident recovery operations, including unloading or subsequently opening the cask at a facility, would be affected. Accidents damaging the fuel but not damaging the cask and potential consequent risk to workers are not included in this study.

5.2 Accident Probabilities

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

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

[19] In U.S. Department of Transportation terminology, an "accident" is an event that results in a death, an injury, or enough damage to the vehicle that it cannot move under its own power. All other events that occur in nonroutine transportation are "incidents." This document uses the term "accident" for both accidents and incidents.

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

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

Table 5-1 Illustrations of Net Probability

Accident Probability for a 5,000 km (3,107-mile) Cross-Country Trip[a]	Accident Scenario	Conditional Probability[b]	Net Probability of Accident
0.0099	Truck collision with a gasoline tank truck	$0.82 \times 0.003 = 0.00246$	$0.82 \times 0.003 \times 0.0099 = 2.44 \times 10^{-5}$
0.00066	Derailment into slope >80 kph (>50 mph), no fire	$0.7355 \times 0.9846 \times (0.06048+0.00005) \times 0.9887 \times 0.0011 = 0.0000476$	$0.0000476 \times 0.00066 = 3.14 \times 10^{-8}$
0.00066	Railcar accident on a bridge at 48-80 kph (30-50 mph), no fire	$0.7355 \times 0.9846 \times 0.2665 \times 0.0113 = 0.00218$	$0.00218 \times 0.00066 = 1.44 \times 10^{-6}$

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

Accident probability is calculated from the number of accidents per kilometer (accident frequency) for a particular type of vehicle as recorded by the DOT and reported by the Bureau of Transportation Statistics. Large truck accidents and freight rail accidents are the two data sets used in this analysis. The DOT has compiled and validated national accident data for truck and rail from 1971 through 2007 (DOT, 2008), but the accident rates declined definitively between 1971 and the 1990s. For this analysis, rates from 1996 through 2007 are used: 0.0019 accidents per thousand large truck-km (0.0031 accidents per thousand large truck miles) and 0.00011 accidents per thousand railcar-km (0. 00018 accidents per thousand railcar miles).

Figure 5-1 shows the accidents per truck-km and per railcar-km for this period. The logarithmic scale is used on the vertical axis to show the entire range.

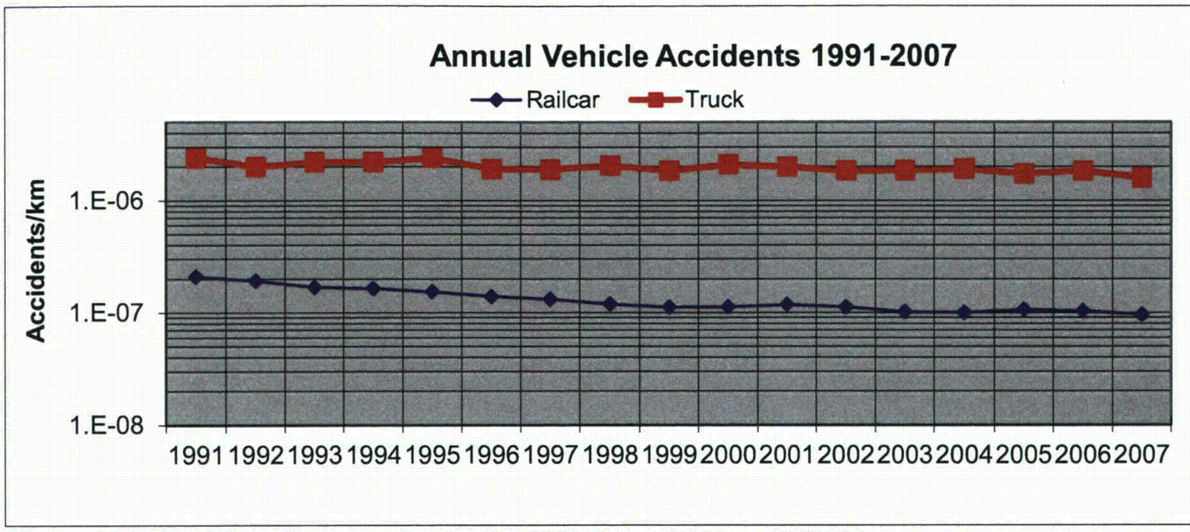


Figure 5-1 Accident frequencies in the U.S. from 1991 until 2007
(1 km = 0.62137 miles)

As Chapters 3 and 4 show, however, the only accidents that could result in either loss of radiation shielding or release of radioactive material are rail accidents involving the Rail-Lead cask when fuel is directly loaded inside the cask (i.e., the fuel is not contained in a welded canister inside the cask). These accidents are listed below.

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

- Fires of long-enough duration to compromise the lead shielding.

Whether these accidents happen depends on the likelihood (conditional probability) of the accident scenario as well as on accident frequency. The event trees for truck and rail, Figures V-1 and V-2 of Appendix V, show some elements of accident scenarios in each branch of the respective event tree. The dependence on probability is illustrated in Figure V-6, which shows the sequence of events necessary for a pool fire that can burn long enough to compromise the seals and lead shielding.

Table 5-2 shows the conditional probabilities of accidents that could result in a radiation dose to a member of the public. Sections V.3 to V.5 of Appendix V provide the analysis resulting in these conditional probabilities. The calculation of these probabilities is done using the typical method for risk assessments, but because of the large degree of safety that spent fuel casks provide, only extremely low probability events have the possibility of leading to a radiation dose to the public. For these extremely low probability events, the results are reported to the precision of the calculation (to aid understanding of derivation of results), but they should be considered accurate only to the order of magnitude.

Table 5-2 Scenarios and Conditional Probabilities of Rail Accidents Involving the Rail-Lead Cask

Accident Scenario for the Rail-Lead Cask	Conditional probability of gamma shield loss or radioactive material content release exceeding 10 CFR 71.51 quantities[a]
Loss of lead shielding from impact[b]	8.3×10^{-10}
Loss of lead shielding from fire[c]	10^{-14} to 10^{-10}
Radioactive materials release from impact[d]	5.1×10^{-10}
Radioactive materials release from fire	0

a More than 99.999999 percent of potential accidents would result in neither loss of lead shielding nor a release of radioactive material.
b From the cases in Table V-2 of Appendix V with lead slump greater than 1 percent.
c From the fire event tree, Figure V-6 in Appendix V.
d From the sum of probabilities in the last row of Table 5-10 for the casks with metal seals. The probability of release would be less If the cask is shipped with elastomer seals.

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

The conditional probability that an accident involving a lead-shielded cask will be the type with no release and no lead shielding loss, as the footnote to Table 5-2 states, is 99.999999 percent. The only type of cask that could lose gamma shielding is a lead-shielded cask such as the Rail-Lead cask. The only type of cask that could release radioactive material in an accident is a cask carrying uncanistered spent fuel. Although the Truck-DU cask carries uncanistered fuel, it would not release any radioactive material under any scenario postulated in this report. The Rail-Steel cask carries only canistered fuel and would not release any radioactive material. Neither Truck-DU casks nor Rail-Steel casks are lead-shielded; therefore shielding loss would not occur.

Doses to emergency responders from an accident in which no material is released and no loss of lead gamma shielding are shown in Table 5-3, and collective doses to the public from this type of accident are shown in Table 5-4 and Table 5-5. These radiation doses depend on the following—

- The external dose rate from the cask (Table 2-1).
- A10-hour stop (DOE, 2002) at the scene of the accident, until the vehicle and cask, or both, can be moved safely. Ten hours is believed to overstate the stop time for most accidents.
- An average distance of 5 meters (16.4 feet) between the cask and the first responders and others who remain with the cask.
- For collective doses, the average rural, urban, and suburban population densities for each route.

The radiation doses in Table 5-3, Table 5-4, and Table 5-5 are the consequences of all Truck-DU accidents, all Rail-Steel accidents, and 99.999999 percent of the Rail-Lead accidents.

Table 5-3 Dose to an Emergency Responder[a] from a Cask in a No-Shielding Loss, No-Release Accident

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

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

Table 5-4 and Table 5-5 show collective doses in Sv for the 10-hour stop following the accident. Doses are shown for rural, suburban, and urban segments of each route, but an accident only happens once on any route. Therefore, each listed dose is the collective dose residents on that route segment could receive if the accident happened at any spot on that type of route segment.

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

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban[a]	Total	Rural	Suburban	Urban[a]	Total
MAINE YANKEE								
ORNL	$3.1x10^{-6}$	$5.3x10^{-5}$	$6.6x10^{-6}$	$6.3x10^{-5}$	$2.3x10^{-6}$	$4.0x10^{-5}$	$5.0x10^{-6}$	$4.8x10^{-5}$
DEAF SMITH	$2.3x10^{-6}$	$5.7x10^{-5}$	$6.8x10^{-6}$	$6.6x10^{-5}$	$1.7x10^{-6}$	$4.3x10^{-5}$	$5.2x10^{-6}$	$5.0x10^{-5}$
HANFORD	$5.7x10^{-6}$	$5.2x10^{-5}$	$6.3x10^{-6}$	$6.4x10^{-5}$	$4.3x10^{-6}$	$3.9x10^{-5}$	$4.8x10^{-6}$	$4.8x10^{-5}$
SKULL VALLEY	$2.8x10^{-6}$	$5.1x10^{-5}$	$5.3x10^{-6}$	$6.0x10^{-5}$	$2.1x10^{-6}$	$3.9x10^{-5}$	$4.0x10^{-6}$	$4.5x10^{-5}$
KEWAUNEE								
ORNL	$3.1x10^{-6}$	$5.7x10^{-5}$	$7.2x10^{-6}$	$6.8x10^{-5}$	$2.3x10^{-6}$	$4.3x10^{-5}$	$5.4x10^{-6}$	$5.1x10^{-5}$
DEAF SMITH	$1.5x10^{-6}$	$6.1x10^{-5}$	$7.2x10^{-6}$	$6.9x10^{-5}$	$1.2x10^{-6}$	$4.6x10^{-5}$	$5.4x10^{-6}$	$5.2x10^{-5}$
HANFORD	$1.5x10^{-6}$	$5.3x10^{-5}$	$6.6x10^{-6}$	$6.1x10^{-5}$	$1.2x10^{-6}$	$4.0x10^{-5}$	$5.0x10^{-6}$	$4.6x10^{-5}$
SKULL VALLEY	$2.0x10^{-6}$	$6.2x10^{-5}$	$6.0x10^{-6}$	$7.0x10^{-5}$	$1.5x10^{-6}$	$4.7x10^{-5}$	$4.5x10^{-6}$	$5.3x10^{-5}$
INDIAN POINT								
ORNL	$2.6x10^{-6}$	$7.2x10^{-5}$	$8.7x10^{-6}$	$8.3x10^{-5}$	$2.0x10^{-6}$	$5.4x10^{-5}$	$6.6x10^{-6}$	$6.3x10^{-5}$
DEAF SMITH	$1.9x10^{-6}$	$5.9x10^{-5}$	$7.5x10^{-6}$	$6.9x10^{-5}$	$1.4x10^{-6}$	$4.5x10^{-5}$	$5.7x10^{-6}$	$5.2x10^{-5}$
HANFORD	$1.9x10^{-6}$	$5.6x10^{-5}$	$7.2x10^{-6}$	$6.5x10^{-5}$	$1.4x10^{-6}$	$4.3x10^{-5}$	$5.5x10^{-6}$	$5.0x10^{-5}$
SKULL VALLEY	$2.2x10^{-6}$	$6.0x10^{-5}$	$6.6x10^{-6}$	$6.9x10^{-5}$	$1.7x10^{-6}$	$4.6x10^{-5}$	$5.0x10^{-6}$	$5.2x10^{-5}$
IDAHO NATIONAL LAB								
ORNL	$1.9x10^{-6}$	$6.0x10^{-5}$	$5.8x10^{-6}$	$6.8x10^{-5}$	$1.4x10^{-6}$	$4.6x10^{-5}$	$4.4x10^{-6}$	$5.2x10^{-5}$
DEAF SMITH	$8.0x10^{-7}$	$6.0x10^{-5}$	$5.3x10^{-6}$	$6.6x10^{-5}$	$6.0x10^{-7}$	$4.6x10^{-5}$	$4.0x10^{-6}$	$5.0x10^{-5}$
HANFORD	$1.0x10^{-6}$	$6.0x10^{-5}$	$6.7x10^{-6}$	$6.8x10^{-5}$	$7.5x10^{-7}$	$4.6x10^{-5}$	$5.1x10^{-6}$	$5.2x10^{-5}$
SKULL VALLEY	$2.0x10^{-6}$	$5.9x10^{-5}$	$7.1x10^{-6}$	$6.8x10^{-5}$	$1.5x10^{-6}$	$4.4x10^{-5}$	$5.4x10^{-6}$	$5.1x10^{-5}$
AVERAGE	$2.3x10^{-6}$	$5.8x10^{-5}$	$6.7x10^{-6}$	$6.7x10^{-5}$	$1.7x10^{-6}$	$4.4x10^{-5}$	$5.1x10^{-6}$	$5.1x10^{-5}$

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

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

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

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

The average individual U.S. background dose for 10 hours is 4.1×10^{-6} Sv (0.41mrem). Average background doses during the 10-hour stop for the 16 truck routes analyzed are—

- rural: $(4.1\ 10^{-6}\ \text{Sv}) \times (16.8\ \text{persons/km}^2) \times \pi \times (0.8\ \text{km})^2 = 0.000138$ person-Sv (13.8 person-mrem)
- suburban: $(4.1\ 10^{-6}\ \text{Sv}) \times (463\ \text{persons/km}^2) \times \pi \times (0.8\ \text{km})^2 = 0.00382$ person-Sv (382 person-mrem)
- urban: $(4.1\ 10^{-6}\ \text{Sv}) \times (2{,}682\ \text{persons/km}^2) \times \pi \times (0.8\ \text{km})^2 = 0.0221$ person-Sv (2,210 person-mrem)

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

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

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

5.4 Accidental Loss of Shielding

Section V.3.1 to Appendix V (loss of gamma shielding) and Section V.3.2 (loss of neutron shielding) provide details on dose calculations from shielding losses.

5.4.1 Loss of Lead Gamma Shielding

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

Each SNF transportation cask analyzed uses a different material to serve as gamma shielding. They also may use different neutron shielding, but it is not usually part of the accident analysis. The Rail-Steel cask has a steel wall thick enough to attenuate gamma radiation to acceptable levels. The Truck-DU cask uses metallic DU. Neither of these shields would lose their effectiveness in an accident. The Rail-Lead cask has a lead gamma shield that could have its effectiveness reduced in an accident. Lead is relatively soft as compared to DU or steel and melts at a considerably lower temperature (330 degrees C, 626 degrees F).

In a hard impact, the lead shield will slump, and a small section of the spent fuel in the cask will be shielded only by the steel shells. Figure 5-2 and Figure 5-3 show the maximum individual radiation dose at various distances from the damaged cask for a range of gaps in the lead shield. In the figures, the dose estimates for the large gaps are depicted on the left side of the graph and the fraction of lead shield lost (gap size) increases from left to right. Figure 5-2 shows that doses larger than the external dose that 10 CFR 71.51 allows (0.01 Sv/hour (1 rem/hour) at 1 meter (3.3 feet) from the cask) occur when the lead shielding gap is more than 2 percent of the shield.

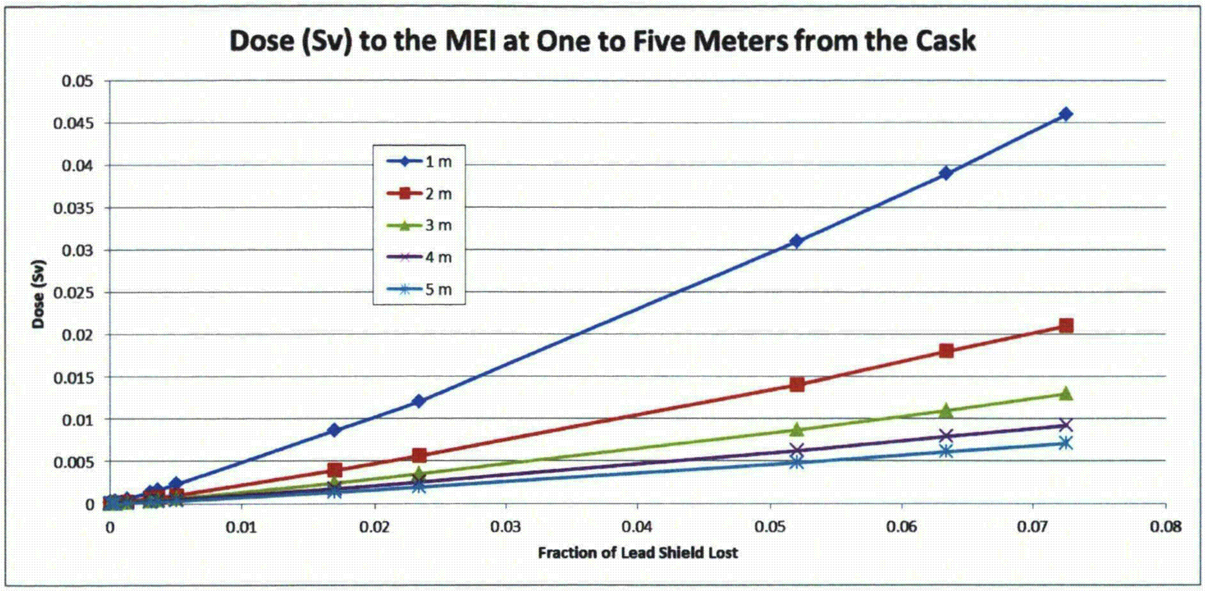


Figure 5-2 Radiation dose rates to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from 1 to 5 meters from the cask carrying spent fuel. The horizontal axis represents the fraction of shielding lost (the shielding gap). (1 m = 3.3 feet, 1 Sv = 10^5 mrem)

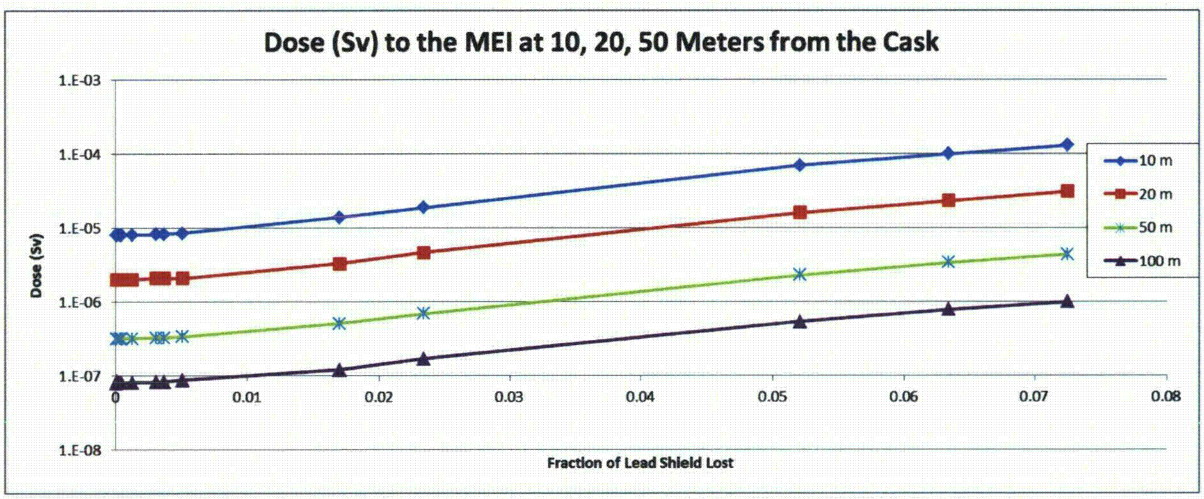


Figure 5-3 Radiation dose rates to the MEI from loss of lead gamma shielding at distances from 10 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic so that all of the doses can be shown on the same graph. The horizontal axis represents the fraction of shielding lost (the shielding gap) (1 m = 3.3 feet, 1 Sv = 10^5 mrem).

One in a billion accidents (from the first row of Table 5-2) could cause loss of lead shielding that results in a dose rate exceeding the regulatory dose rate specified in 10 CFR 71.51. The "one in a billion" is a conditional probability, conditional on an accident happening. The total probability of such an accident includes both this conditional probability and the probability that there will be an accident. The probability of an accident is shown in the right-hand column of Table 5-6. For example, the probability that an accident resulting in lead shielding loss leading to a dose rate greater than 0.01 Sv/hr (1 rem/hr) will happen on the rail route from Maine Yankee Nuclear Plant site to Hanford is:

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

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

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

Table 5-6 Average Railcar Accident Frequencies and Accidents per Shipment on the Routes Studied

ORIGIN	DESTINATION	AVERAGE ACCIDENTS PER KM	ROUTE LENGTH (KM)	PROBABILITY OF AN ACCIDENT FOR THE TOTAL ROUTE
MAINE YANKEE	ORNL	6.5×10^{-7}	2125	0.00139
	DEAF SMITH	5.8×10^{-7}	3362	0.00194
	HANFORD	4.2×10^{-7}	5084	0.00214
	SKULL VALLEY	5.1×10^{-7}	4086	0.00208
KEWAUNEE	ORNL	4.3×10^{-7}	1395	0.00060
	DEAF SMITH	3.3×10^{-7}	1882	0.00062
	HANFORD	2.4×10^{-7}	3028	0.00073
	SKULL VALLEY	3.7×10^{-7}	2755	0.00103
INDIAN POINT	ORNL	8.8×10^{-6}	1264	0.0112
	DEAF SMITH	6.2×10^{-7}	3088	0.00192
	HANFORD	4.4×10^{-7}	4781	0.00212
	SKULL VALLEY	5.5×10^{-7}	3977	0.00217
INL	ORNL	3.6×10^{-7}	3306	0.00120
	DEAF SMITH	3.5×10^{-7}	1913	0.00067
	HANFORD	3.2×10^{-7}	1062	0.00034
	SKULL VALLEY	2.8×10^{-7}	455	0.00013

The overall collective dose risks to the resident population from a lead shielding loss accident on the 16 rail routes studied are shown in Table 5-7. These include accidents in which resulting dose rates would be within regulatory limits. The doses are the total of rural, suburban, and urban doses from Table V-7 in Appendix V. The expected dose to any member of the populations along the routes, at least 10 meters (33 feet) from the cask, is within the limits of 10 CFR 71.51. The Indian Point-to-ORNL collective dose risk is comparatively large because the suburban and urban populations along this route are about 20 percent higher than along the other routes, and the rail accident rate per kilometer is an order of magnitude larger.

Table 5-7 Collective Dose Risks per Shipment in Person-Sv for a Loss of Lead Shielding Accident Involving a Lead-Shielded Rail Cask (1 Sv=10^5 mrem)

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

Table 5-7 is a summary of Table V-7 in Appendix V. The collective dose (consequence) for each route is calculated by dividing the dose risks in Table V-7 by the appropriate probabilities. The resulting total consequence for all routes is about 800 person-Sv (80000 person-rem).

The conditional probability that a lead shielding gap will occur after a fire involving the cask is about 10^{-19}. The conditional probability is so small because the following has to occur before a fire is close enough to the cask—and burns hot enough and long enough—to do any damage to the lead shield:

- The train must be in an accident resulting in a major derailment or the location of the fire will be too far removed from the cask to damage the lead shielding.
- There must be at least one tank car of flammable material involved in the accident (either on the train carrying the spent fuel cask or on another train involved in the accident).
- The derailment must result in a pileup. By regulation, railcars carrying spent fuel casks are required to have buffer cars and are never located directly adjacent to a railcar carrying hazardous or flammable material.
- The flammable material must leak out so that it can ignite.
- The pileup must be such that the resulting fire is no further from the cask than a railcar length.

The probability of a pileup and the probability that the cask is within a railcar length from the fire are very small. Assessing the conditional probability without these two events, and considering only the more likely events, results in a conditional probability of about 10^{-10}, or approximately 1 in 10 billion.

Appendix V discusses in detail the event trees and probabilities for fire accidents.

5.4.2 Loss of Neutron Shielding

The type of fuel that can be transported in the three casks considered has relatively low neutron emission but does require neutron shielding, usually a hydrocarbon or carbohydrate polymer that often contains a boron compound. All three of the casks studied have polymer neutron shields. Table 5-8 shows the total radiation dose resulting from a loss of neutron shielding to individuals who are approximately 5 meters from a fire-damaged cask for 10 hours. The dose allowed by 10 CFR 71.51 is provided for comparison. Neutrons are absorbed by air much better than gamma radiation; therefore, external neutron radiation would have an impact on receptors close to the cask but not on the general public.

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

Table 5-8 Doses to an Emergency Responder or Other Individual 5 Meters (16.4 feet) from the Cask for 10 Hours

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

The neutron doses do not exceed the allowable dose cited in the regulation. These doses could result from a regulatory fire accident. The conditional probability of this neutron dose is 0.0063 for a truck fire accident and 0.0000001 for a rail fire accident. The conditional probability of a fire for the Truck-DU cask is much higher than that for the two rail casks. These occur, in part, because truck accidents always include a potential source of fuel (the gas tanks of the truck) whereas many railcar accidents do not involve the locomotive. They also occur, in part, because of the way the event trees were constructed. The truck event tree does not distinguish between minor fires and those severe enough to damage the neutron shielding, while the rail event tree only considers severe fires. Therefore the conditional probability of a truck fire is quite conservative (overstated). Details are discussed in Section V.3.2 of Appendix V.

The loss of neutron shielding produces a much smaller dose to an emergency responder than would happen if there was a loss of gamma shielding of 7 percent. The 10 hour dose to an emergency responder at 5 meters (16.4 feet) for the rail lead cask after a loss of neutron shielding accident from Table 5-8 is 0.0076 Sv (760 mrem), while the multiplying the 5-meter (16.4-foot) dose rate in Figure 5-2, 0.007 Sv/hr (700 mrem/hr) by the assumed ten-hour exposure time results in a dose of 0.07 Sv (7,000 mrem) after a loss of 7% of lead shielding accident. Both of these doses are probably overestimates of what would actually happen in either of these types of accidents because loss of shielding is relatively easy to mitigate, and such actions would likely take place before any extended emergency response activities close to the cask were carried out.

5.5 Accidental Release of Radioactive Materials

Radioactive materials released into the environment are dispersed in the air and some deposit on the ground. If a spent fuel cask is in a severe enough accident, spent fuel rods can tear or be otherwise damaged, releasing fission products and very small particles of spent fuel into the cask. If the cask seals are damaged, these radioactive substances can be swept from the interior of the cask through the seals into the environment. Release to the environment requires the accident be severe enough to damage the fuel rods and release the pressure in the rods or there will be no positive pressure to sweep material from the cask into the environment.

Chapters 3 and 4 discuss the potential accidents that could result in such a release. This chapter discusses the probability of such accidents and the consequences of the release of these radionuclides.

5.5.1 Spent Fuel Inventory

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

The fuel studied in this analysis is PWR fuel that has "burned" 45,000 MWD/MTU and cooled for 9 years.[20] The Rail-Lead cask, the only cask studied that could release radioactive material in an accident, is certified to carry 26 PWR assemblies.

The spent fuel inventory for accident analysis was selected by normalizing the radionuclide concentrations in the spent fuel by radiotoxicity (see Section V.4.1 to Appendix V). The resulting inventory is shown in Table 5-9.

[20] This was approximately the shortest time needed for the fuel to cool sufficiently to meet thermal requirements for cask certification. Although relatively short-term, this time was considered somewhat typical when this study began. Considerably longer-term spent fuel storage scenarios are now being considered, but these longer-term scenarios were not considered in this study.

Table 5-9 Radionuclide Inventory for Accident Analysis of the Rail-Lead Cask

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

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

5.5.2 Conditional Probabilities and Release Fractions

Seven accident scenarios involving the Rail-Lead cask, described in Chapter 3, could result in material releases to the environment. Table 5-10 provides details of these scenarios pertinent to calculating the resulting doses. Section V.4.3 to Appendix V provides a detailed description of the movement of radionuclide particles from fuel rods to the cask interior and from the cask interior to the environment. The last row in the table provides the conditional probabilities of each of these releases. The total conditional probability that an accident will lead to a release for the cask using metal seals is 1.08×10^{-9} (or one in a billion accidents) and for the cask using elastomer seals it is 3.57×10^{-10}.

Table 5-10 Parameters for Determining Release Functions for the Accidents that Would Result in Release of Radioactive Material[a]

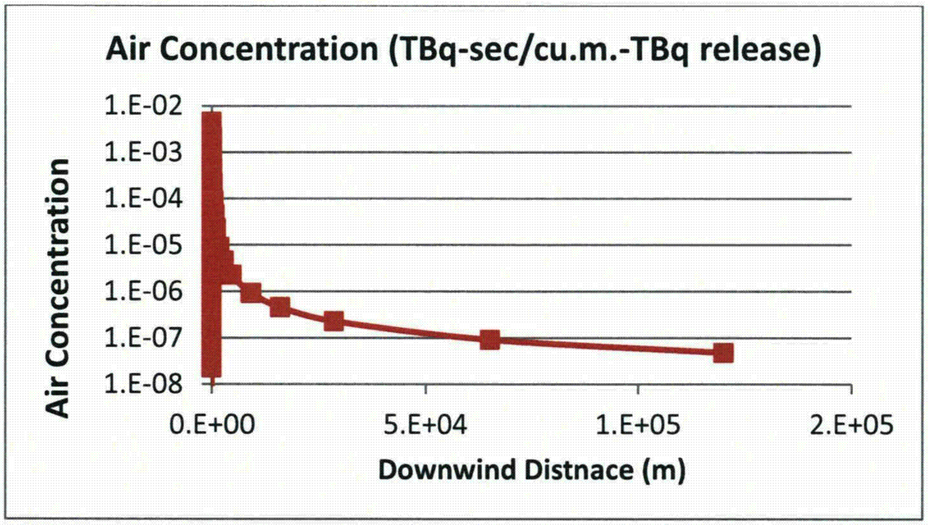
	Cask Orientation	End	Corner	Side	Side	Side	Side	Corner
	Rigid Target Impact Speed, kph (mph)	193 (120)	193 (120)	193 (120)	193 (120)	145 (90)	145 (90)	145 (90)
	Seal	metal	metal	elastomer	metal	elastomer	metal	metal
Cask to Environment Release Fraction	Gas	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	Particles	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	4.80×10^{-6}	4.80×10^{-6}	4.80×10^{-6}	4.80×10^{-6}	4.80×10^{-6}	4.80×10^{-6}	2.40×10^{-6}
	Volatiles	3.00×10^{-5}	3.00×10^{-5}	3.00×10^{-5}	3.00×10^{-5}	3.00×10^{-5}	3.00×10^{-5}	1.50×10^{-5}
	CRUD	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Conditional Probability	5.96×10^{-12}	3.57×10^{-11}	1.79×10^{-11}	1.79×10^{-11}	3.40×10^{-10}	3.40×10^{-10}	6.79×10^{-10}

[a] Discussion of the values in this table is given in Section V.4.3 to Appendix V.

5.5.3 Dispersion

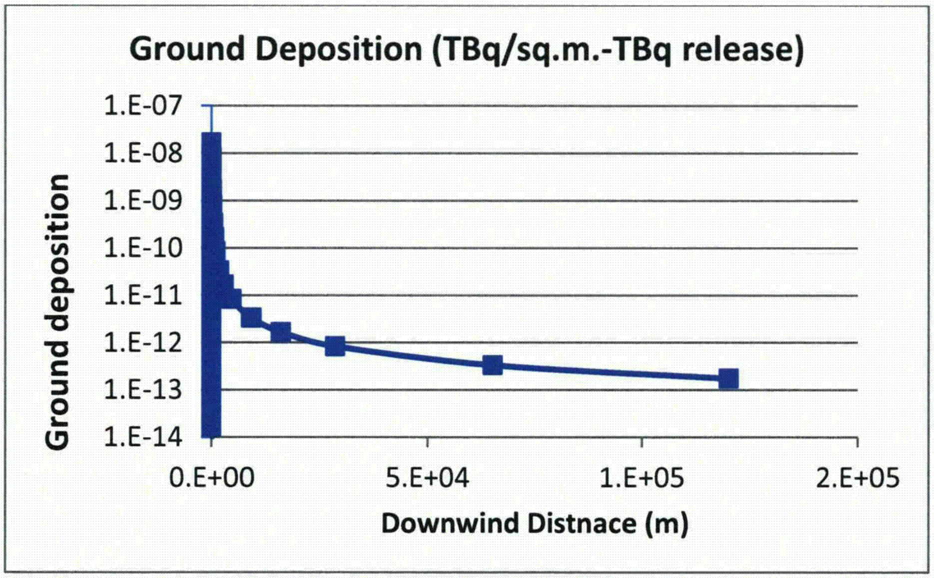
Material swept from the cask and released into the environment is dispersed by wind and weather. The dispersion is modeled using the accident model in RADTRAN 6, which is a Gaussian dispersion model. The release would be at about 1.5 meters above ground level since the cask is sitting on a railcar. The gas sweeping from the cask is warmer than ambient; therefore, the release is elevated. Under these conditions, the maximum ground level air concentration and deposition are 21 meters downwind from the release. The dispersion was modeled using neutral weather conditions (Pasquill: stability D, wind speed 4.7 m/sec (10.5 mph)). It was repeated using very stable meteorology (Pasquill: stability F, wind speed 0.5 m/sec (1.1 mph)), but the difference was negligible because of the relatively low elevation of the release. The MEI would be located directly downwind from the accident, 21 meters (69 feet) from the cask.

Figure 5-4 shows air and ground concentrations of released material as a function of downwind distance. The upwind side of the maximum concentration is short because the plume rise is very fast. Therefore the x-axis (downwind distance) is foreshortened so that the plume rise and gradual decay can be shown in the same graph. The concentrations shown are along the plume centerline and are the maximum concentrations in the plume. The figure shows the exponential decrease of airborne concentrations as the downwind distance increases. The ground (deposited) concentration also decreases in the downwind direction.



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

(note: 1 meter = 3.3 feet)



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

Figure 5-4 Air and ground concentrations of radioactive material following a release

(note: 1 meter = 3.3 feet)

5.5.4 Consequences and Risks from Accidents Involving Release of Radioactive Material

The dose from accidents that would involve a release is shown in Table 5-11. Section V.4.3 to Appendix V provides a detailed discussion on how these values were obtained.

Table 5-11 Doses (Consequences) in Sv to the Maximally Exposed Individual from Accidents that Involve a Release (1 Sv=10^5 mrem)

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

The doses listed in Table 5-11 are consequences, not risks. The dose to the MEI is not the sum of the total doses. Each cask orientation is a different accident scenario and results in a set of internal (includes inhalation and resuspension) and external (includes cloudshine and groundshine) doses. Only one accident scenario can happen at a time. These doses would not result in either acute illness or death (Shleien et al., 1998). The internal and external doses are listed separately because they have different physiological effects. In external doses, the receptor would receive a dose only as long as he or she is exposed to the deposited or airborne material. If people near the accident are evacuated—and evacuation can take as much as 1 day—then they would only receive an external dose for 1 day. The most significant dose is the inhalation dose. All exposures to the dispersed material last until the end of the evacuation time, which for this analysis was 24 hours.

Inhaled radioactive particles lodge in the body and are eliminated slowly through physiological processes that depend on the chemical form of the radionuclide. The inhaled dose is called a "committed" dose because the exposure is for as long as the radionuclide is in the body. The activity of the nuclide, however, decreases exponentially as it decays (as shown in the Inhalation column of Table 5-11). The resuspension dose is also an inhaled dose. The NRC considers the total effective dose equivalent: the sum of the internal and external doses, which allows the doses to be added (the total is shown in the last column of Table 5-11).

A pool fire co-located with the cask and burning for a long enough time could severely damage the seals. None of the fires analyzed in this report caused sufficient seal damage to result in a release of radioactive material. The conditional probability of the series of events required to produce the most severe fire scenario analyzed is about 10^{-19} (discussed in detail in Section V.3.1.2 to Appendix V), so analysis of a more severe fire is meaningless. Even a fire offset from the cask but close enough to damage lead shielding has a conditional probability of between 10^{-14} and 10^{-10}.

Table 5-12 shows the total collective dose risk from the universe of release accidents. The accident with the most severe consequence could result in a release of 8.4 times the amount of radioactive material that can be transported in a container that is not accident resistant (8.4 A_2s). Such an accident would result in a collective dose of 6.8 person-Sv to an exposed population of 58,000, calculated by multiplying RADTRAN output for dose and plume footprint area by a population density of 41.46 persons/km2 (107.4 persons/mi2) (the U.S. average minus Alaska). Of the three casks in this study, only the Rail-Lead cask could result in a release in each type of accident considered.

Table 5-12 Total Collective Dose Risk (Person-Sv) for Release Accidents per Shipment for Each Route (1 Sv=10^5 mrem)

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

These dose risks are negligible by any standard.

Table 5-13, which is the same as Table 5-7, shows total dose risks from loss-of-lead shielding accidents. Table 5-7 is repeated here for ease of comparison. The sum of the two tables is shown in Table 5-14.

Table 5-13 Total Collective Dose Risk (Person-Sv) for Each Route from a Loss of Lead Shielding Accident (1 Sv=10^5 mrem)

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

Table 5-14 Total Collective Dose Risk (Person-Sv) from Release and Loss of Lead Shielding Accidents (1 Sv=10^5 mrem)

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

Table 5-15 shows the total collective dose risk for an accident involving the Rail-Lead shielded cask in which there is no loss of lead shielding or release. Since the collective dose risk for this type of accident depends on the TI, the collective dose risk from an accident involving the truck cask would be the same. For the Rail-Steel cask carrying canistered fuel, the collective dose risk would be slightly less because the TI is smaller. For this analysis, the cask was assumed to be immobilized for 10 hours.

Table 5-15 Total Collective Dose Risk (Person-Sv) from No-Release, No-Loss of Shielding Accidents Involving the Rail-Lead Cask (1 Sv=10^5 mrem)
Table note: (See Table 5-4)

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

Table 5-16 shows the collective accident risk for the 16 rail routes from loss of neutron shielding for the Rail-Lead cask. This table is extracted from Table V-14 in Appendix V.

Table 5-16 Total Collective Dose Risk (Person-Sv) from Loss of Neutron Shielding for Accidents Involving the Rail-Lead Cask (1 Sv=10^5 mrem)

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

5.6 Chapter Summary

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

- The 16 truck and 16 rail routes selected for study are an adequate representation of U.S. routes for SNF transportation, and there was relatively little variation in the risks per kilometer over these routes.
- The overall collective dose risks are vanishingly small.
- The collective dose risks for the two types of extra-regulatory accidents (accidents involving a release of radioactive material and loss-of-lead-shielding accidents) are negligible compared to the risk from a no-release, no-loss-of-shielding accident. There is no expectation of any release from spent fuel shipped in inner welded canisters from any impact or fire accident analyzed.
- The collective dose risk from loss of lead shielding is comparable to the collective dose risk from a release, though both are very small. The doses and collective dose risks from loss of lead shielding are smaller than those calculated in NUREG/CR-6672 because of better precision in the FE modeling and a more accurate model of the dose from a gap in the lead shield.

- The conditional risk of either a release or loss of lead shielding from a fire is negligible.
- The consequences (doses) of some releases and some loss of lead shielding scenarios that occur with extremely low probability are larger than those cited in 10 CFR 71.51; but are neither acute nor lethal. Only one in a billion accidents would result in these doses.