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Comparative Safety of the Transport of High-Level Radioactive Materials on Dedicated, Key, and Regular Trains

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This study compares the risks in transporting spent nuclear fuel and high-level radioactive waste under three rail shipment alternatives: 1) regular train service, operating without restrictions with the exception of current hazardous materials regulations; 2) dedicated train service, operating with consist and operational restrictions; and 3) key train service, similar to regular train service with the additional speed limitation of 50 mph. Dedicated train shipments have a lower overall radioactivity exposure risk during incident-free transport than shipments by regular or key trains; the advantage is primarily derived from the differences in the duration and frequency of yard visits, which account for a significant portion of total exposure for impacted populations. Crew population doses, however, are higher for dedicated trains because of crews working closer to the cask. Estimated population group exposures are low and do not include any additional protective measures, which may be implemented to mitigate exposure.

The accident analysis estimated the difference in accident probability between dedicated, regular, and key trains, and it identified two significant risks potentially impacting the cask—high-speed collisions and derailments, and long duration, high-temperature HAZMAT-involved fires. The analysis shows that speed restrictions reduce collision probability at high speeds and result in an overall reduction in the derailment rate. Dedicated trains reduce the likelihood of high-temperature fires due to lessened exposure to other hazardous material. The risk for loss of shielding accidents is shown to be lower for the shorter dedicated trains due to the decreased number of potentially derailed cars.

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Preface

This study was undertaken to fulfill the requirements of the Hazardous Materials Transportation Uniform Safety Act of 1990, which required a comparative analysis of the safety of using dedicated versus regular trains for the shipment of spent fuel. As directed by the Congress, the Federal Railroad Administration (FRA) consulted with its major stakeholders at the onset of this study; stakeholders' concerns were included in the construction of the analytical framework employed in this study. This report documents the results of that study, conducted by the Volpe National Transportation Systems Center, for the FRA of the U.S. Department of Transportation (DOT).

Several Federal agencies are involved in spent fuel transportation, most notably the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, and the DOT. These agencies have provided input into this analysis, including identifying probable shipment routes, published information on likely material characteristics and volumes, and scientific data on the behavior of the transportation cask. Sandia National Laboratories contributed assistance in the construction of simulations to estimate population effects of shipments using the RADTRAN software program. Other important contributions to the analysis were made by incorporating the results of ongoing safety analyses being conducted by FRA. This report therefore reflects very recent data and up-to-date analyses by FRA on the safety of spent fuel transportation by rail.

This report provides a comprehensive assessment of the possible differences in transportation safety resulting from the use of regular, dedicated and key (as defined by the Association of American Railroads) trains for the shipment of high-level radioactive waste (HLRW) and spent nuclear fuel (SNF). Furthermore, this report provides both a framework and a comparative analysis of alternative shipment methods. The framework can be extended to further comparisons with regard to safety as future requirements emerge. FRA will maintain an ongoing review of safety and may again employ the techniques described in this report, when necessary. For example, this report provides the comparison of three shipment methods because key trains were offered as an alternative to either regular trains or dedicated trains in the intervening years since the study originated.

The potential health hazards of SNF and HLRW are serious and are, therefore, addressed by current regulatory requirements. While these regulatory requirements provide a high level of safety for HLRW and SNF transportation, improvements in safety can still be gained. Due to its potential health hazard and the persistence of its effects, the transportation system does not treat radioactive material in the same way as other hazardous materials. The safety requirements for radioactive material transportation are generally more stringent. This is due to the actual risk posed by the material and society's perception of that risk. Given the special nature of this material, it must be assumed that the public is concerned not only with the potential for catastrophic failures of the transportation cask, but also with any non-catastrophic accident (or other event) that would increase the radiation exposure of the crew, workers, emergency response personnel, or the public. For that reason, the potential for non-catastrophic accidents was also evaluated in this report, and a comparison of those risks was factored into the overall analysis and conclusions.

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Executive Summary

This report compares the relative safety of rail shipment alternatives for the transport of spent nuclear fuel (SNF) and high-level radioactive waste (HLRW). These alternatives involve the use of: (1) regular trains: operating without restrictions with the exception of current hazardous materials and rail safety regulations; (2) key trains: similar to regular trains but operating with a maximum speed limit of 50 miles per hour (mph) or 80.4 kilometers per hour (km/hr) and other handling restrictions; and (3) dedicated trains: operating with a maximum speed limit of 50 mph (80.4 km/hr) and additional operating restrictions.

In preparation for this report, the U.S. Department of Transportation's (DOT) Volpe National Transportation Systems Center (Volpe), a part of the DOT Research and Innovative Technologies Administration (RITA), in support of the DOT Federal Railroad Administration (FRA), performed a study to provide a safety analysis on whether FRA should require carriers to use dedicated trains for shipment of SNF and HLRW.

The study was initiated once funding was appropriated for it in the spring of 1992. Representatives from the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), potentially affected States and Native American tribes, the railroad industry, and SNF/HLRW shippers were invited to attend and consult with FRA and the study contractor at a 2-day Dedicated Train Workshop held in Denver, CO, in September 1992.

In preparing this report, FRA coordinated closely with the DOT Pipeline and Hazardous Materials Safety Administration (PHMSA), which also issues regulations governing transportation of hazardous materials in all modes,[1] and with the DOT Office of the Secretary. In addition, FRA consulted with DOE and NRC. Although comments from other governmental agencies were incorporated, this report is ultimately the responsibility of DOT.

As more fully explained later in this report, the transportation of SNF/HLRW is thoroughly regulated, and several agencies of government play active, highly coordinated roles in endeavoring to ensure its safety. Over the past 45 years, approximately 600 train movements of these materials have occurred by rail without any incidents occurring that have affected the integrity of the shipping package. At the discretion of the shipper/carrier parties involved, the majority of these shipments were made using special or dedicated trains.[2] The responsible agencies work to continually verify the safety of packaging, rolling stock, procedures, and the training of personnel involved in transportation. The railroad industry also issued its own standard for movement of these commodities, which seeks to establish performance guidelines for a cask/car/train system transporting high-level radioactive material. These guidelines are

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[1] FRA, in concert with the Research and Special Programs Administration (RSPA), develops hazardous materials regulations specifically applicable to the rail mode for issuance by RSPA. FRA enforces hazardous materials regulations applicable to transportation by rail. Both agencies act by delegation from the Secretary of Transportation. Actions referred to in this report where RSPA is referenced were taken by RSPA. The PHMSA, created by P.L. 108-427, is the successor organization to RSPA for DOT's hazardous materials transportation and pipeline safety responsibilities and did not yet exist for purposes of this report.

[2] As used in this report, a special or dedicated train is a train that consists only of equipment and lading associated with the transportation of SNF/HLRW. That is, the train consists only of necessary motive power, buffer cars, and cask car(s), together with a car for escort personnel. Such a train does not transport other rail rolling stock, other revenue, or company freight.

designed to ensure safe transportation, minimize time in transit, and incorporate best available technology to minimize the potential for a rail accident.[3] This report addresses one additional means by which a greater level of safety might be achieved, the use of dedicated trains.

The study analyzed both non-incident risk from radiation emitted from the cask during transportation and accident risk. Non-incident risk from the entire future shipping campaign is estimated to be on the order of approximately one latent cancer fatality (LCF) for every 40,000 shipments in non-dedicated trains and approximately one LCF for every 50,000 shipments in dedicated trains. Using the number of rail shipments expected over the life of the shipping campaign, as stated in DOE's Environmental Impact Statement on Yucca Mountain as a measure, the potential expected LCFs would be appreciably less than one. Therefore, regardless of the type of train, the potential exposures are essentially benign when compared to a lifetime of normal background radiation exposure from the sun or heightened radiation exposure from flying in a commercial airliner at 30,000 feet. The potential exposures are also benign when compared to radiation risks associated with smoking tobacco. Given public interest in the subject matter, however, the basis for these estimates is set forth below. As the results show, if a discernable difference in risk for affected populations exists, the risk is less using a dedicated train.

With respect to accident risk, safeguards are already in place–principally NRC package certification requirements, railroad industry key train requirements, and FRA's focused inspection program–that have reduced the potential, to an extremely low probability, that a cask could be damaged in rail transportation to the extent it might release radioactive material into the environment. However, further reducing the possibility of a train accident involving a SNF/HLRW cask is highly desirable, despite the very low probability that the cask might be compromised. It is also recognized that any train accident involving a cask shipment would degrade public confidence in the ability to safely transport this material, and the presence of a cask would greatly complicate emergency response and wreck clearance operations, thus compounding costs to responders and the railroad.

Importantly, the study results support the conclusion that use of dedicated trains would reduce both the probability of a SNF/HLRW cask being involved in a train accident and the possibility that other hazardous materials might be involved that could subject a cask to a fire environment with possible loss of shielding. Although the study intentionally uses worst-case assumptions (e.g., minimum compliance with NRC fire exposure criteria) and should not be taken as an absolute measure of risk, on a comparative basis, it is apparent that a dedicated train strategy should have a favorable impact on any residual risk.

Background

SNF is fuel that has been withdrawn from a nuclear reactor following irradiation and has undergone at least 1 year's decay since being used as a source of energy in a power reactor. Further, reprocessing has not separated the constituent elements of SNF. This fuel includes: (1) intact, non-defective fuel assemblies; (2) failed fuel assemblies in canisters; (3) fuel assemblies in canisters; (4) consolidated fuel rods in canisters; (5) nonfuel components inserted in pressurized water reactor fuel assemblies; (6) fuel channels attached to boiling water reactor fuel assemblies; and (7) non-fuel components and structural parts of assemblies in canisters [42 U.S.C. § 10101(23), 40 CFR 191.02, and DOE Order 5820.2A].

[3] Association of American Railroads (AAR) Standard S-2043: Performance Standard for Trains Used to Haul High Level Radioactive Material; AAR Circular Letter C-9619, dated April 29, 2003.

HLRW results from the reprocessing of SNF in a commercial or defense facility. It includes liquid waste produced directly in reprocessing and any solid waste derived from the liquid that contains a combination of transuranic waste and fission products in concentrations requiring permanent isolation [42 U.S.C. § 10101(12), 10 CFR Part 72.3, and DOE Order 5820.2A]. HLRW meeting this definition has been shipped by modes other than rail.

SNF and HLRW must be transported in casks constructed to NRC requirements. Casks are secured to specially constructed rail cars capable of transporting the heavy load.[4] This study assumes that the cask car(s) will be surrounded by two buffer cars and accompanied by an escort car. This complement of cars is referred to as the cask consist. A dedicated train is comprised of the cask consist and multiple locomotives. A regular or key train will include the cask consist, locomotive(s), along with any number of additional cars potentially containing other regulated hazardous materials, various other general cargo, and/or empty rail cars.

Regular trains typically operate at allowable freight track speed, make numerous classification yard entries, and adhere to hazardous materials transportation regulations when transporting any regulated hazardous material, including SNF and HLRW. Since it was not possible to analyze all possible consist and operational arrangements of regular trains within the confines of this study, the model consisted of a generic regular train of 70 cars, with the cask consist in the middle of the train.[5]

In 2001, the AAR issued a Recommended Practice Circular defining any consist containing SNF or HLRW as a key train and routes with specified levels of hazardous materials including SNF and HLRW as key routes.[6] Key trains are similar to regular trains in length and general operating rules except for the following:

- No consist restriction in excess of current regulatory requirements
- Cask is placed on a flatcar between two buffer cars
- Train has a railcar with escort personnel aboard who monitor/guard the shipment
- A 50 mph (80.4 km/hr) speed restriction
- Passing not restricted unless on lower than Class 2 Track
- All cars in the consist are equipped with roller bearings with rules about alarms
- Key routes have hot bearing detection equipment at minimum intervals and the track must be inspected twice annually for internal flaws and geometry irregularities.

[4] A typical cask assembly weighs about 250,000 pounds, and a loaded cask car weighs about 394,500 pounds, in contrast to a typical rail load of 286,000 pounds. Like other cars constructed to carry heavy loads, cask cars use additional axles and span bolsters to distribute the weight over a larger portion of the track structure. Other special loads transported on the railroad include large transformers and specialized industrial equipment.

[5] FRA does not mandate specific placement of loaded and empty cars in trains except in the case of placarded cars carrying regulated hazardous materials in accordance with 49 CFR 174.85. However, industry guidelines and carrier rules exist to address train make-up in light of joint industry-government research. From the point of view of train dynamics, a heavy vehicle such as a cask car would typically require placement in the first third of the train.

[6] AAR Recommended Practice Circular OT-55D, Recommended Railroad Operating Practices for Transportation of Hazardous Materials, 2001.

In the study, by contrast, dedicated trains were assumed to operate according to the following:

- Consist is restricted–no freight other than SNF and/or HLRW is carried.
- Cask is placed on a specially designed and equipped flatcar between two buffer cars.
- Multiple locomotives.
- Train has a railcar with escort personnel aboard who monitor/guard the shipment.
- A 50-mph (80.4 km/hr) speed restriction. For completeness a 35 mph (56.3 km/hr) speed restriction was also analyzed, although this restriction no longer applies since the publication of AAR circular OT-55-D.
- Passing is restricted on all track classes. When a dedicated train is passed by another train, one of the trains remains still while the other train passes at a speed less than or equal to 50 mph (80.4 km/hr). Again, for completeness a 35-mph (56.3 km/hr) speed was also analyzed.

Between 1979 and 1997, over 1,300 shipments of commercial SNF and HLRW were made totaling over 1,102 tons (1,000 metric tons). Although only about 11 percent of the shipments were by rail, these accounted for over 75 percent of the tonnage [NRC, 1998].[7] To date, approximately 800 shipments of naval SNF and HLRW have also been safely made in both regular trains and dedicated trains. In the future, DOE estimates that a total of between 11,000 and 17,000 casks of SNF and HLRW will need to be shipped by rail [DOE, 2002b].[8] A shipment by rail can consist of a single movement of a single cask or a single movement of multiple casks with escort and buffer cars, as needed.

Safety Compliance Oversight

Regulations addressing hazard communication, training, security plans, packaging, and modal operational requirements for transporting regulated hazardous materials, which includes SNF and HLRW, exist in 49 CFR Parts 100-185 (Hazardous Materials Regulations). Rail safety regulations in 49 CFR Parts 200-244 address safety requirements for railroad operations, including: rail equipment, track, signal systems, communications, train crews, and grade crossings. These rail safety regulations apply regardless of whether any hazardous material is transported in a train.

The Nation's rail carriers conduct their own inspections in their efforts to ensure compliance with all applicable regulations. FRA and participating State agencies that have FRA-Certified State inspectors continually use the resources available to them to the extent possible to conduct inspections of the Nation's rail carriers and to ensure that regulatory compliance is being achieved.

In addition to these efforts, FRA developed and implemented the Safety Compliance Oversight Plan (SCOP),[9] a coordination and inspection plan specific to all known rail shipments of SNF and

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[7] U.S. Nuclear Regulatory Commission. Public Information Circular for Shipments of Irradiated Reactor Fuel. Washington, DC: NUREG-0725 REV13. October 1998.

[8] U.S. Department of Energy. Final Environmental Impact Statement for a Geological Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. Washington, DC: Office of Civilian Radioactive Waste Management, DOE/EIS-0250 Vol. I and II. February 2002.

[9] FRA's SCOP, can be viewed and downloaded from FRA's Web site at

HLRW. Implementation of SCOP focuses available resources to ensure the safe and secure transportation of SNF and HLRW. The SCOP addresses what tasks FRA and its FRA-certified State inspection partners will perform for shipments of SNF and HLRW. The tasks cover all operational aspects of the rail transportation environment, as well as planning and coordination tasks with entities and agencies involved in the transportation of this material.

To date, FRA has implemented the SCOP for each movement due to the infrequency of these shipments. However, FRA recognizes that as shipments ramp up, which could be as early as 2007, it will be become increasingly difficult to implement the SCOP tasks in their entirety as they currently exist for every shipment. Congress has recognized the importance of ensuring that shipments of SNF and HLRW move safely and securely and has provided FRA with the ability to add inspection personnel via the budget process. Regardless of the type of train used for this function, FRA and participating State agencies will continue to facilitate the safest possible transportation of SNF/HLRW by enforcing the railroad safety laws and regulations, and the Hazardous Materials Regulations. It is evident, however, that FRA's task in this regard is greatly simplified and the likelihood of success is enhanced, where dedicated equipment is employed and the route is as direct and well suited to the mission as possible. Concentrating on the safety of a discrete subset of locomotives and cars, and surveying a route that avoids congested yards will increase the likelihood that safety concerns are reliably identified and remedied before the railroad accepts the shipment.

Comparative Risk Assessment

The study assumed two basic types of risks involved with transporting SNF and HLRW: (1) incident-free risks and (2) accident-related risks. The incident-free risks associated with normal emissions of very low radiation doses from the cask involved absolute risks of appreciably less than one LCF for the entire exposed population for the highest risk case, the regular train, over an entire shipping campaign. Primarily because of the reduced time in transportation, incident-free risk was lowest for dedicated trains (again appreciably less than one LCF for the shipping campaign). These estimates are higher than would be realized in actuality, as they assume the maximum allowed emissions from the casks in non-exclusive use transportation rather than the generally lower emissions from actual shipments.[10]

Incident-free risks result from continuous emissions of low doses of radiation, which the cask shielding cannot totally contain. The emissions, however, can and are limited to acceptable safe levels (a maximum of 10 millirems per hour (mrem/hr) at 3.3 ft (1 m) from the surface of the package [49 CFR 173.441]). All individuals exposed to the radiation being emitted from the cask during transport, handling, loading, and unloading are exposed to very low doses of incident-free radiation.

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www.fra.gov/downloads/safety/scopfnl.pdf.

[10] Before proffering a cask for shipment, the shipper must demonstrate compliance of the cask design with 10 CFR Part 71, as promulgated by NRC. Experience has shown that radiation levels emitted by the package are generally below the maximum allowed by regulation for non-exclusive use shipments due to the shielding built into the packages and the efforts of the shipper to reduce the external radiation levels to be as low as possible. In addition, radiation levels are checked by State and Federal Government agencies before being offered into transportation and can also be monitored while in transportation. FRA recently secured additional staff to support this function.

Accident-related risks result from the potential of exposure to radiation after an accident occurs. Radiological consequences were calculated for accidents where consequences vary with the use of a regular, key, or dedicated train service. For each accident type, incident durations from 3 to 72 hours were analyzed to account for a range of severities, and three locations types, urban, suburban, and rural, were analyzed. For the purposes of this study, accidents were broken down into four severity categories:

- *Category I* Delay event. Accident well within the Hypothetical Accident Conditions (HAC) modeled by the cask packaging test criteria of 10 CFR Part 71; dose rate assumed equivalent to the allowed non-exclusive use transport rate of 10 mrem/hr at 3.3 feet (1 m) from the cask surface. Accidents in Category I could result in an increased duration of exposure to certain individuals (such as crew and nearby population) due to the extended time required to clear the wreck scene and resume transport.

- *Category II* Serious accident. An accident close to the HAC, which could result in a hundredfold increase in radiation levels, but no release of radioactive material occurs. The dose rate is assumed equal to 1 rem/hr (1,000 mrem/hr) at 3.3 feet (1 m) from the cask surface. Accidents in Category II could expose populations to higher doses of radiation for extended time periods.

- *Category III* Major accident. An accident that generates forces or temperatures that exceed the HAC. A greater loss of shielding or internal damage occurs but no release of radioactive material occurs. The dose rate is assumed to be equal to 4.3 rem/hr (4,300 mrem/hr) at 3.3 feet (1 m) from the cask surface. Accidents in Category III could expose populations to higher doses of radiation for extended time periods.

- *Category IV* Severe accident. An accident resulting in forces or temperatures well in excess of the HAC. A significant loss of shielding or cask damage resulting in the release of some radioactive material. This category was not analyzed as it was considered equally unlikely for any of the shipping options, and the consequences would not be substantially different.

The consequences of any of these four types of accidents are determined by the environment in which the accident occurred; the potential for a second event, such as a fire following the initial impact, puncture, or fall; and the time required to respond to the accident.

Incident-free and accident-related risks are analyzed for entire populations, and results are expressed as population doses (person-rem). These population doses are also converted into an estimate of health effects (i.e. LCFs). Doses for individuals (where applicable and possible) are expressed in units of mrem.

The use of LCF as a metric of deleterious health effect is based upon the assumption that any amount of radiation exposure may pose some risk. This is the linear, no-threshold (LNT) model, in which any increase in dose has an incremental increase in the risk of occurrence of cancer. LNT is the accepted model used in the United States, as well as by international radiation protection bodies. The LCF rate for worker population is 0.0004 per person-rem, while the LCF rate for the general population is 0.0005 per person-rem [NCRP 1993].[11] When the rates are applied to an

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[11] National Council on Radiation Protection and Measurement (NCRP). Limitation of Exposure to Ionizing

individual, the units are for a lifetime probability of LCFs per rem (or 1,000 mrem) of radiation dose. When the rates are applied towards a population of individuals, the units are excess number of cancers per person-rem of radiation dose. The difference between the worker dose and the general public risk is attributable to the fact that the general population includes more individuals in sensitive age groups (that is, less than 18 years of age and over 65 years of age).

Calculating Risk

The total risk associated with transporting SNF and HLRW is the result of both incident-free risk and accident-related risk. The amount of the low-level exposure associated with incident-free transport depends on the details of the number of shipments, specific routes, and operating variations. Accident risks are associated with relatively low probability events. The accident probabilities are based on historical accident data independent of a specific route or location. Incident-free and accident-related risks of radiological exposure are calculated independently for regular, key, or dedicated train service. The results from these calculations are then compared against commonly accepted radiological exposures to put the calculated risk into perspective.

Incident-Free Risk

Incident-free risk involves calculating the total expected radiation dose to the public and other impacted populations for specific routes, assuming no accidents, and comparing that calculation to the incident-free risk for regular, key, and dedicated trains. A radiation level of 10 mrem per hour measured at 3.3 ft. (1 m) from the package surface was used to calculate population exposures; this is the maximum level for radioactive material packages in non-exclusive use service. The results are also compared to the radiation received by a passenger on a 4-hour airline flight. Regulations in 49 CFR 173.441 for exclusive-use shipments do allow for higher radiation levels to exist both at the package surface and at 1 m from the package, and yet still allow the package to be transported, but only if additional safety measures are implemented. Experience with shipments of SNF and HLRW to date have shown that the radiation levels are well within the prescribed lower regulatory limits for non-exclusive use shipments and therefore are the norm.

Though SNF/HLRW casks are very well shielded by design, they continuously emit low levels of radiation throughout all phases of transportation. Hence, radiation exposure to crew, handlers, yard personnel, and the wayside population occurs even in the event that an accident does not occur. Therefore the probability of exposure is equal to one. The exposure of all affected populations during regular transport is defined as the incident-free risk. The radiological consequences of SNF/HLRW shipments are a function of the selected route, the cask design and material being transported, the size of the impacted populations, the population distance from the cask, the total exposure time, and the amount of shielding between the cask and the impacted populations.

RADTRAN 5, a set of computer models for the analysis of the consequences and risks of radioactive material transport, was used to calculate the incident-free risk. The package dose rate and the package-specific characteristics are used to model the transport cask as a point source for extended distances. For shorter distances, within two characteristic lengths of the cask, the package is treated as a line source. The transportation system characteristics are incorporated into a rail-specific model, with input parameters for population along the route and at stops, which

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Radiation. Bethesda, MD: NCRP Report No. 116 1993.

include vehicle velocity and stop duration. The population density is defined by the user along each route segment. Inputs include the specific characteristics of sub-populations like the number of passengers, crews, and rail workers. The general population is broken into three sub-groups: urban, suburban, and rural.

The calculations were conducted for in-transit exposures (off-link and on-link) and exposures at stops. Off-link doses are defined as those received by persons on the ground within 875 yards (800 m) of a passing train. On-link doses are defined as doses received by persons on passing trains, as well as by the escorts and crews on board the cask-carrying train. Stop doses were calculated as doses received by persons on the ground as well as crew and escorts within 875 yards (800 m) of the train during a stop.

Six routes were chosen for analysis. These routes were chosen to cover a representative number of origination locations across the country with currently operating nuclear power plants or waste repositories that handle SNF or HLRW. The presumed destination point for all routes is Yucca Mountain in Nevada. Table 1 provides a breakdown of the length of each route, as well as the associated average population densities along each route broken down into urban, suburban, and rural sub-groups. The selected routes are likely candidates and are representative in terms of their geographic location and length.

Many designs and sizes of casks exist for transporting SNF and HLRW. For purposes of this study, it is assumed that the cask will be a large 125-ton (113-metric ton) multi-purpose rail cask [DOE, 1993].[12] The incident-free dose rate was taken as 10 mrem/hr at 3.3 feet (1 m). As described above, the transport cask emission rate was modeled as either a point source or a line source depending on the distance of the exposed population from the transport cask.

Table 1. Routes Used in the Analysis

Route Number	Origin	Length	Average Population Density persons/sq mile (persons/sq km)		
		Miles (km)	Urban	Suburban	Rural
1	Humboldt Nuclear Power Plant, CA	1,090 (1,754)	6,237 (2,408)	1,164 (449)	26 (10)
2	Crystal River Nuclear Power Plant, FL	2,988 (4,809)	5,641 (2,178)	976 (377)	38 (15)
3	Dresden Nuclear Power Plant Dock, IL	1,920 (3,090)	5,169 (1,996)	1,006 (389)	26 (10)
4	River Bend Nuclear Power Plant, LA	2,471 (3,977)	4,964 (1,917)	919 (355)	30 (12)
5	Seabrook Nuclear Power Plant, NH	3,086 (4,966)	6,109 (2,359)	1,028 (397)	30 (12)
6	Hanford Repository, WA	1,226 (1,973)	4,744 (1,832)	1,307 (505)	17 (7)

Source: 2000 U.S. Census.

The exposed populations were broken down into the following categories:

- General population, which is individuals residing and working near rail lines (waysides) over which the cask passes as well as people who live near yards and sidings where the cask consist may stop temporarily

[12] U.S. Department of Energy. MPS Conceptual Design. Draft 1993.

- Persons on trains sharing the route of the shipment
- Vehicle occupants at grade crossings along the shipment route
- Train crew located in the lead locomotive on the train transporting the SNF/HLRW
- Escorts on the train transporting the SNF/HLRW
- Railroad personnel who work in close proximity to the cask in classification yards and inspect the train at various points
- Other rail yard workers not in close proximity of the shipment

Each of the different groups experience different exposure levels and durations. Wayside populations and passengers on passing trains will be exposed as the shipment passes. High-resolution population data was used from the 2000 U.S. Census to allocate population density along the length of each route in a 1-mile wide corridor. Greater exposure will be calculated for longer routes that are highly populated. This is because exposure time is the determining factor in the amount of radiation members of a population group receive. Time spent near both moving and standing shipments affect exposure. Train operational restrictions, such as train speed and run-through operations, impact exposure time at stops and in transit.

The train density and train occupancy data derived from the Rail Garrison[13] network studies were used to assign the number of persons likely to be sharing the railway with the shipment. The average passenger train density was used for the three general population sub-groups: urban at 0.4 trains/hr, suburban at 0.2 trains/hr, and rural at 0.14 trains/hr. The weighted average train speed for each type of train is the determining parameter for exposure. The faster the trains are allowed to travel, the shorter the exposure time.

Vehicle occupants at grade crossings on each side of the railroad can be exposed to emissions from passing shipments. The exposure to this sub-population was split into two different calculations: one for the general sub-population and the second for cars within a prescribed distance to the passing shipment. For purposes of this study, it was assumed that five vehicles would be occupying either side of the track during the passing of a shipment.

Members of the train crew and escorts are exposed for the full duration of the shipment and therefore experience the highest exposure levels of any sub-population. The exposures for these sub-populations are governed by distance from the source, length of route, and stops. Crew members on regular or key trains have the advantage of being further away from the cask consist than those on dedicated trains. The position of the escorts on any train type, however, is the same.

During stops at yards or sidings, other railroad personnel will be exposed for the duration of the stop. Since train stops usually occur at rail yards, the population in and near a rail yard is modeled as a uniformly distributed population and the dose is integrated into this population. For rail stops, the public dose was calculated using the suburban population density. Greater exposure occurs for longer stop times and along routes that have more stops.

[13] Peacekeeper Rail Garrison Program, Rail Network Database developed by Earth Technology Corporation for the Department of The Air Force. Network not publicly available, but similar network data available from National 1:100,000 Scale Rail Network, distributed on the National Transportation Atlas Database produced by the Bureau of Transportation Statistics (BTS).

Exposure time for incident-free risk is determined by train speed, whether run-through operations are allowed, and the number of stops required at yards or sidings. The speed restrictions on key and dedicated trains increase in-transit exposure time when compared to regular trains. The difference, however, is greatly affected by such factors as the class of track over which the shipment traverses. Higher track classes allow for greater train speeds.

The last critical factor associated with exposure is the type of shielding factor that is applied to the various sub-populations to determine gamma radiation attenuation (absorption by physical structures). For the general wayside population different shielding factors were applied depending on the population density. Rural populations were assigned a shielding value of 1.0, which corresponds to no shielding. Suburban populations were assigned a shielding factor of 0.87 because of the presence of closely spaced structures generally constructed from wood and cinderblocks. The urban population had the highest shielding factor of 0.018 due to the concentration of buildings constructed from concrete and steel. Occupants at grade crossings, train passengers, escorts, and inspectors/handlers were assigned a shielding factor of 1.0 (no shielding). Crewmembers were assigned a shielding factor of 0.5 assuming that the intermediate locomotive(s) provides gamma radiation attenuation. General yard workers were assigned a shielding factor of 0.1 due to the mitigating effects of gamma radiation attenuation by rail cars and structures in the rail yard. The suburban shielding factor was used for the general population for all stops.

Risk to all population groups is strictly a function of the period of exposure, distance from the cask, and the assumed level of shielding provided by intervening equipment or buildings. Transit time and time in yards becomes a major determinant when comparing service options.

Accident-Related Risk

Accident-related risk involves comparing the radiological exposure due to accidents with that for regular, key, and dedicated train service by using three components: accident involvement probability, accident severity probability, and expected consequences.

Accident-related risk is the second form of risk associated with the transport of SNF and HLRW along the national rail corridors between originations and final destination. Aggregate accident-related exposure is not calculated; aggregate accident probabilities, not specific to routes, are calculated. Potential accident-related exposure is examined by predicting the accident likelihood for the three rail transport methods and then assigning radiological consequences, broken down into four severity categories. The baseline accident probability is calculated for regular train transport using historical accident data from 1988 to 2001. Dividing the total number of accidents by reported train miles for each year normalized these historical accident rates. The rates were then adjusted to reflect the special constraints associated with key and dedicated trains.

Event schematic trees based on these probabilities were then constructed that show the probability of any mainline or yard accident for regular train service. During this 1988-2001 period, the number of train miles varied from year to year but has generally risen. A long period was chosen to help determine the probability of extremely rare events, such as major fires or high-speed collisions. The variation in accident probability in terms of train miles is not expected to noticeably change with the addition of dedicated trains in the future. Changes in operating practices and improvements in equipment and infrastructure maintenance should reduce these rates. For this analysis, the accident probability is assumed to be constant, as reflected by the event trees. These trees were then modified to reflect the effect of key and dedicated trains on accident probabilities. Aside from speed limits, the dedicated train modifications included operational restrictions, consist limits, and reduced visits to yards.

Radiological-related risks from accidents are based upon the following factors: the design of the cask and its ability to withstand mechanical, thermal, and combined mechanical and thermal accident loads; the likely level of loss-of-shielding (LOS) resulting from accident loads; and the effect of that radiation on crews, escorts, emergency response personnel, and the general population surrounding an accident site.

A key assumption in the analysis was the response of the generic cask design. Analysis results were taken from a Sandia National Laboratories study performed on a bare cask with no impact limiters, impacting surfaces with varying hardness, at a range of impact speeds, and in different orientations. Force-crush characteristics were taken from that study for the hypothetical 125-ton (113 metric ton) steel-lead-steel cask. These characteristics were then used as inputs into a simplified collision dynamics model to investigate residual cask impact speeds for secondary impacts. The conservative assumption was made that any impacts in the rail environment would be considered as impacts into a hard but not unyielding surface. The speed equivalent of the NRC-required package certification HAC drop test criteria in 10 CFR Part 71 onto an essentially unyielding planar surface has been determined to be 30 mph.

Substantial kinetic energy is associated with a train in the event of a collision or derailment. This energy must be dissipated through various mechanisms before the train comes to a complete stop. Energy consumption through plastic deformations of colliding objects, plowing of rails and ballast, and emergency braking are only a few ways that the collision energy is absorbed. Of concern for this analysis is the consumption of energy through plastic deformations of rail equipment and the cask. Two collision types were studied: a primary impact against a heavy freight locomotive and a subsequent secondary impact against the surrounding infrastructure or environment.

A transport cask impact with a heavy freight locomotive was chosen as a representative example of a worse case primary impact in the rail environment. Two impact load paths were assumed for crush of a generic freight locomotive. Using each crush trajectory, force-crush characteristics were developed based upon previous crashworthiness work. The force-crush characteristics of both the transport cask and the freight locomotive were used to establish LOS from a direct impact of the cask with a locomotive. LOS addresses the extent or degree that a SNF/HLRW cask may experience alteration of the radiation shielding component of the cask package, potentially resulting in increased radiation fields outside the cask package envelope. It was determined that cask damage could not occur for primary impacts with a heavy freight locomotive.

The second collision type studied was secondary impact of bare transport casks, without force limiters with the surrounding rail environment. The cask residual speed after a primary impact at various cask orientations and speeds was calculated for the following classes of collisions: head-on, rear-end, rail-rail crossings, and raking/corner impacts. Calculations were performed to determine scenarios where residual cask speeds exceeded the required NRC package certification drop test speed equivalent. This information was then used to estimate the accident consequences for the four severity categories.

Three event trees were constructed for regular train service: one for mainline incidents, one for yard incidents, and one for fires. Fires are treated independently because they can be initiating events or a secondary event following one of the other accident scenarios. The distinction between mainline and yard accidents is made to account for the significant difference in the number of yard entries made by a regular/key train versus a dedicated train. A significant decrease in accident probability results from this operational distinction. This information is used when modifying the accident rates for dedicated trains.

Each event tree begins with the overall train accident rate per train mile based upon the historical accident review. Accidents are further subdivided into the following categories: collision, derailment, highway-rail grade crossing, fires/explosions, and miscellaneous. The probabilities for these sub-accident distinctions are reflected in the second level nodes on the event tree. These sub-accidents can result in a derailment, so the probability of a subsequent derailment is also calculated. Accident severity is calculated using the range of speeds that the derailment occurs at and is broken down into the four severity categories. The severity category is based upon the comparison of the final derailment speed to the required NRC package certification drop test speed equivalent.

Study Results

Incident-Free Risk

The total exposure during incident-free transport of SNF and HLRW is extremely low for all train service types (regular, key, and dedicated). In all of the examined representative routes, the expected number of LCFs incurred by any type of train service is less than one for the total estimated number of shipments over the entire projected DOE shipping campaign.

The magnitude of radiation dosage to any population in incident-free shipping of SNF and HLRW is dependent on the total exposure time and the distance from the shipping cask. Exposure time, therefore, is heavily influenced by the amount of stop time (mostly in rail yards) and the amount of time the shipment is in transit.

Although all train service types have extremely low dose levels, measurable differences exist in radiological exposure due to the service type. Regular and key train service would result in higher potential doses to the general public, with estimates of 0.0235 person-rem to 0.0495 person-rem per single cask shipment. This translates into LCF estimates of 1.17×10^{-5} to 2.48×10^{-5} per single cask shipment; in the worst case, this is roughly one LCF for every 40,000 shipments. DOE estimates that approximately 11,000 to 17,000 waste packages are to be shipped by rail over the entire campaign [DOE 2002b]. Dedicated trains reduce this exposure range to 0.0177 person-rem to 0.0364 person-rem per shipment, or 8.85×10^{-6} to 1.82×10^{-5} LCF. The highest range of this estimate corresponds to approximately one LCF per 50,000 shipments. This reduction is primarily due to the fact that dedicated trains do not stop in yards for classification, reducing the total exposure time.

The total radiation dose to a person standing 98.5 ft (30 m) from a train carrying a single SNF/HLRW car as it passes at 15 mph (24 km/hr) is calculated to be approximately 0.0004 mrem (this value is independent of train type). For comparison, the average dose received by a passenger on a 4-hour jet flight is roughly 3 mrem or 4 orders of magnitude greater than a cask shipment.

Rail worker doses are lower for dedicated trains than for key and regular trains. The total radiation dose to all rail workers through regular or key trains for the examined routes ranges from 0.0988 person-rem to 0.1755 person-rem per shipment, or 3.95×10^{-5} to 7.02×10^{-5} LCF. The highest range of this estimate corresponds to approximately one LCF per 14,000 shipments. Dedicated train single shipment doses ranged from 0.0496 person-rem to 0.0987 person-rem, which translates into 1.98×10^{-5} to 3.95×10^{-5} LCF. This small decrease in absolute dose value is primarily due to the reduced yard visits of dedicated trains.

Train crew doses are actually higher for dedicated trains than for the other service types due to the proximity of the cask car to the locomotive in a dedicated train consist; however, in all cases the radiation exposure of the train crew from a single cask shipment is multiple orders of magnitude less than the annual limits prescribed by Federal regulations (10 CFR 20). The highest exposure estimate of a dedicated train crewmember is 0.808 mrem per single cask shipment. For comparison, the regulatory maximum annual dose for non-radiation workers is 100 mrem, or over 100 single cask shipments in a year by the same crewperson for this worst-case dose estimate. The highest crewperson dose per single cask shipment for regular or key trains is less, approximately 0.016 mrem.

Accident-Related Risk

The assumptions used to analyze the accident consequences and probabilities make regular and key trains nearly identical in terms of risk.

The historical accident probabilities were sorted by the resulting radiological severity category. The consequences of Category I, II, and III accidents are slight in terms of resulting LCF for all train service types. Analysis indicates that Category II and III accidents are very unlikely events, regardless of service type.

The event trees constructed from historical accident data indicate that the most likely sources of Category II accidents are derailment accidents and yard accidents. The probability of an accident that is more severe than the NRC HAC package certification regulatory test requirements (Category III) is extremely low for all service types. Dedicated trains have the lowest accident probability due to the decreased stopping distance of the shorter consist, the fewer number of cars to derail, and fewer yard visits (decreasing yard accident probabilities). The probability of a fire engulfing the cask car is lower for dedicated trains because cars carrying hazardous materials are restricted from the consist.

The predicted LCF consequences of Category I, II, and III accidents are multiple orders of magnitude less than one per incident, regardless of service type. As with incident-free transport, differences in service are delineated in the results of this study. Regular or key trains involved in a Category III accident are estimated to result in less than 0.03 LCF. The LCF prediction for dedicated trains involved in a Category III accident is considerably lower, less than 0.009 LCF. The differential is due to the fact that the greater number of cars in regular and key trains requires more rerailing time. The accident consequences of Category I and II accidents are substantially less severe, resulting in several orders of magnitude less than one LCF per incident.

Significance of Findings

The study concluded that the maximum individual radiological exposure resulting from an incident-free shipment of SNF or HLRW by regular, key, and dedicated trains is approximately equal to the exposure received in the first 2 seconds of a typical 4-hour airline journey. Figure 1 compares incident-free exposure rate with other common exposures.

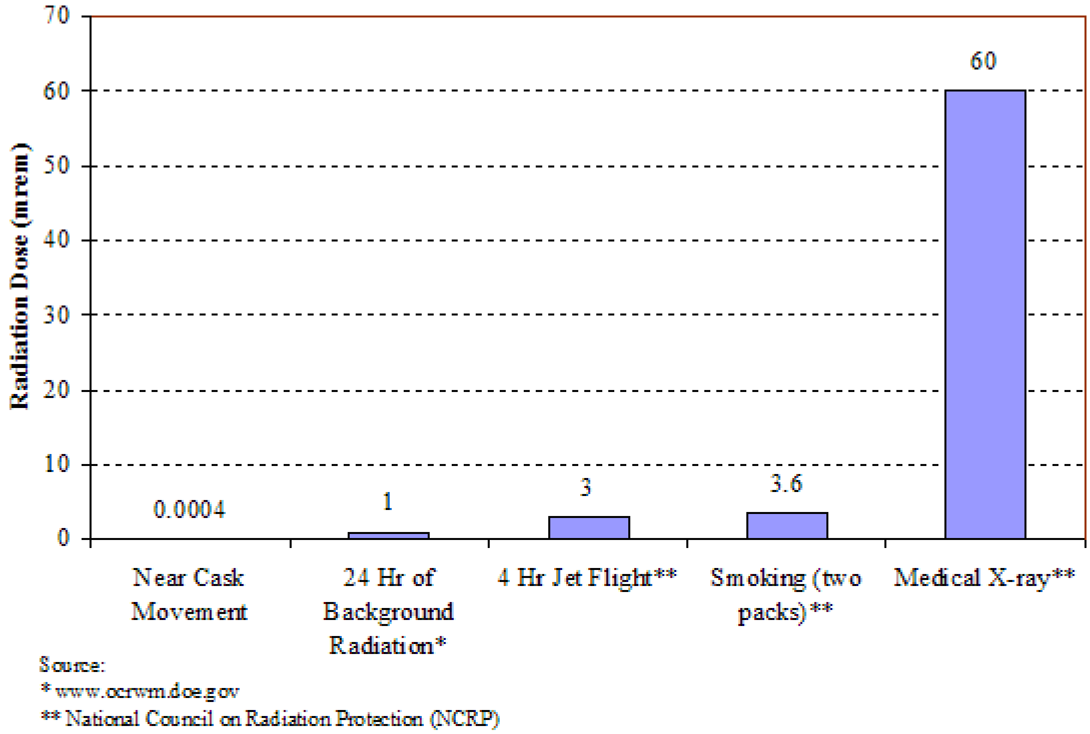

Figure 1. Comparison of Incident-Free Exposure Rate versus Other Common Exposures

The dominant feature that differentiates the three types of service in the incident-free analysis is transit time. Although key and dedicated trains have a 50 mph operating speed limit, dedicated trains will have the shortest transit times because they would spend less time in yards.

Dedicated trains would be expected to have lower collective population exposures because of the shorter transit times. Dedicated train crew exposures would be higher because of the cask being closer to the crew. The study did not take into account potential as low as reasonably achievable (ALARA) radiation controls that could be used by train crews to further limit their potential exposure.

When considering the accident-related radiological risks, three relevant issues exist, which are: the likelihood of an accident, the severity of the accident, and the recovery time from the accident. When considering the accident risk, the likelihood of a category III accident, where cask damage exceeds regulatory limits but does not involve radioactive material release, dominates the analysis. For all types of service studied, the category III events are very rare. The resulting exposure would still result in a small fraction of one LCF.

Dedicated trains, compared to regular and key trains, reduce the potential radiation exposure in any accident, as accident clearing can be expedited with shorter trains. In addition, since no other hazardous materials are in the consist, little chance of a fire would occur, which would prolong the response and accident clearing duration.

Key trains, similar to dedicated trains, provide an increase in safety resulting from speed restrictions but are more similar to regular trains in terms of overall risk. Key trains have a risk of high-speed impacts equal to or slightly greater than that of dedicated trains, which could result in cask damage that could potentially exceed the criteria to which it was certified. A severe fire involvement and yard accident probability of a key train is equal to the risk for regular trains. Given a derailment, the length of regular and key trains and the likely number of derailing cars will extend the time necessary to address an accident and increase the radiation dose to surrounding populations.

Analysis of the location and pattern of accident occurrences indicates that route-specific factors, such as the number of yards encountered, can have a significant impact on risks. The use of dedicated trains will expedite shipments and will reduce the hazards associated with frequent yard visits, especially on long routes where multiple stops in yards are required. Use of dedicated trains also allows more flexibility to avoid higher risk locations and to impose restrictions such as lower operating speeds.

In this study a consist of only one cask was assumed to be present in any of the transport options. Operating consists of multiple casks could be included in any of the trains, changing the cumulative exposures to crewmembers and the general public. Multiple cask consists would, in general, reduce the cumulative radiation exposure for the incident-free case but might slightly increase the probability of severe accidents due to a cask-to-cask collision.

Total System Risk

Some analyses of the merits of dedicated trains suggest that their use would increase train miles and, thus, overall increase risk in rail transportation. FRA appreciates this perspective but believes this consideration is not dispositive for the following reasons:

- Any additional net increase in exposure is significantly less than that associated with the dedicated train. A conventional train would need to switch the shipping point, incurring risk similar to that incurred by the dedicated train. Depending upon the configuration of the rail facilities, including the industry track, additional risk might be introduced related to cars left on the main line (collision potential, roll-away potential) in the conventional train configuration. The same issues apply at destination.
- As reflected in the Volpe study, the more direct route taken by the dedicated train reduces both non-incident and accident-related risks associated with this type of shipment.
- Under the new AAR Standard, the likelihood of derailment associated with transportation of the overweight cask car will be further mitigated through use of a state-of-the-art consist. (Although defined in terms of key trains, this is actually a dedicated train concept and is wholly incompatible with a general manifest train.)
- Use of Electronically Controlled Pneumatic (ECP) brakes by a dedicated train will reduce or greatly mitigate collision events, including highway-rail crossing collisions.
- The principal element of exposure for all types of trains are highway-rail grade crossing accidents. This exposure, and it is the same for dedicated, key, and regular trains, is in decline due to improvements in engineering, education, and enforcement (when compared with the incident rate during earlier studies).[14]

As a society, some risks are tolerated more readily than others. Normal risks associated with rail transportation are more readily tolerated than the risk of a significant event involving a SNF/HLRW movement, in part because of limited public understanding regarding the safeguards

[14] Exposure related to trespassers on railroad property is a material issue, but it is by no means clear that the number of casualties varies by number of trains operated or by train miles.

provided. Where public tolerance is low, value (in the form of reduced anxiety and increased acceptance) exists in further reducing the already low risk that a serious event will occur.

Summary and Conclusion

The study indicates that risk to employees and the public from transportation of SNF/HLRW is low, but on a comparative basis dedicated trains appear to offer advantages over general consists. Several of these inherent advantages─avoiding yards, reducing derailment potential, and reducing the risk of involvement of other hazardous materials in an accident scenario─could be further exploited with careful attention to conditions of transportation.

For instance, the recent AAR Standard S-2043,[15] which was issued too late for formal consideration, calls for use of ECP brakes on trains carrying SNF/HLRW. ECP brakes have the capability of reducing stopping distances by 40-60 percent. Coupled with uniform composition of the consist, ECP brakes should significantly enhance the ability of the locomotive engineer to control in-train forces and mitigate the severity of collision with other trains and obstructions on the right-of-way, including vehicles at highway-rail crossings. In some cases, collisions may be avoided entirely. Use of the communications backbone provided by ECP brakes may also make possible the use of onboard sensors that can identify safety problems, such as overheated bearings, before they progress to failure. These kinds of engineering enhancements should be possible with equipment dedicated to these special trains. By contrast, such enhancements will not be implemented for some time on the general interchange fleet.

FRA's SCOP efforts are also much more likely to be successful if dedicated equipment and special trains are employed. While inspection processes are a proven, essential element of quality control, they work best as part of a total system approach. Being able to examine dedicated equipment at regularly established shop locations and following the service history of the equipment to identify any propensities for wear or malfunction will increase the reliability of the inspection process both for the railroad and FRA.

Historically, the principal objection to use of dedicated trains was cost to the shipper. FRA's preliminary analysis, however, indicates that use of dedicated trains should not result in significantly higher costs for these movements. Bypassing switching yards dramatically shortens transit times and lowers the cost of dedicated train operations. Dedicated trains comprised of state-of-the-art equipment maintained for this service and operated in small consists should incur many fewer mechanical malfunctions (e.g., broken coupler knuckles, unintended emergency brake applications) that could delay transportation and result in unexpected costs to shippers and the railroad.

A cost comparison of the six routes used in the study indicates that the operational and escort labor costs of dedicated train shipments of at least three casks or more are approximately equal to or less than if shipped by a train which would require yard switching. Thus the inherent cost of a dedicated locomotive and crew can be offset by the shorter transit time. Public costs should also be lower, since SCOP inspections can focus on a smaller number of route miles and fewer units of rolling stock.

[15] AAR. Performance Standard for Trains Used to Haul High Level Radioactive Material. Washington, DC: AAR Circular Letter c-9619/AAR Standard S-2043. April 2003.

1. Introduction

This report compares the relative safety for three rail shipment methods (regular, key, and dedicated trains) for the transport of SNF and HLRW. This analysis of the three rail shipment methods considers the safety impacts resulting from accidents, as well as from radioactive emissions, that occur continuously during incident-free shipments.

1.1 Purpose

This study compares the safety of using trains operated exclusively for transporting HLRW and SNF (hereafter referred to as dedicated trains) with the safety of using standard freight manifest trains. SNF is fuel that has been withdrawn from a nuclear reactor following irradiation, has undergone at least 1 year's decay since being used as a source of energy in a power reactor, and the constituent elements of which have not separated by reprocessing. SNF includes (1) intact, non-defective fuel assemblies, (2) failed fuel assemblies in canisters, (3) fuel assemblies in canisters, (4) consolidated fuel rods in canisters, (5) non-fuel components inserted in pressurized water reactor fuel assemblies, (6) fuel channels attached to boiling water reactor fuel assemblies, and (7) non-fuel components and structural parts of assemblies in canisters (40 CFR 191.02 and DOE Order 5820.2A). HLRW is the waste material that results from the reprocessing of SNF in a commercial or defense facility, including liquid waste produced directly in reprocessing and any solid waste derived from the liquid that contains a combination of transuranic waste and fission products in concentrations requiring permanent isolation (10 CFR Part 72.3 and DOE Order 5820.2A).

1.2 Background

This study was performed in response to the Congressional request to examine whether or not regulations from the DOT should be issued to all carriers of HLRW and SNF that shipments be moved by dedicated train. Specifically, Section 116 of the Hazardous Materials Transportation Uniform Safety Act (HMTUSA) of 1990 states:

> Transportation of Certain Highly Radioactive Materials
>
> (a) Railroad Transportation Study. The Secretary, in consultation with the Department of Energy, the Nuclear Regulatory Commission, potentially affected States and Indian Tribes, representatives of the railroad transportation industry and shippers of high-level radioactive waste and spent nuclear fuel, shall undertake a study comparing the safety of using trains operated exclusively for transporting high-level radioactive waste and spent nuclear fuel (hereinafter in this section referred to as 'dedicated trains') with the safety of using other methods of rail transportation for such purposes. The Secretary shall report the results of the study to Congress not later than one year after the date of enactment of this section.
>
> (b) Safe Rail Transport of Certain Radioactive Materials. Within 24 months after the date of enactment of this section, taking into consideration the findings of the study conducted pursuant to subsection (a), the Secretary shall amend existing regulations as the Secretary deems appropriate to provide for the safe transportation by rail of high-level radioactive waste and spent nuclear fuel by various methods of rail transportation, including by dedicated train.

FRA consulted with the DOE, NRC, affected States and Indian Tribes, representatives of the railroad industry, and other stakeholders on September 28 and 29, 1992, in Denver, CO (see stakeholder positions in Appendix B). The results of those consultations have provided useful information for the analyses reported in this document. Ongoing analyses conducted by other concerned agencies, such as DOE and NRC, warranted modifications in analyses conducted by FRA. This report employs the most recently available data from all sources through 2001.

For the purposes of this study, safety is defined in terms of the risk of the loss of human life. This analysis considers train crews, escorts, yard personnel, emergency responders, vehicle occupants at grade crossings, and wayside population. Loss of life of any of these individual counts are equal.

1.3 Definitions of Spent Nuclear Fuel and high level Radioactive Waste

SNF

SNF is "fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing" [DOE, 2002a].

SNF comes from commercial nuclear power plants, research reactors, and nuclear powered U.S. Navy warships. SNF also results from the production activities of the DOE-owned reactors, reactor design testing, and energy research. Currently, most SNF assemblies are stored at the reactor site in pools of water, above-ground vaults, or concrete casks; some are shipped to another temporary storage site.

HLRW

HLRW is "(1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (2) Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation" [DOE, 2002a].

HLRW is stored temporarily in underground tanks and vaults at Government sites. Four locations in the United States currently process and store the majority of HLRW: Hanford, Washington, the Idaho National Engineering and Environmental Laboratory, the Savannah River site in South Carolina, and the West Valley Demonstration Project in upstate New York.

Shipment Assumptions

Based upon the current plan presented by DOE in the "Final Environmental Impact Statement (FEIS) for a Geological Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain" [DOE, 2002b], this report assumes the following:

- *Commercial Spent Fuel (CSF)*. By 2046 the projected total quantity of CSF to be shipped to the Yucca Mountain facility is 63,000 metric tons heavy metal (MTHM). CSF is shipped in fuel assemblies that are bundled together and shipped within a rail shipping cask. Shipments of CSF are assumed to contain a number of assemblies per large shipping container (see Figure and Figure).

- *DOE SNF and HLRW*. The FEIS shows that in the current plan the total volume of inventory DOE SNF to be shipped is 2,333 MTHM and 8,315 canisters of HLRW. The DOE SNF is placed within individual canisters (see Figure 2 and Figure 3), and five canisters are shipped in a rail cask. HLRW is assumed to be shipped in either small 1.5-ft (46-cm) or large 2-ft (61-cm) diameter canisters; DOE assumes that either nine small or four large canisters would be shipped per railcar cask shipment.

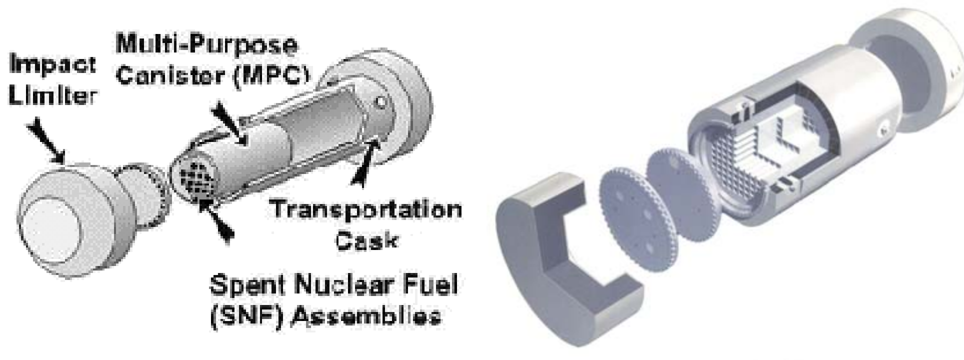

Figure 2. Cask Systems–DOE Multi-Purpose Canister (MPC) and Mitsubishi Dual Purpose Cask

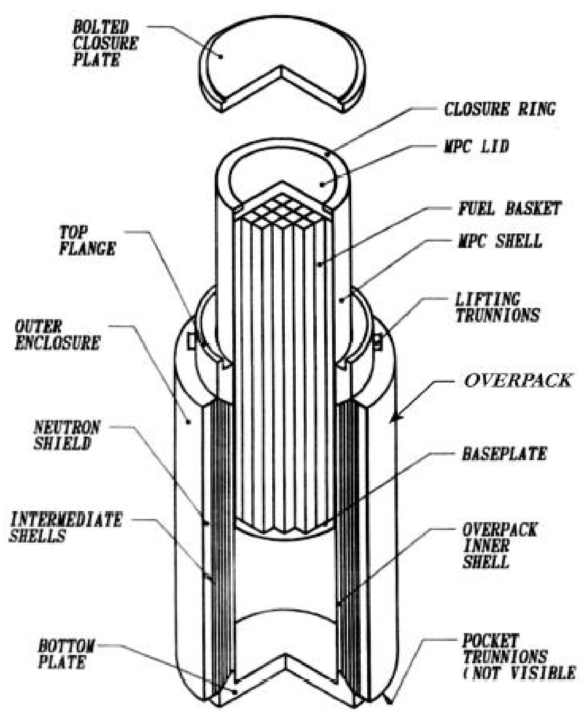

Figure 3. MPC and Overpack

The total radioactivity of shipments of any of these three types of material depends upon the content of the material and the volume in the shipping container. CSF represents the bulk of material to be shipped, and the highest radioactivity of materials to be shipped per shipment. The analyses in this study, therefore, focus on the safety of shipment of typical CSF in terms of incident-free and accident-related radiation exposure. FRA assumes that these effects are an upper bound on the likely outcome of shipments of commercial SNF, DOE SNF, or HLRW. Aggregate risk projections reflect the frequency of all types of shipments.

1.4 Past, Current, and Future SNF Shipments

SNF shipments in the United States have a long history of safe transport. This chapter will discuss past, current, and future SNF/HLRW rail shipment procedures and volumes.

1.4.1 Experience and Technology for Safe Shipments

More than 3,000 shipments of SNF were made between 1965 and 2001 by truck and rail. Since 1949, nine incidents involving the transportation of SNF and HLRW by rail have occurred. Six of the incidents were train accidents; however, none of the cases resulted in damage to the cask, release of material, deaths, or injuries. The three non-accident related incidents involved leakage of slight amounts of waste water or other material. It is important that the most recent accident occurred more than 15 years ago and that the most recent leakage occurred more than 25 years ago. This may be an indication that enhancements to cask design, material handling procedures, and other safety enhancements have had a positive effect in improving the safety of railroad shipments of nuclear materials.

Between 1979-1997, there were 1,334 commercial SNF shipments totaling over 1,102 tons (1,000 metric tons). Most of these were relocations of SNF to facilities that could provide interim storage. Only 11.5 percent of the shipments were by rail, but these accounted for 75.5 percent of the tonnage [NRC, 1998]. To date, over 700 shipments of naval SNF have also occurred, mostly to the Idaho National Engineering Laboratory. All of these shipments were by rail; more than half were moved in regular trains and the rest in dedicated trains.

1.4.2 Future Shipments

By the year 2046 DOE estimates that waste inventories will be between 63,000 and 105,000 MTHM for commercial SNF; 2,333 to 2,500 MTHM for DOE SNF; and 8,315 to 222,280 canisters of HLRW [DOE, 2002b]. This material will be transported to the national repository either directly from 72 commercial and 5 DOE sites across the United States or indirectly via interim storage and consolidation facilities (see Figure 4). The number of rail shipments for SNF and HLRW over a 24-year campaign could range from 300 to 18,300 depending on the mode emphasis of the shipping campaign. This traffic would at most average two shipments per day, depending primarily upon the presence and location of an interim facility (or facilities).[16]

1.4.3 Past Operational Restrictions

Historically, SNF has been shipped by ordinary freight trains, freight trains operating under restrictions, and dedicated trains. Ordinary freight trains have ranged between 50 to over 100 cars in length, have traveled at or below maximum allowable speeds, and have operated under multiple methods of train control (including cab signals, wayside signals, track orders, and in dark territory). Traditionally, shipments of SNF by regular freight train were accomplished as with any other commodity. In some cases, SNF shippers required some modifications to the regular train. These modifications included requirements for buffer cars, speed restrictions, and some other operational restrictions, such as a requirement that only one train move when opposing or passing movements are made.

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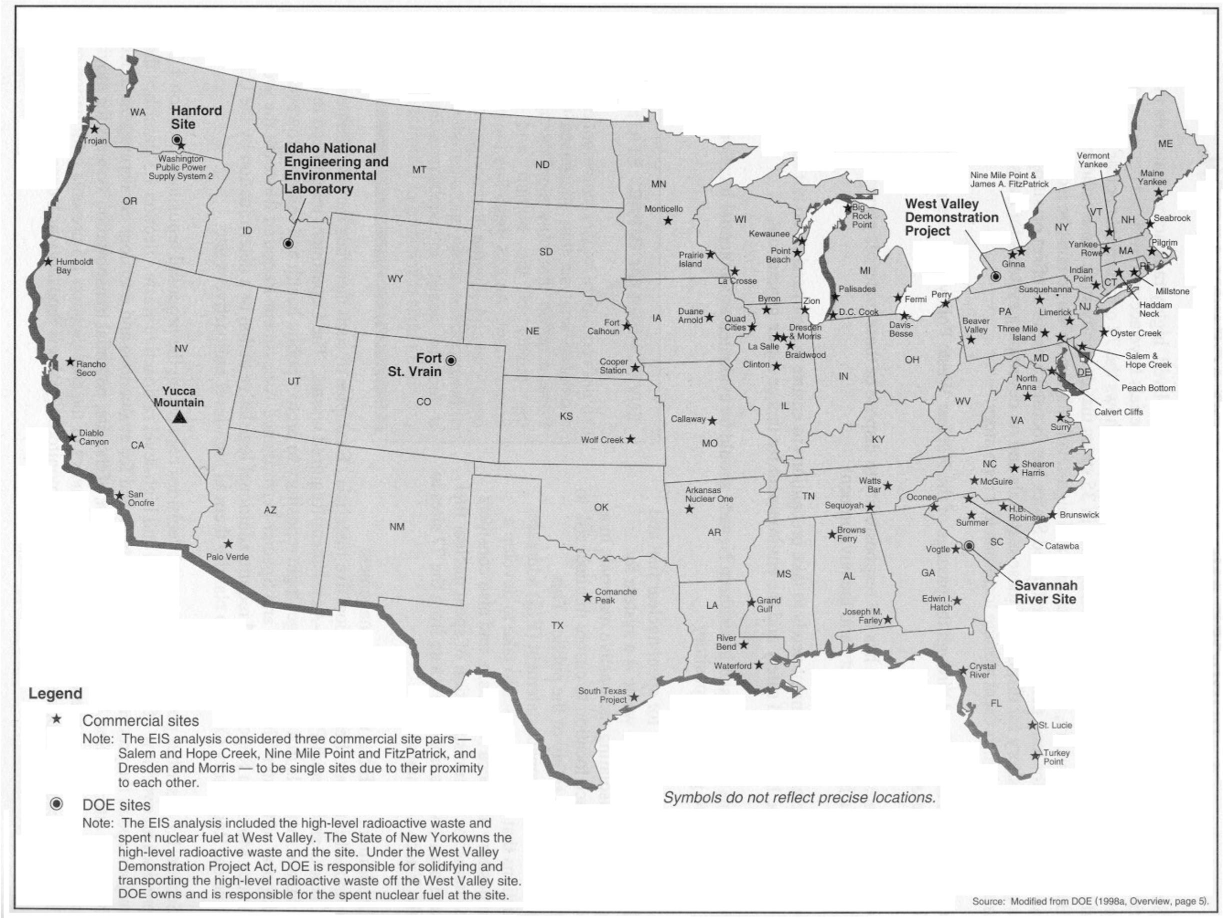
[16] Rail shipments to the proposed private fuel storage (PFS) facility in Utah will alter these numbers considerably since SNF would move there first and be moved again to the Yucca Mountain Repository when it opens.



Source: [DOE, 2002b], Figure 1-1

Figure 4. SNF Shipment Locations

Not all of the operational restrictions analyzed in this study have been typically employed in shipping SNF or HLRW. Since accident probabilities and consequences are inevitably based upon comparisons with the normal transportation scenario, however, it is worthwhile to describe transport by normal freight as well as by the method of shipment of SNF and HLRW as prescribed by DOE. SNF and HLRW have been shipped using diverse rail services (ranging from dedicated trains to regular freight) and under various operational restrictions. The regulatory and legal history of rail transport of SNF illustrates some of the issues raised to date.

AAR Recommendations of 1974. Until the mid-1970s, rail shipments of radioactive material (RAM) were handled routinely in regular train service. In March 1974, the Board of Directors of AAR approved a recommended operating practice for the transportation of SNF, "Shipments of casks containing irradiated spent fuel cores should move in special trains containing no other freight, not faster than 35 mph (56.3 km/hr). When a train handling these shipments meets, passes or is passed by another train, one train should stand while the other moves past not faster than 35 mph (56.3 km/hr)." Shortly thereafter, a number of railroads took actions, which had the effect of imposing both the use of dedicated trains and special train tariffs that were much higher than regular train rates. Some railroads sought to avoid handling these shipments altogether. These actions were challenged by the Energy Research and

Development Administration (one of DOE's forerunners), U.S. Department of Defense (DOD), NRC, numerous electric utilities, and other constituents of the nuclear power industry.

Interstate Commerce Commission (ICC) Decision of 1977. A number of proceedings before the ICC[17] and in the courts followed. The case that most directly and comprehensively addressed the question of the relative safety of regular and dedicated train service was ICC Investigation Docket No. 36325 Radioactive Materials, Special Train Service, Nationwide. In August 1977, Administrative Law Judge Forrest Gordon issued a decision that found that:

1. Respondents [rail carriers] have attempted to show that because of the unusual and highly dangerous nature of spent fuel and radioactive waste they are justified in requiring special train service...
2. Respondents have not been persuasive that special trains are safer than regular trains... In support of that conclusion, the judge determined the following:
   a) Casks in regular train service would be afforded the special treatment due hazardous materials.
   b) Surveillance of a cask car placed at the end of a regular train could be just as effective as similar placement in a dedicated train.
   c) Benefits of a 35 mph (56.3 km/hr) speed limit, associated with special train service, are illusory because average speeds are only about 20 mph (32.3 km/hr) and the poor condition of the roadbed of many railroads...would not lend itself to speeds much in excess of 35 mph (56.3 km/hr).
   d) The purpose of the requirement that one train stop while the other passes is to guard against the possibility that the swaying of the train may cause the extra high or wide load to strike the train it is passing but casks and cask cars are of normal dimensions.
3. The record fails to demonstrate that the transportation of radioactive materials in regular train service involves any greater risk than the transportation of other hazardous materials for which no special train service is required.
4. Risks are so small in any event that no conceivable increment of safety could be worth the additional cost for special train service.
5. The record will support a finding that special trains for the carriage of spent nuclear fuel is unnecessary and wasteful transportation… [ICC, 1978].

Further it was held that railroads may not require special trains as a safety measure in their tariffs for radioactive materials.[18]

In a later proceeding, ICC found that complainants, DOE and DOD, were entitled to recover damages amounting to the difference between the assessed special train charges and regular train rates after November 11, 1975 [ICC, 1992b]. A 1992 ICC proceeding [ICC, 1992a] determined that damages and

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[17] The ICC's jurisdiction in this area has been transferred to the Surface Transportation Board (STB).

[18] Special Trains Service Decision, Radioactive Materials, Special Trains Service, 359 ICC 70 (1978); Trainload Rates on Radioactive Materials, Eastern Railroads, 362 ICC756 (1980), aff'd. sub nom, Consolidated Rail Corp. v. ICC, 646 F.2d642 (DC Cir 1981), cert denied, 455 U.S. 1047 (1981).

interest totaling nearly $10 million should be paid to the complainants by 12 railroads for 187 of the total 319 shipments handled by special train after that date.

Transcontinental rail shipment, from east to west of the Mississippi River or lower Missouri River or Red River, would have required at least one change of carriers. This would have involved several operations, including origin pickup, inter-train classification, road haul, block exchange, interchange transfer, enroute inspections (and possibly repairs), and destination delivery. Compared with other hazardous materials, the shipping patterns for radioactive material (SNF and HLRW) are relatively simple because a limited number of origins and destinations exist. Commercial shipments of SNF principally originate at the nuclear power reactors operated by utilities; some shipments from university and other research reactors also occur. This means that the primary risks associated with transport could be evaluated by comparing representative routes and the effects of variation in train service (either regular or dedicated) along that route.

Inherent risk components of shipment of SNF and HLRW by normal freight operations have included derailments, collisions, and grade crossing risks. These risk components have been influenced by track condition, length of train, consist arrangement, and speed. Derailments and collisions have had varying consequences for given levels of severity of crash forces and the duration of any ensuing events such as fires. For this reason, some limitations on shipment of SNF and HLRW by normal freight methods have been imposed. These limitations are meant to reduce risk to crew members due to radiation exposure and/or reduce risk of collisions and/or derailments.

The “Restricted Normal Freight” transportation operation had its origins in the indemnity agreement entered into in 1959 between the Atomic Energy Commission (AEC) and the railroad industry that is still in effect. That agreement states that radioactive shipments will “require unusual transportation services and handling … under circumstances and conditions prescribed by the Government.” It then provides that the railroads “are willing to cooperate in moving these commodities … provided the Commission [AEC] will indemnify them.”

Consistent with the 1959 agreement, one or more of the following restrictions were imposed:

1. Do not exceed 35 mph (56.3 km/hr) maximum speed
2. Do not hump cars in switching yards
3. Do not switch with locomotive detached
4. Place car(s) on rear of train next to caboose
5. Place car(s) in clear of rail switch points when in a yard or siding
6. Provide protection after classification

Additional operational restrictions have since been imposed on SNF shipments, including the restriction that the cask car must be surrounded by buffer cars (one front and one rear) and accompanied by a car carrying safety and security personnel.[19]

[19] A major consideration in the Government attaching any instructions to the bills of lading is that Navy SNF contains valuable scientific information. These Navy shipments are not the concern of this study. The instructions over the years helped ensure that the contents were not jostled or damaged enroute and that the information they contained was not destroyed. At the same time, the instructions helped ensure that the shipping program was not disrupted. The 35-mph (56.3 km/hr) speed limit was solely a DOD requirement (no longer required by DOD). The DOE does not request any speed limit for any of its radioactive shipments [ICC, 1992].

Operational restrictions have imposed a significant limitation on the method of shipment of SNF casks by normal freight operations, and, in some cases, they may have exacerbated certain kinds of accident probability. AAR contended that the placement of the cask car and its weight may have had potentially harmful effects on train-track dynamics and may inhibit the safe transport of SNF by rail. Therefore, AAR had originally recommended the use of dedicated trains for the movement of SNF.

AAR recommended several technological and operational approaches to manage the risks of transporting SNF from civilian reactors. One of the primary recommended risk reduction measures was the use of a train "designed to minimize the possibility of accidents" [AAR, 1995]. These trains would be run in concert with hot box detectors and with the best possible braking systems. AAR recommended a short train, capable of stopping in a short distance and operations at timetable speed. Automatic car identification or satellite tracking technology was also recommended, as well as onboard defect detection systems to monitor the performance of the train during operation.

Dedicated trains, as recommended by AAR in 1995, were to be operated with the following restrictions:

1. No freight other than SNF or radioactive waste was to be carried.

2. Cask had to be placed on a flatcar surrounded by two buffer cars.

3. The train had to have a caboose with personnel aboard who monitor the shipment.

4. Speeds were restricted to 35 mph (56.3 km/hr).

5. When a special train carrying SNF or HLRW was passed by another train, one of the trains had to remain still while the other train passed at a speed less than or equal to 35 mph (56.3 km/hr).

AAR identified specific factors that indicated that the movement of cask cars in normal freight service involved additional risk. One factor was that the weight of the large multi-purpose canister (MPC) transportation cask system presented concern to the industry in the areas of track and bridge strength and train operations. DOE had specified that the gross rail load (GRL) of a loaded MPC railcar would not exceed 394,500 lbs (178,942 kg). The AAR standards required that any four-axle car weighing in excess of 263,000 lbs (119,295 kg) and six-axle cars in excess of 394,500 lbs (178,942 kg), carrying a regulated material, must move under special exception. Due to track weight limits (on some lines 263,000 lbs (119,295 kg) GRL) and bridge restrictions, the car carrying the 125-ton (113 metric tons) MPC may have required more than the normal four axles to distribute the weight safely over its intended route. A normal 89-ft (27-m) flat car capable of carrying 200,000 lbs (90,718 kg) weighs about 85,000 lbs (38,555 kg) empty, so that even if the 125-ton (113-metric ton) cask could be carried on a four-axle car, it would have exceeded the 263,000-lb (119,295 kg) weight restriction mentioned above. Furthermore, cars with more than four axles required special design and testing and may still have required speed restrictions to minimize derailment potential. AAR analyzed the FRA accident database and found that six-axle cars derailed at approximately twice the rate of four-axle cars [AAR, 1995][20]. In 1998, FRA amended its inspection policy and directed FRA inspection for every railcar transporting SNF at the initial terminal before departure and at interim inspection points along the route to ensure that the cars are free from defects and safe to operate.

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[20] For purposes of this study, it was assumed that special span-bolster, eight-axle cars would be used to transport the shipping cask. A higher derailment rate was not assumed for these cars because: (1) they would receive special maintenance and operational attention and (2) the relative results between regular, key, and dedicated trains would not be affected by the derailment rate.

AAR expressed additional concerns about the cask certification procedure and impact test standards, with respect to their applicability. AAR contended that the weight of rail vehicles has increased from the typical 70-ton (64-metric ton) load in the 1960s and 1970s, when NRC standards were developed, to 100-125 tons (91-113 metric ton) today, while the impact standards were developed under the assumption of an impact with the lighter 70-ton (64-metric ton) car.

Although not required by ICC findings, DOE publications (such as the final request for proposals for transportation of SNF and HLRW) have specified that the Regional Services Contractor (RSC) may include special train service:

> Appendix 8 to this Section C contains additional requirements related to a forthcoming document entitled 'OCRWM Transportation Policy and Procedures' which is to be used by the RSC in developing its Transportation Plan. This document will provide additional rationale and guidance relative to overall operational protocols and will be provided to the RSC (Regional Service Contractor) twelve months prior to the completion of Phase A. Any revisions to this document will be provided to the RSC.
>
> The RSC's Transportation Plan shall at a minimum, provide for:
>
> 1. The establishment and maintenance of communication capability with other RSCs, DOE, States, and Tribes
> 2. Identification of participating organizations including their specific functions and responsibilities
> 3. Maximum use of special train service and advanced rail equipment features where this type of service or equipment can be demonstrated to enhance operating efficiency, dependability, cost effectiveness or lessen the potential of adverse railroad equipment incidents
> 4. Use of buffer cars and escort/security cars which are dynamically compatible with the train consist
> 5. Proposed primary and alternate routes in accordance with applicable NRC and DOT regulations for all transportation modes selected; cask modal/intermodal determination and designation [DOE, 1998].

1.4.4 Current Operational Restrictions

AAR updated the current recommended railroad operating practices for the transportation of radioactive and other hazardous materials in 2001 [AAR, 2001] (see Appendix A). AAR states that trains carrying one or more car loads of SNF or HLRW are classified as key trains. These key trains operate along AAR specified key routes throughout the country. These key trains traveling along key routes have the following restrictions placed on their operations:

- A key train cannot operate above 50 mph (80.4 km/hr).
- The key train will hold the main track at meeting or passing points unless the siding or auxiliary track meets FRA Class 2 standards.
- All cars in a key train movement must be equipped with roller bearings..

In addition, AAR has imposed several other safety requirements:

- *Bearing Defect Detection*. When a defect in a key train bearing is reported by a wayside detector, a visual inspection is required. If no defect is found in the visual inspection, the consist is allowed to return to service but must not exceed the speed of 30 mph (48 km/hr) until it has passed over the next wayside detector. If the same car triggers the next detector or it is found to be defective, the car must be removed from the trainset. Wayside defective bearing detectors shall be placed at a minimum of 40 miles (64 km) apart on key routes.

- *Track Inspection.* The main track on key routes must be inspected at least twice a year to check for rail defects and track geometry anomalies.

- *Yard Procedures.* In operating yards loaded placarded cars shall not be coupled at a speed greater than 4 mph (6.4 km/hr).

1.5 Previous Research

The risk of SNF transport by rail has been a topic of interest and contention since the 1970s. Since 1977, at least eight studies have attempted to address the safety of both dedicated trains and regular train service for SNF shipments. These reports provide some relevant insights into the potential risk and risk reduction associated with either method.

1.5.1 1977-1978 ICC Investigation Studies

During the 1977-1978 ICC investigation four studies were published, under Docket No. 36325 Radioactive Materials, Special Train Service. These were: (1) *Final Environmental Impact Statement–Transportation of Radioactive Materials by Rail* [NRC, 1977a]; (2) *A Safety and Economic Study of Special Trains for the Shipment of SNF* [Battelle, 1977]; (3) *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes* (NUREG-0170) [NRC, 1977b]; and (4) *An Analysis of the Radiological Risks of Transporting SNF and Radioactive Wastes by Truck and Ordinary and Special Trains* [DOT, 1978]. Each of these studies is summarized below:

(1) *Final Environmental Impact Statement-Transportation of Radioactive Materials by Rail.* ICC staff, with support from NRC and Sandia National Laboratories, documented their analysis in this report in August 1977. The study addresses movement of SNF from reactors to reprocessing facilities and HLRW from reprocessing facilities to storage. This and later studies all found that the dominant risk (99.8 percent in this case) was death due to non-radiological causes, such as grade crossing accidents, principally associated with the extra trains created to provide dedicated service. This assumes that non-radiological fatalities and injuries would result (in the aggregate) if the accident rate for dedicated and regular trains remains constant. The study found, among other conclusions, that incident-free radiological risk was higher for dedicated trains. The increased risk was attributable to the assumption that the duration of stops for dedicated trains would be nearly the same as for regular trains and the assumption that the five crew members on board are more than three times closer to the cask car on a dedicated train.

(2) *A Safety and Economic Study of Special Trains for the Shipment of SNF (*prepared by Battelle for DOE under contract E4-76-C-06-1830). In December 1977, Battelle published findings on the safety effects of each of three operational restrictions usually associated with dedicated trains: (1) excluding other freight, (2) limiting speed to 35 mph (56.3 km/hr), and (3) requiring one train to stop during a pass. Battelle's examination of FRA accident data showed no indication that safety was improved by employing dedicated trains. The Battelle analysis determined that the likelihood of cask involvement in

a severe fire is virtually the same for regular and dedicated trains. This assumption may be faulty because the consist of a regular train could contain much more flammable material than that of a dedicated train and dedicated trains spend less time in yards than regular trains. The only flammable material carried on dedicated trains is the diesel fuel in the locomotive tanks (typically 2,500 gallons (9,463 liters)), located under the locomotive unit between the trucks. Regulations (49 CFR 174.85) require at least one non-placarded car (combustibles excepted) to be placed between the cask car and the locomotive. In contrast, a cask in a regular train may be placed a similar distance away from a loaded tank car containing ten times that amount of flammable material. In addition, it is possible that other cars in the train consist may legally carry other hazardous materials. The effect may, in fact, be an increase in the risk of cask car involvement in a severe fire in a regular train.

(3) *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes* [NUREG 0170]. The NRC published this study in December of 1977. The report addresses issues of alternative modes of rail shipment (dedicated and regular train service) noting that no data existed on the comparative safety of dedicated trains. The authors determine the maximum possible benefit from using dedicated trains by assuming that no radiation dosage would be associated with these trains and no accidents would occur while they were in use. The risk associated with transportation of SNF and waste by regular train for 1985 was calculated, and it was then assumed that dedicated trains would eliminate that risk entirely. The maximum reduction in risk amounted to 0.0365 LCFs per year–one LCF avoided every 30 years. Based upon this health effect benefit and an estimate of the additional costs, the authors concluded that the benefit/cost ratio for use of dedicated trains was approximately 1:19.

(4) *An Analysis of the Radiological Risks of Transporting SNF and Radioactive Wastes by Truck and Ordinary and Special Trains.* In June 1978, SNL published the results of this study done for NRC. In what was essentially a refinement of the NUREG-0170 work, the authors estimated the change in radiological impacts due to substituting dedicated trains for regular trains in nuclear fuel cycle transportation for 100 light water reactors (LWRs). Dedicated (special) trains were assumed to travel at speeds less than 35 mph (56.3 km/hr), operate under a passing restriction that would hold other trains while the dedicated train moved, and carry a consist containing no freight other than SNF. The authors also assumed that collisions and derailments with impact speeds greater than 30 mph (48 km/hr) would be eliminated. Second, the passing restriction was assumed to completely eliminate the raking collision probability and derailment risk due to passing trains. Finally, the consist restriction was assumed to have no significant effect upon accident rates but have a possible effect on the likelihood that the cask might be involved in a fire. For the special train case, rail shipments account for 5 percent of the accident-free LCFs and 46 percent of the accident-related LCFs. Due to assumptions about crew proximity, protection, and the duration of their exposure during a dedicated train shipment, the study concluded that dedicated trains had lower accident risk but higher non-accident risk than regular trains.

1.5.2 1980s Studies

Two relevant studies done in the mid-1980s are *Are Special Trains Really Safer?* [ADL, 1984] and *A Revised Rail-Stop Exposure Model for Incident-Free Transport of Nuclear Waste* [DOE, 1986]. The following summarizes these studies:

(1) *Are Special Trains Really Safer?* [ADL, 1984]. FRA accident data for 1983 was used to estimate the accident frequency and spill size effects of using regular and dedicated trains for shipment of hazardous materials (of all kinds). These data examine tank car incidents, the effect of different shipment modes on the accident involvement, and release rates per million train miles for trains carrying these materials. Boghani concluded that dedicated trains are sometimes, but not always, safer. He further concluded that case-specific analyses should be conducted to determine which method of shipment was preferable for a specific shipment.

(2) *A Revised Rail-Stop Exposure Model for Incident-Free Transport of Nuclear Waste* [DOE, 1986]. SNL examined the effect of the assumptions describing stopped time on shipment duration and radiological exposure. As noted in the 1978 SNL study, the effect of crew exposure during shipments is one of the largest determinants of risk calculated by RADTRAN (the computer program developed by SNL). This report provides a description of the assumptions and algorithms now incorporated into the model, which operates as part of RADTRAN. Dedicated and regular trains were compared for radiological, incident-free risk only. The assumed speeds for both types of trains were identical, but a considerable difference existed in both the fixed and distance-dependent stopped time. The close-proximity crew dose factor associated with handling and inspecting casks and cask cars in regular trains was estimated to be 16 times greater than for dedicated trains. Overall dose (stopped plus moving) for regular trains was found to be nearly four times that of dedicated trains.

1.5.3 2000 to Present Studies

In 2000 and 2001 revised studies of spent fuel transportation were conducted. Two of these studies, the *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain* [DOE, 2002b] and *Reexamination of Spent Fuel Shipment Risk Estimates, NUREG CR6672* [NRC, 2000], provided significant revisions to previous estimates of radiological risks from transportation of spent fuel and HLRW. The following summarizes these studies:

(1) *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* [DOE, 2002b]. DOE provided an up-to-date estimate of the number of shipments, type of fuels (high, medium, and low burnup), and the radiological and non-radiological risks resulting from transportation of this inventory of HLRW and SNF to Yucca Mountain by rail, truck, or a combination of the two. DOE evaluated the potential risk reduction from use of dedicated trains in a non-quantitative manner, comparing the hazards to crews, wayside population, and inspectors using either dedicated or regular trains. Table 2 illustrates the main areas of comparison between dedicated and regular train service evaluated by DOE. The basis of comparison between these two methods of service were accident rates, incident-free exposure, accident related exposure, security, and utilization of resources. While DOE found a slight (or greater) advantage for dedicated trains on nearly every one of the attributes, they concluded that the differences between the two types of service were not substantial enough to warrant requirement of dedicated trains. They stated that:

> … available information does not indicate a clear advantage for the use of either dedicated trains or general freight service. Thus, DOE has not determined the commercial arrangements it would request from railroads for shipment of spent nuclear fuel and high-level radioactive waste. Table 2 compares the dedicated and general freight modes. These comparisons are based on the findings of the U.S. Department of Transportation study and the Association of American Railroads.[21]

[21] [DOE, 2002b], Appendix J page J-75.

Table 2. Comparison of General Freight and Dedicated Train Service

Attribute	General Freight	Dedicated Train
Overall accident rate for accidents that could damage shipping casks	Same as mainline railroad accident rates.	Expected to be lower than general freight service because of operating restrictions and use of the most up-to-date railroad technology.
Grade crossing, trespasser, worker fatalities	Same as mainline railroad rates for fatalities.	Uncertain, greater number of trains could result in more fatalities in grade crossing accidents. Fewer stops in classification yards could reduce work related fatalities and trespasser fatalities.*
Security	Security provided by escorts required by NRC regulations.	Security provided by escorts required by NRC regulations; fewer stops in classification yards than general freight service.
Incident-free dose to public	Low, but more stops in classification yards than dedicated trains. Classification yards, however, would tend to be remote from populated areas.	Lower than general freight service. Dedicated trains could be direct routed with fewer stops in classification yards for crew and equipment changes.
Radiological risks from accidents	Low, but greater than dedicated trains.	Lower than general freight service because operating restrictions and equipment could contribute to lower accident rates and reduced likelihood of maximum severity accidents.
Occupational dose	Duration of travel influences dose to escorts.	Shorter travel time would result in lower occupational dose to escorts.
Utilization of resources	Long cross-country transit times could result in least efficient use of expensive transportation cask resources; best use of railroad resources; least reliable delivery scheduling; most difficult to coordinate state notifications.	Direct through travel with on-time deliveries would result in most efficient use of cask resources; least efficient use of railroad resources. Railroad resource demands from other shippers could lead to schedule and throughput conflicts. Easiest to coordinate notification of State officials.

Source: Table J-25. Comparison of General Freight and Dedicated Train Service [DOE, 2002b].

* Trespasser fatalities on the mainline and in yards could be reduced by speed restrictions and fewer yard stops.

(2) *Reexamination of Spent Fuel Shipment Risk Estimates, Vols.1, 2* [NRC, 2000]. This is a comprehensive update to the original NUREG 0170, Final Environmental Impact Statement. The purpose of this study was to identify how the risk estimates constructed in NUREG 0170 [NRC, 1977b] may have varied over time, both due to improved understanding of cask performance and resulting from the application of very conservative assumptions in the original study. SNL provided substantial updates to the significant parameters that determine human health risks due to radiological exposure; these included source terms describing the level of radioactivity likely to be released given an accident, the likely effects of impacts and fires on cask integrity, and the probability of the events resulting in high-velocity impacts (over 60 mph (96.4 km/hr) onto an unyielding surface) or high-temperature (1,832° F (1,000° C)), long duration (30 minutes or more) fires. Cask response to external loads was modeled using finite element methods, and thermal responses were modeled in terms of the time required to fail the seal on the cask. The duration of fires, temperatures, and transfer of heat from the external source to the internal contents were detailed in SNL's model. Based upon their analyses, SNL concluded that accident dose risks are "negligible when compared with incident-free dose risks."[22] SNL's conclusions in this report are different from NUREG 0170 and the Modal Study. Based upon SNL's calculations for rail transport, NUREG-0170 Model I accident population dose risks are approximately 10 times larger than the rail accident risks estimated using Modal Study rail accident source terms, which are approximately 4 times larger than the risks estimated using NUREG-0170 Model II source terms, which are approximately 50 times larger than the risks estimated using the rail accident source terms developed by this study.[23] The significance of these new conclusions with respect to dedicated train is evident in the overall effect of dedicated service on the duration of point-to-point service. Longer shipment duration requirements (in regular train service) expose wayside populations, crews, and others to higher cumulative doses since the dominant exposure results from incident-free exposures. Shipment methods that reduce overall shipment duration reduce risk.

1.6 Methodology

These studies include an assessment of normal incident-free train operations, as well as select accident conditions. The operational definition of safety for this study has been to determine the total risk incurred by all people involved in SNF and HLRW transportation and to quantitatively measure the difference in this risk when either a regular or dedicated train is employed. Safety risks (specifically latent cancer fatalities) were considered for the train while moving and while at rest, including the effects of radioactive materials transport on anyone exposed during the transportation process, such as the general population, train crews, railroad yard employees, and security escorts.

Unlike most hazardous materials, SNF and HLRW shipments pose a small risk at all times during transport. This is because even the most resilient shipment cask will allow some amount of radioactivity to be emitted. While well within regulatory limits of 10 mrem/hr at 3.3 ft (1 m), this very low level of radioactivity may pose a small health risk. Potential casualties from accidents involving SNF or HLRW shipments could pose larger risks, such as exposure to elevated radiation doses due to damage to the container or to the container contents or, less likely, direct exposure to SNF or HLRW materials due to failure of a cask.

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[22] NUREG CR6672, page 9-2.

[23] ibid, page 9-3.

To compare the relative risk between dedicated and regular train service, the total expected radiation dose to the public (assuming no accident) has been calculated for shipments of SNF by dedicated or regular train, and the consequences have been compared. Accident probabilities for all types and severities of train accidents are calculated, and the consequences of typical events of the severity of these scenarios are calculated. The likelihood of having an accident of a given severity and consequence is then compared for regular and dedicated trains.

1.7 Report Overview

This chapter provides a brief characterization of the original requirement for this study and the circumstances under which SNF and HLRW shipments were to be made. This chapter presents definitions of the important components of the study, including the characteristics of dedicated and regular trains and their derivation. In addition, definitions of the characteristics of comparison (LCFs, injuries, and fatalities due to accidents) were provided and their derivation explained.

Chapter 2 provides a description of the calculation of comparative safety of dedicated, regular, and key train transport of SNF and HLRW, under the assumption that no accident occurs during transport. RADTRAN, a computer model, was used to calculate the consequences based on inputs from the Volpe Center, SNL, industry standards, historical data, government databases, and expert opinions [SNL, 1998]. The methodology of calculation, including the computer program used to calculate population exposure, is described. This chapter also includes input parameters and assumptions for the calculation. Other radiological and non-radiological consequences, such as environmental damage and property damage, were not considered.

Chapter 3 provides an analysis of accidents and their likely effect on SNF containers. In this chapter an analytical method is used to describe expected forces from collisions, falls from bridges, derailments resulting in impacts on the cask, and fires. The analytical method employed in this chapter determines which objects and velocities or heights pose a threat to SNF container integrity.

The probability that these events might occur is then estimated using event trees, based upon historical accident records, and railroad bridge characteristics provided for the State of California. These probability values are specific to shipment methods and are, therefore, segregated to event trees that represent either dedicated or regular train shipments. These event trees reflect the cumulative probability that a severe accident (one that results in forces in excess of the compliance test regulatory limit) occurs. In incident-free transport, the duration and number of stops during shipment and placement of the cask in the train have a significant bearing on the total population dose. In accident scenarios, the consequences of failure are invariant with respect to the type of service since the same population exposure will ensue from a cask release. The accident analysis, therefore, focused on comparing the likelihood of severe accidents under the three methods of shipment and not on their aggregate consequences. Examples of each type of accident are characterized in terms of radiation dose (person-rem) and LCF; however, the total accident-related LCF for all routes were not calculated.

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2. Incident-Free Risk Analysis

2.1 Incident-Free RISK Methodology–Radiological Consequences and Risk Calculations

This analysis estimates radiological risks associated with incident-free transportation of SNF by rail. The consequences of incident-free transportation are the estimated population radiation doses for the various population groups surrounding the cask being analyzed. As shown in Figure 5, the radiological consequence of an SNF shipment is a function of the selected routes, the cask design, and the package dose rate (cask emission), the size of impacted populations (number of persons exposed), the population distance from the cask, the total exposure time, and the amount of shielding between the cask and exposed populations.

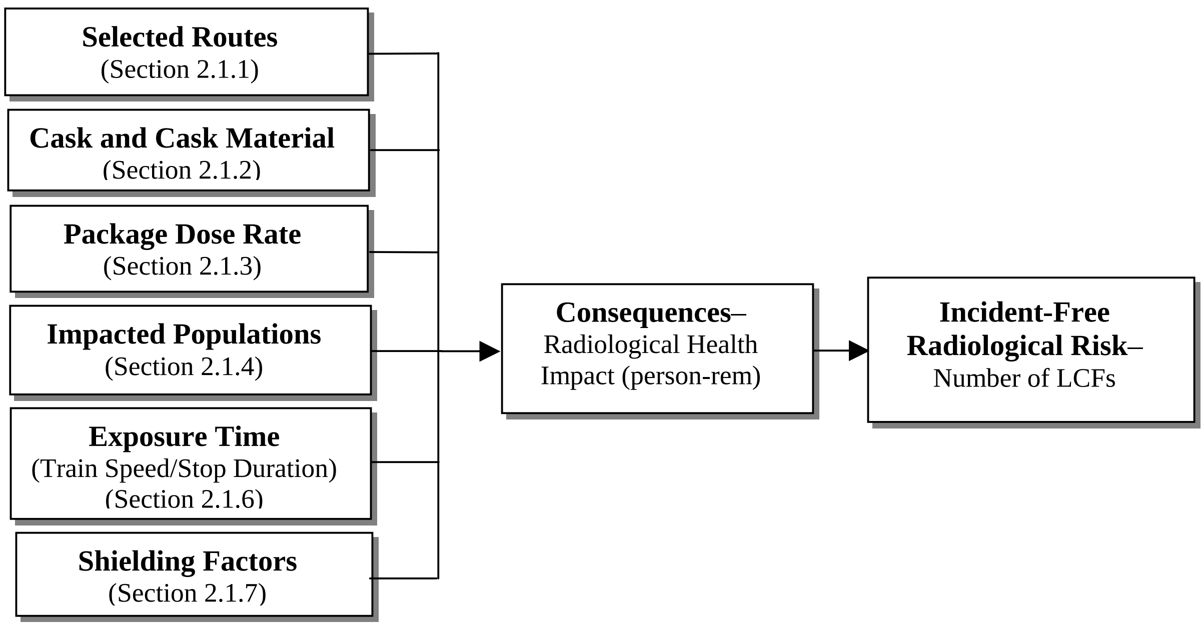


Figure 5. Incident-Free Risk Calculation

Though very well shielded, SNF casks continuously emit low levels of radiation throughout all phases of transportation. Radiation exposure to crew, handlers, yard personnel, and wayside population will occur in all SNF movements under all service types even under those circumstances where no accident has occurred. Since a cask will always have some level of emission, for incident-free transportation, the exposure probability is assumed to be 1. Incident-free transportation consequences and risk are thus indistinguishable.

Incident-free risk was calculated using RADTRAN 5, a set of models developed by SNL for the analysis of the consequences and risks of radioactive material transportation by highway, rail, air, and waterborne modes. RADTRAN was first developed by SNL in 1977 in conjunction with NUREG-0170, Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes [NRC, 1977b; DOE 1982]. RADTRAN combines user-determined demographic, transportation, packaging, and material data with health physics data to calculate the expected radiological consequences of transporting radioactive materials. The incident-free RADTRAN calculations produce expected values of population dose with the package, population distribution, and transportation models. For analysis of incident-free conditions in RADTRAN, the package dose rate and packaging-specific characteristics are used to model a package (or shipment) of radioactive material as a modified point source and, for receptor distances less than two characteristic package dimensions from large packages, as a line source. Transportation system characteristics are incorporated into a rail mode-specific model, which uses a set of input parameters to describe the population along the route and at stops, and other mode-dependent characteristics, such as vehicle velocity and stop duration. Population densities for each route segment must be defined by the user, in addition to the characteristics each sub-population (e.g., passenger, crew, rail workers, general population) that receive radiation doses. The magnitudes of the calculated doses depend on variables, such as population density, distance traveled, and vehicle speed. The values describing these potentially exposed subgroups may be varied by population-density zone (urban, suburban, and rural). The user is given considerable latitude in adjusting parameters for analysis, but the quality and quantity of the available data limits the accuracy of the results. Details of RADTRAN calculations can be found in the *RADTRAN 5 User Manual* [SNL, 1998]. Several factors were input into the RADTRAN model. The following sections describe the values used and the source for each.

Results are provided for in-transit (off-link and on-link) radiation doses as well as for radiation doses for stops. Off-link doses are those received by persons on the ground who are within 875 yds (800 m) of a passing train. On-link doses are those received by passengers on trains which pass the SNF cask carrying train and those received by the crew and escorts on board the SNF cask carrying train. Stop doses are those received by persons on the ground or by crew and escorts who are within 875 yds (800 m) of the SNF carrying train while the train is at rest.

2.1.1 Selected Routes

More than 20 percent of the Nation's electricity is produced by more than 100 nuclear power plants located around the country. Because commercial spent fuel is currently stored in nearly every region of the United States, most states have potential transportation routes to Yucca Mountain. For this analysis, six routes were chosen to be representative of overall SNF transport (see Table 3). All six of the selected route origin points are locations of nuclear power plants or waste repositories with existing commercial SNF or DOD HLRW (see Figure 6). The destination point for each of the selected routes was Yucca Mountain.

Table 3. Routes Used in the Analysis

Route Number	Origin	Destination
1	Humboldt Nuclear Power Plant, CA	Yucca Mountain, NV
2	Crystal River Nuclear Power Plant, FL	Yucca Mountain, NV
3	Dresden Nuclear Power Plant Dock, IL	Yucca Mountain, NV
4	River Bend Nuclear Power Plant, LA	Yucca Mountain, NV
5	Seabrook Nuclear Power Plant, NH	Yucca Mountain, NV
6	Hanford Repository, WA	Yucca Mountain, NV

Although at this time no preferred routes have been selected by DOE for spent fuel shipments to Yucca Mountain, major east-west rail links can be identified as likely candidates. The links from each origin and destination pair were determined using Oak Ridge National Lab's (ORNL) Interline model.[24] The selected routes are the most likely traveled routes and are representative in terms of their geographic location and length of route.

[24] Interline is an interactive tool for simulating routing practices on the U.S. rail system. Oak Ridge National Laboratory developed this routing model.

Figure 6. Selected SNF Shipment Routes

2.1.2 Cask and Cask Material

Cask Description

Spent fuel packages provide the bulk of the insurance against radioactivity release. Irradiated or spent fuel is moved in shielded containers referred to as casks. They are Type B [49 CFR 173.413/10 CFR 71] packaging and must be certified by either NRC [49 CFR 173.471] or DOE. These casks are authorized for shipment under DOT regulations. For this analysis, a 125-ton (113-metric ton) MPC system was used.

Consist Description

Three types of trains are considered in the analysis: regular, key, and dedicated trains (see Figure 7). This report assumes that the cask car(s) will be surrounded by two buffer cars and accompanied by an escort car. This complement of cars, referred to as the cask consist, in addition to the locomotive(s), comprises a dedicated train. A regular or key train will include the cask consist, locomotive(s), and any number of additional cars.

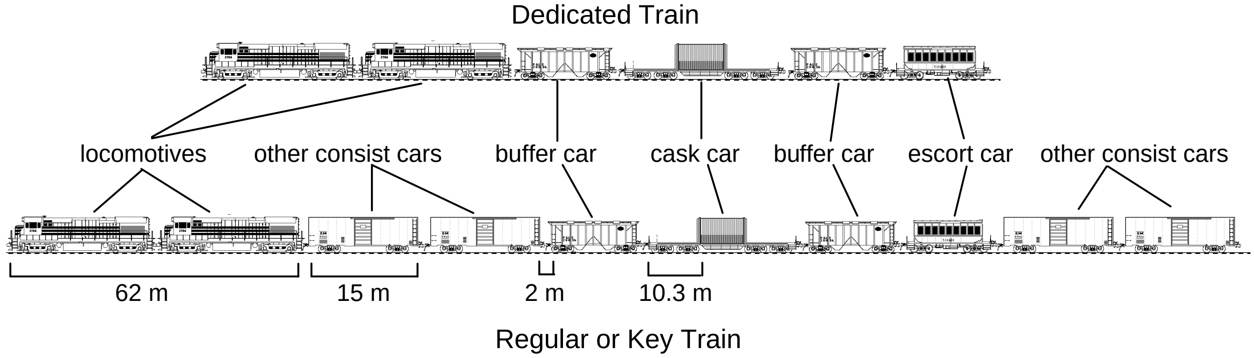


Figure 7. Train Consist

2.1.3 Package Dose Rate (Source Strength)

NRC and DOT regulate packaging, transport, and disposal of radioactive materials by all modes of transportation in the United States. Regulations promulgated by NRC are contained in 10 CFR 71-73; regulations promulgated by DOT are primarily contained in 49 CFR 171-178. These regulations establish maximum permissible package dose rates and maximum permissible dose rates to vehicle crew members.

Characteristics of radioactive material that affect incident-free transportation are the package dose rate and the fractions of gamma and neutron radiation. The package dose rate is expressed as a transportation index (TI) for certain package types. TI is defined as the highest radiation dose rate in millirem per hour (mrem/hr) from all penetrating radiation at 3.3 ft (1 m) from any accessible external surface of the package, rounded to the highest tenth (49 CFR 173.403). For the purposes of this analysis, it was conservatively assumed that the dose rate is the regulatory limit of 10 mrem/hr at 3.3 ft (1 m). The estimated dose rate for the MPC cask selected for this analysis is below this regulatory limit.

2.1.3.1 Package Dose Rate Estimations for Affected Populations

The package dose rate and packaging-specific characteristics are used to model a shipment of radioactive material as a modified point source for distant receptors and as a line source for close proximity receptors. Exposed persons at stops are modeled as being located at a given distance from a stationary source for a specified amount of time (point source model). Crew members, classification workers, and inspectors work in close proximity to a package, so the dose for these groups is calculated with a line-source model.

Point Source Model. The formulation for estimating an incident-free population dose from radioactive materials in most cases is based on an expression for dose rate as a function of distance from a point source (radiation in all directions with equal magnitude). For such a source, dose rate is inversely proportional to the square of the distance from the source.

Line Source Model. For exposure groups such as classification workers and inspectors who work in close-proximity (within 10 m) to the cask, a line-source approximation model is used. A line source is defined as a one-dimensional source that emits radiation normally along its entire length. A line source model gives a conservative approximation of actual dose rate measured at distances of less than twice the characteristic package dimension (length).

The implementation of these models in RADTRAN is available in the user manual [SNL, 1998].

2.1.4 Impacted Populations

While moving and at rest, cask emissions can potentially impact various groups of people to varying degrees. The populations considered in this analysis are:

- General population, including individuals residing and working near the rail lines (wayside) over which the cask passes and people who live near yards and sidings where the cask stops temporarily.
- Persons on trains sharing the route with the SNF shipment.
- Vehicle occupants at railroad grade crossings along the shipment route.
- Train crew located in the lead locomotive on the train containing the SNF shipment.
- Escorts on the train containing the SNF shipment; experts and/or guards who monitor the cask from the nearby personnel car.
- Railroad personnel who work in close proximity to the cask in classification yards and inspect the train at various points.
- Other rail yard workers, including rail workers other than classification personnel and inspectors working in rail yards where the train stops but not in close contact with the shipment.

Each of these groups can be impacted by emissions from SNF casks on standing or moving trains, and each group has different exposure levels and durations (see Table 4). Members of train crews or escorts will be exposed to any external radiation field around a cask for the duration of a trip. The cask may be inspected and classified during transport by inspectors or rail yard workers. Populations beside the rail route and passengers on passing trains will be exposed as the train passes. The dose to each of these population subgroups was calculated.

Table 4. Impacted Population Groups

	Incident-Free	
Impacted Population Group	**In-Transit (Moving) Dose**	**Stop Dose**
General (Wayside) Population Along Route[25]	◆	
General (Wayside) Population Near Stops		◆
Train Passengers Sharing Route	◆	
Vehicle Occupants at Grade Crossings	◆	
Train Crew	◆	◆
Shipment Escorts	◆	◆
Handlers/Inspectors		◆
Other Rail Yard Workers	◆	◆

2.1.4.1 Impacted Population Number Determination

Population numbers or population densities were defined for each route segment, along with the characteristics of each of the sub-populations that receive doses while the cask is stopped or in-transit. The following describes the values used for the general population.

Wayside Population. High resolution population data from the 2000 U.S. Census was used to determine wayside population densities. For the general population along the route, an average population density

[25] Although in reality the transportation of a radioactive material will involve passage through variable population densities, RADTRAN is given three population density zones (rural, suburban, and urban) aggregate all route segments. The total population dose resulting from the trip is made up of the sum of the doses received in each population-density zone or route segment.

within a 1-mi (1.6 km) bandwidth of the selected rail line was used for each route segment. Population densities were calculated by selecting census blocks through which the rail route passes and assuming an even density distribution (see Figure 8).

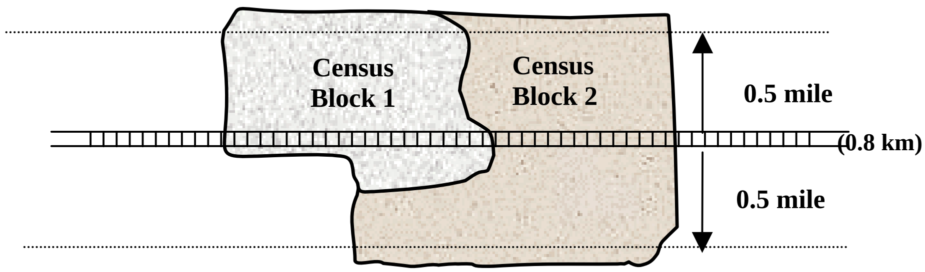


Figure 8. Population Density Selection

Table 5 shows the census-based population density values used for each of the six routes.

Table 5. Average Population Density

persons/sq mi (persons / km^2)

Route	Urban	Suburban	Rural
1	6,237 (2,408)	1,164 (449)	26 (10)
2	5,641 (2,178)	976 (377)	38 (15)
3	5,169 (1,996)	1,006 (389)	26 (10)
4	4,964 (1,917)	919 (355)	30 (12)
5	6,109 (2,359)	1,028 (397)	28 (11)
6	4,744 (1,832)	1,307 (505)	17 (7)

Source: Census 2000.

If the transport vehicle stops for crew change, freight transfer, refueling, or inspection, persons in the vicinity of the stop point can be exposed. Since rail stops usually occur in rail yards, the population in and near a rail yard are modeled as uniform populations distributed around the rail shipment, and dose is integrated over this population. For rail stops, public dose is estimated using the suburban population density for the route because most rail yards are located in less densely populated areas.

Train Passengers Sharing Route. Train density and train occupancy data from the 1996 Rail Garrison data were used to determine the number of persons likely to be sharing the railway with the SNF shipment. Table 6 shows data for average train density rates.

Table 6. Average Passenger Train Density

	Urban	Suburban	Rural
Average Train Density*	0.4 trains/hr	0.2 trains/hr	0.14 trains/hr

* Source: Rail Garrison Data 1996.

Vehicle Occupants at Grade Crossings. Vehicle occupants on each side of the railroad link, especially at highly trafficked crossings, could be exposed to a passing SNF train during the time the crossing gates are down. The Railroad/Highway Grade-Crossing Inventory estimates an average of greater than 2,000 vehicles per day traversing each public crossing.

The top 33 percent of crossings (by volume) handle 5,700 vehicles per day or almost 60 per average 15-minute period. Crossings in the bottom 67 percent (by volume) average 500 vehicles per day, about 5 per 15-minute interval. This possibility is less likely for highly congested urban crossings. While this could be considered the maximum vehicle exposure for a passing cask-carrying train, a maximum of only ten vehicles (five vehicles on each side of the crossing) would be within a 98.4 ft (30 m) limit, which would need to be analyzed separately; the rest would be assimilated in the general urban population (off-link) dose.

To calculate the maximum dose at urban grade crossings for each route and for trains of each speed restriction, RADTRAN's maximum individual dose rate routine was utilized (see Table 7). The individual maximum dose was multiplied by the number of expected vehicle occupants at the urban grade crossings on the route-run. The total dose was calculated as the number of urban crossings on the route times the number of vehicles at each crossing (10), times the vehicle occupancy (1.63 persons per vehicle). The number of crossings equals the total length of railroad segments passing through urban areas multiplied by 4.41 crossings per mile (2.74 per km), a typical value for an urban freight corridor [ADL, 1999].

Table 7. Values for Occupants at Grade Crossing Dose Calculation

Route	Weighted Average Speed –Urban mph (km/hr)		Max Individual Dose at 49 ft (15 m) mrem (rem)		Urban Route Length miles (km)	Crossings per Mile (per km)	Vehicles per Crossing	Occupants per Vehicle*	Total Dose to Vehicle Occupants at Grade Crossings (person-rem)	
	35 mph (56.3 km/hr)	50 mph (80.4 km/hr)	35 mph (56.3 km/hr)	50 mph (80.4 km/hr)					35 mph (56.3 km/hr)	50 mph (80.4 km/hr)
1	29.28 (47.12)	34.84 (56.07)	4.74×10^{-04} (4.74×10^{-07})	3.98×10^{-04} (3.98×10^{-07})	59.84 (96.31)	4.41 (2.74)	10	1.63	**2.04×10^{-03}**	**1.71×10^{-03}**
2	29.08 (46.80)	33.42 (53.78)	4.85×10^{-04} (4.85×10^{-07})	4.21×10^{-04} (4.21×10^{-07})	18.94 (30.48)	4.41 (2.74)	10	1.63	**6.60×10^{-04}**	**5.73×10^{-04}**
3	30.00 (48.28)	35.96 (57.87)	4.64×10^{-04} (4.64×10^{-07})	3.91×10^{-04} (3.91×10^{-07})	7.82 (12.58)	4.41 (2.74)	10	1.63	**2.61×10^{-04}**	**2.20×10^{-04}**
4	30.00 (48.28)	35.00 (56.33)	4.64×10^{-04} (4.64×10^{-07})	3.98×10^{-04} (3.98×10^{-07})	4.03 (6.48)	4.41 (2.74)	10	1.63	**1.34×10^{-04}**	**1.15×10^{-04}**
5	29.48 (47.45)	34.63 (55.73)	4.74×10^{-04} (4.74×10^{-07})	4.05×10^{-04} (4.05×10^{-07})	59.91 (96.42)	4.41 (2.74)	10	1.63	**2.04×10^{-03}**	**1.74×10^{-03}**
6	21.05 (33.88)	22.22 (35.76)	6.75×10^{-04} (6.75×10^{-07})	6.37×10^{-04} (6.37×10^{-07})	1.86 (3.00)	4.41 (2.74)	10	1.63	**9.06×10^{-05}**	**8.55×10^{-05}**

Note: Doses for individuals are expressed in units of mrem (1 mrem = 1/1,000 rem). Population doses (sum of the individual doses) are expressed in units of person-rem.
*2001 National Household Travel Survey (NHTS)–all trips.

Train Crew. Train crews are estimated at two per train for the dedicated, regular, and key trains.

Shipment Escorts. Four escorts per train are assumed for dedicated, regular, and key trains.

Inspectors/Classification Yard Workers. Railroad employees that classify or inspect the rail casks cars during stops are likely to receive close proximity exposures. Functions performed at stops include marshalling of cars, arrival and departure train inspections, and repair of damaged railcars. A determination of exact numbers of close-in rail yard workers was not established. Instead, doses for this population were estimated based on the total person-hour/meter estimate used by RADTRAN [DOE, 1986].

Other Rail Yard Workers. An average of 125 workers within a 0.2-mi^2 (0.5-km^2) area at each yard is assumed based on estimates provided by consulted railroads. This gives a yard worker population density of 625 workers per mi^2 (250 workers per km^2).

2.1.5 Distances from the Source

The distance from the source is a determining factor in the amount of radiation dose members of a population group receive. Distance is important because the radiation level varies with the inverse square of the distance from the cask.

The various impacted populations are at different distances from the source. Figure 9 the distances assumed in this analysis. The figure also shows the model used (line source or point source) for each of the impacted populations.

Train Crew. Train crew distances from the cask vary depending on the shipment service selected. The cask car(s) was assumed to be buffered front and rear. A 49.2 ft (15-m) car length and 6.6 ft (2 m) between cars was assumed. For regular and key train service, it was assumed that the cask car was car number 35 in a 70 car train. For dedicated service, it was assumed that the train consisted of two locomotives (with crew in first unit), buffer car, cask car, buffer car, and escort car (see Figure 7). Crew distances were thus 2,140 ft (652.3 m) and 300 ft (91.3 m) for regular/key and dedicated service, respectively.

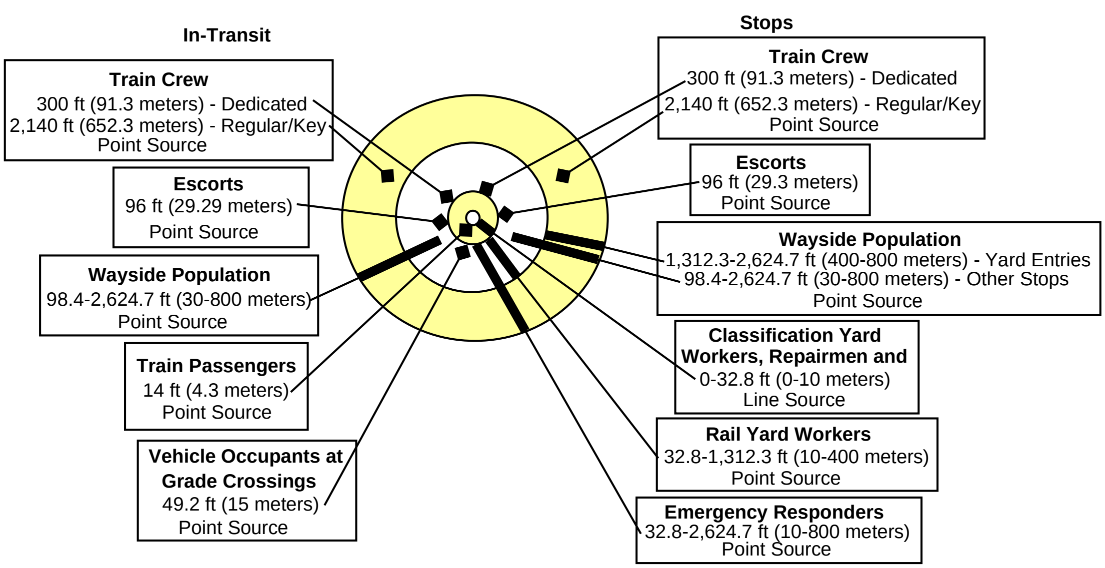


Figure 9. Population Distance from Source

Shipment Escorts. For all service cases it was assumed that the escort distance from the cask was 96 ft (29.3 m). The cask was assumed to be buffered front and rear, with escorts in a car following the rear buffer car. Although the position of the escort railcar could differ for regular and key train service, placement used for this analysis results in the most conservative estimate.

Passengers in Passing Trains. The centerline distance between passing trains was assumed to be 14 ft (4.26 m) (see Figure 10). No exposure estimations were made for passengers of trains moving in the same direction as the train carrying the cask.

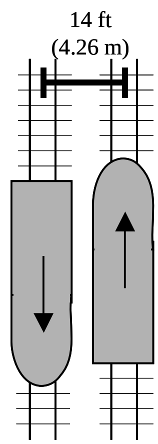


Figure 10. Passing Train Distance

Vehicle Occupants at Grade Crossing. Since vehicle occupants who are 98.4 ft (30 m) from the source and beyond are included in the general population off-link dose discussed above, only vehicle occupants between 32.8 ft and 98.4 ft (10 m and 30 m) from the source were considered here. For the purposes of isolating and analyzing the dose of vehicle occupants closer than the 98.4 ft (30 m), it was assumed that on average each occupant was 49.2 ft (15 m) from the source. This is an approximation, since doses to persons further than the mean distance would be reduced by the distance squared, and persons closer than the 49.2 ft (15 m) would be higher.

2.1.6 Exposure Time

Exposure time is a determining factor in the amount of radiation members of a population group receive. In determining the total exposure durations of populations, time spent near moving and standing trains is considered. Train operational restrictions, such as train speed and run-through operations, impact exposure time during stops and when en-route.

Train Speed. Train speed impacts the duration of exposure while the train is moving. The greater the train speed, the lower the in-transit exposure to the general population. Route segments of similar characteristics were grouped into categories by population density and speed. Speeds for each category of route segment were derived by weighting the individual segment speeds by their distance then averaging them. This average distance weighted speed was calculated for the 35 mph and 50 mph cases. If the distance weighted average speed exceeded the 35 or 50 mph case, the speed was limited to the case mph limit. Table 8 shows the average weighted speeds for the six routes used for this analysis.

Table 8. Distance and Average Weighted Speed by Route

Route	Route Length miles (km)				Average Weighted Speed over Entire Routemph (km/hr)	
	Total	Rural	Suburban	Urban	35 mph (56.3 km/hr) Case	50 mph (80.4 km/hr) Case
1	1,090.36 (1,754.76)	655.61 (1,055.10)	374.90 (603.35)	59.84 (96.31)	26.27 (42.28)	31.30 (50.22)
2	2,988.02 (4,808.76)	2210.98 (3,558.23)	758.10 (1,220.04)	18.94 (30.48)	29.08 (46.80)	34.38 (55.33)
3	1,919.56 (3,089.23)	1,555.11 (2,502.71)	356.63 (573.94)	7.82 (12.58)	29.86 (48.06)	35.46 (57.07)
4	2,470.58 (3,976.02)	2,023.04 (3,255.77)	443.52 (713.77)	4.03 (6.48)	29.05 (46.75)	34.39 (55.35)
5	3,085.59 (4,965.77)	2,017.06 (3,246.15)	1,008.62 (1,623.21)	59.91 (96.42)	29.05 (46.75)	34.64 (55.75)
6	1,226.03 (1,973.11)	1,046.23 (1,683.75)	177.94 (286.36)	1.86 (3.00)	28.27 (45.50)	33.03 (53.16)

Run-Through Operations. Time spent in classification yards can more than double transit time, especially for shorter shipment distances. Reducing this time significantly reduces the radiological risk for both onboard and yard personnel and people in the vicinity of yards or other locations where a car might await a connecting train.

A fixed consist that bypasses classification yards en route cuts transit time. This reduces exposure of onboard personnel and populace near yards in which it would have stopped. It also avoids the relatively high accident potential of yard operations.

For Moving Train. Exposure time for moving trains is dependent on the train speed and route length (see Table 8). Speeds of 35 mph (56.3 km/hr) and 50 mph (80.4 km/hr) were used for this analysis. For crews and escorts, transit time was calculated for each route by multiplying the average speed by the route length.

For vehicle occupants at grade crossings, exposure time is the duration of the SNF shipment pass-by. The determining factor of this exposure is the train speed. The train's speed was set at the distance-weighted average speed for all urban links on the route for each service type.

For Standing Train. Two types of stops were assumed for each route: yard stops (classification, switching, and inspection) and non-yard or siding stops (interchange and crew change). Each type has a different stop duration. Stop times for regular and dedicated trains differ since handling, inspections, routes, crew changes, and many other variables affect the time. Stop durations were estimated based on Burlington Northern Santa Fe (BNSF) logistical planning model data, which were used to estimate the amount of time a train would likely be stopped along each of the routes. The model results used in this analysis are BNSF estimates meant to represent a likely scenario for comparison and may be different for operations by other railroads. In general, regular and key trains stop in every yard; dedicated trains stop for crew changes (driven by hours-of-service limits) and when entering territory of a different railroad and changing locomotives (about every 350 miles (563 km)). Trains also could be stopped for inspections (the assumption for this analysis is that these inspections are done at the nearest siding/yard stop). Tables 9 and 10 show the estimated number and duration of stops used in this analysis.

Table 9. Number and Duration of Yard Entries

	Regular/Key Trains		Dedicated Trains	
Route	**Number of Yard Entries**	**Duration of Yard Stops**	**Number of Yard Entries**	**Duration of Yard Stops**
1	4	**Origin**–20 Hours **Intermediate** (2)–17 and 36 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
2	5	**Origin**–20 Hours **Intermediate** (3)–5, 17 and 24 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
3	5	**Origin**–20 Hours **Intermediate** (3)–12, 17 and 24 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
4	5	**Origin**–20 Hours **Intermediate** (3)–5, 17 and 24 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
5	5	**Origin**–20 Hours **Intermediate** (3)–12, 17 and 24 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
6	5	**Origin**–20 Hours **Intermediate** (3)–12, 12 and 17 Hours **Destination**–20 Hours	2	**Origin**–20 Hours **Destination**–20 Hours
Total	**29**	**Origin**–120 Hours **Intermediate**–292 Hours **Destination**–120 Hours	**12**	**Origin**–120 Hours **Destination**–120 Hours

Assumes 70-112 cars for regular/key trains; 6 car train length for dedicated train.
Source: BNSF.

For the general population, stop time is equal to the duration of the stop event. Crew and escort in-transit exposure was calculated as a stop with a duration equal to the total travel time for the trip. Actual stop time for the crew is equal to the total travel time, plus 2 hours for each yard stop, excluding origin and destination (O-D), plus non-classification stop time. Escort stop time is equal to the total travel time, plus the full yard entry times including O-D (it is assumed escorts never leave the shipment), plus non-classification (interchange, crew change, refueling, inspection) stop times. The number of non-classification stops for regular and key trains are fewer than for dedicated trains because some crew changes are assumed to occur in conjunction with classification stops.

Table 10. Number of Non-Classification Stops

	(approx. 1 per 350 miles (563 km)) Duration = 1 hour per stop	
Route	**Regular/Key**	**Dedicated**
1	1	3
2	6	9
3	3	6
4	4	7
5	6	9
6	1	4

Source: BNSF.

2.1.7 Shielding Factors

The amount of shielding between the source and the affected population impacts the received dose rate. Table 11 shows the shielding factors used for impacted populations (RADTRAN defaults).

Table 11. Shielding Factor (Attenuation)

Population		Receptor Shielding Factor	Construction Type
General Wayside Population	Rural	1.0*	No shielding
	Suburban	0.87*	Wood frame construction 45-ft sq (13.7-m sq) buildings; 100 ft (30.5 m) between buildings; 6-in (15.2-cm) thick walls
	Urban	0.018*	Concrete block walls 1-ft (30.5-cm) thick; 1 central wall/ building. Buildings are contiguous in blocks 200-ft (61-m) long, 60-ft (18.3-m) wide streets
Vehicle Occupants at Rail Crossings		1.0	No shielding
Train Passengers		1.0	No shielding
Crew		0.5	Reflects gamma radiation attenuation by locomotives
Escorts		1.0	No shielding
Inspectors/Handlers		1.0	No shielding
General Yard Workers		0.1	Reflects gamma radiation attenuation by other railcars and structures in the rail yard

* Source: Madsen, Wilmot, and Taylor, 1986.
Note: The suburban shielding factor was used for general population for all stops.

2.2 Incident-Free Results

The following section presents the radiological consequences of incident-free transportation of HLRW and SNF by the regular train, key train, and dedicated train service modes for the 35 mph (56.3 km/hr) and 50 mph (80.4 km/hr) speeds. The results are presented by route, service/speed, population type, and in-transit versus stops. The intent of the incident-free analysis was to provide a general estimate of the differences between the alternate service modes and speeds. Simulations of the alternatives were conducted comparing service types for the same sets of routes. The results of these estimates are included as an example of the likely differences in exposure because of changes in service characteristics. All incident-free radiological impact results are given for a single shipment (i.e., a single movement of a single cask).

In general, these results show that dedicated trains expose populations to a lesser radiological dose than regular and key trains at all speeds and that stop time risk dominates total exposure for regular and key trains.

The results are expressed primarily as population doses (person-rem) that are converted into an estimate of health effects (i.e., LCFs).

All incident-free doses calculated in RADTRAN 5 are prompt doses (i.e., doses from short exposures) and are expressed in effective dose equivalents (EDEs). Doses for individuals are expressed in units of mrem. Population doses (sum of the doses for all individuals in the population group) are expressed in units of person-rem.

2.2.1 Results by Route

This section details the total dose of all population groups from incident-free transportation operations for a single movement over each of the six routes. Looking by route, it is evident that route length and percent of distance within heavily populated areas are determining factors. Table 12 and Figure 11 show in-transit and stop dose results for all populations.

Table 12. In-Transit and Stop Doses (person-rem) for All Populations

Route	Service/Speed	In-Transit	Stop	Total
Route 1	Key 50 mph	0.0303	0.1013	**0.1316**
	Regular 50 mph	0.0303	0.1013	**0.1316**
	Regular 35 mph	0.0365	0.1013	**0.1378**
	Dedicated 50 mph	0.0306	0.0413	**0.0720**
	Dedicated 35 mph	0.0371	0.0413	**0.0784**
Route 2	Key 50 mph	0.0627	0.1323	**0.1949**
	Regular 50 mph	0.0627	0.1323	**0.1949**
	Regular 35 mph	0.0758	0.1323	**0.2081**
	Dedicated 50 mph	0.0638	0.0543	**0.1181**
	Dedicated 35 mph	0.0772	0.0543	**0.1315**
Route 3	Key 50 mph	0.0359	0.1169	**0.1528**
	Regular 50 mph	0.0359	0.1169	**0.1528**
	Regular 35 mph	0.0442	0.1169	**0.1611**
	Dedicated 50 mph	0.0366	0.0472	**0.0838**
	Dedicated 35 mph	0.0451	0.0472	**0.0922**
Route 4	Key 50 mph	0.0478	0.1206	**0.1684**
	Regular 50 mph	0.0478	0.1206	**0.1684**
	Regular 35 mph	0.0578	0.1206	**0.1784**
	Dedicated 50 mph	0.0487	0.0493	**0.0980**
	Dedicated 35 mph	0.0590	0.0493	**0.1083**
Route 5	Key 50 mph	0.0683	0.1402	**0.2094**
	Regular 50 mph	0.0683	0.1402	**0.2094**
	Regular 35 mph	0.0848	0.1402	**0.2250**
	Dedicated 50 mph	0.0704	0.0554	**0.1258**
	Dedicated 35 mph	0.0862	0.0554	**0.1416**
Route 6	Key 50 mph	0.0245	0.0978	**0.1223**
	Regular 50 mph	0.0245	0.0978	**0.1223**
	Regular 35 mph	0.0294	0.0978	**0.1272**
	Dedicated 50 mph	0.0250	0.0451	**0.0700**
	Dedicated 35 mph	0.0300	0.0451	**0.0750**

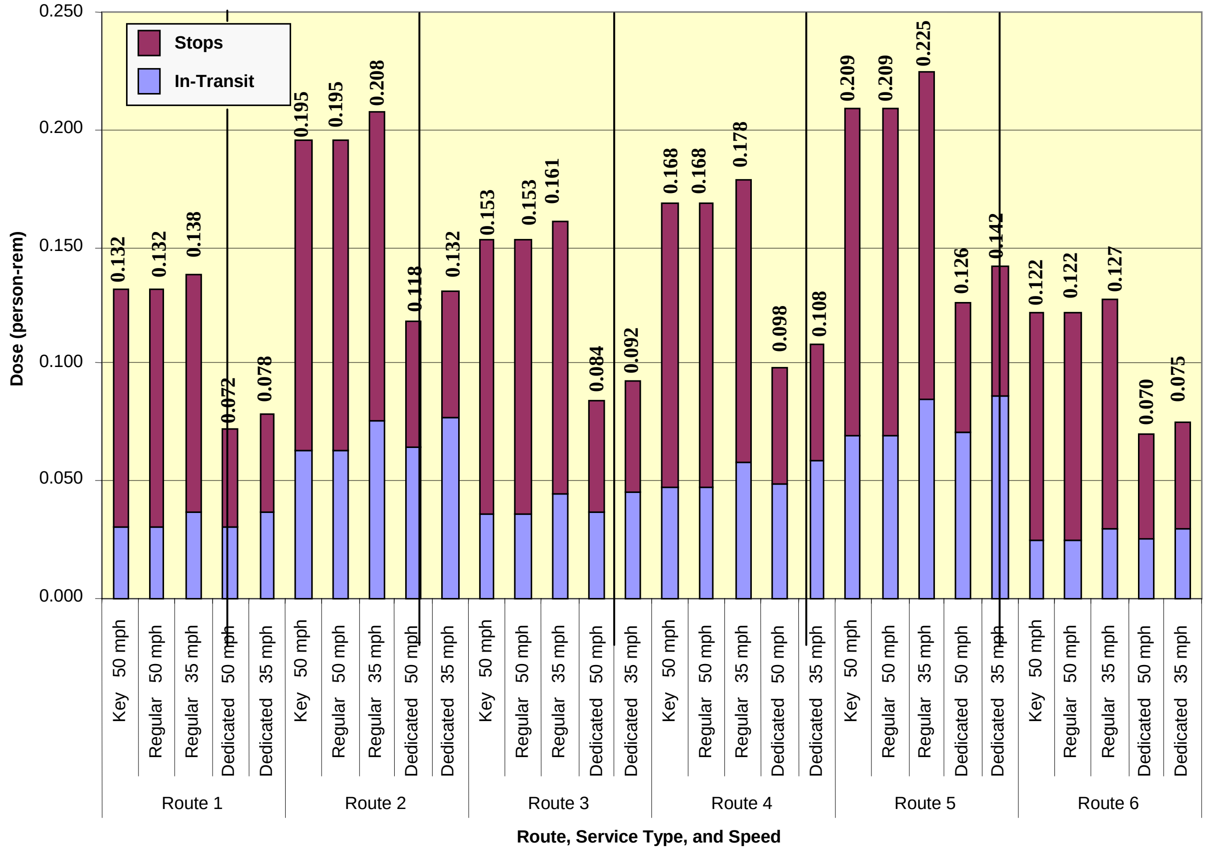


Figure 11. Total Dose–All Populations by Route, Service Type, and Speed

2.2.2 Population Group Exposure by Route, Service Type, and Speed

This analysis of exposures resulting from routine (non-accident or incident-free) transportation focuses on radiation doses received by each of the population groups discussed in Section 2.1.4.

Incident-free exposure comes from the radiation dose received while the train is moving along the tracks (in-transit) and while it is at rest in yards or sidings (stops). Tables 13 and 14 show the total in-transit and stop incident-free doses for all populations.

This analysis deals with the movement of a single train carrying a single SNF cask. The consequences of an extended shipment program would need to consider the cumulative annual doses for potentially extended (10- to 30-year) periods. Values for multiple low-level exposures per year can be estimated by multiplying the single movement person-rem dose by the anticipated number of movements.

Table 13. In-Transit Dose by Population Type (person-rem)

Route	Service/Speed	General Population	Vehicle Occupants at Grade Crossings	Passing Train Passengers	Crew	Escorts	Total
Route 1	Key 50 mph	0.0087	1.71×10^{-03}	1.49×10^{-03}	9.26×10^{-06}	0.0184	0.0303
	Regular 50 mph	0.0087	1.71×10^{-03}	1.49×10^{-03}	9.26×10^{-06}	0.0184	0.0303
	Regular 35 mph	0.0109	2.04×10^{-03}	1.80×10^{-03}	1.10×10^{-05}	0.0218	0.0365
	Dedicated 50 mph	0.0087	1.71×10^{-03}	1.49×10^{-03}	3.01×10^{-04}	0.0184	0.0306
	Dedicated 35 mph	0.0109	2.04×10^{-03}	1.80×10^{-03}	5.62×10^{-04}	0.0218	0.0371
Route 2	Key 50 mph	0.0151	5.73×10^{-04}	1.26×10^{-03}	2.31×10^{-05}	0.0457	0.0627
	Regular 50 mph	0.0151	5.73×10^{-04}	1.26×10^{-03}	2.31×10^{-05}	0.0457	0.0627
	Regular 35 mph	0.0188	6.60×10^{-04}	2.21×10^{-03}	2.73×10^{-05}	0.0541	0.0758
	Dedicated 50 mph	0.0151	5.73×10^{-04}	1.26×10^{-03}	1.18×10^{-03}	0.0457	0.0638
	Dedicated 35 mph	0.0188	6.60×10^{-04}	2.21×10^{-03}	1.39×10^{-03}	0.0541	0.0772
Route 3	Key 50 mph	0.0064	2.20×10^{-04}	7.47×10^{-04}	1.44×10^{-05}	0.0285	0.0359
	Regular 50 mph	0.0064	2.20×10^{-04}	7.47×10^{-04}	1.44×10^{-05}	0.0285	0.0359
	Regular 35 mph	0.0086	2.61×10^{-04}	1.41×10^{-03}	1.71×10^{-05}	0.0339	0.0442
	Dedicated 50 mph	0.0064	2.20×10^{-04}	7.47×10^{-04}	7.33×10^{-04}	0.0285	0.0366
	Dedicated 35 mph	0.0086	2.61×10^{-04}	1.41×10^{-03}	8.71×10^{-04}	0.0339	0.0451
Route 4	Key 50 mph	0.0088	1.15×10^{-04}	1.04×10^{-03}	1.91×10^{-05}	0.0378	0.0478
	Regular 50 mph	0.0088	1.15×10^{-04}	1.04×10^{-03}	1.91×10^{-05}	0.0378	0.0478
	Regular 35 mph	0.0111	1.34×10^{-04}	1.87×10^{-03}	2.26×10^{-05}	0.0447	0.0578
	Dedicated 50 mph	0.0088	1.15×10^{-04}	1.04×10^{-03}	9.73×10^{-04}	0.0378	0.0487
	Dedicated 35 mph	0.0111	1.34×10^{-04}	1.87×10^{-03}	1.15×10^{-03}	0.0447	0.0590
Route 5	Key 50 mph	0.0193	1.74×10^{-03}	1.29×10^{-03}	2.36×10^{-05}	0.0469	0.0693
	Regular 50 mph	0.0193	1.74×10^{-03}	1.29×10^{-03}	2.36×10^{-05}	0.0469	0.0693
	Regular 35 mph	0.0246	2.04×10^{-03}	2.25×10^{-03}	2.82×10^{-05}	0.0559	0.0848
	Dedicated 50 mph	0.0193	1.74×10^{-03}	1.29×10^{-03}	1.21×10^{-03}	0.0469	0.0704
	Dedicated 35 mph	0.0246	2.04×10^{-03}	2.25×10^{-03}	1.44×10^{-03}	0.0559	0.0862
Route 6	Key 50 mph	0.0043	8.55×10^{-05}	6.44×10^{-04}	9.85×10^{-06}	0.0195	0.0245
	Regular 50 mph	0.0043	8.55×10^{-05}	6.44×10^{-04}	9.85×10^{-06}	0.0195	0.0245
	Regular 35 mph	0.0055	9.06×10^{-05}	1.00×10^{-03}	1.15×10^{-05}	0.0228	0.0294
	Dedicated 50 mph	0.0043	8.55×10^{-05}	6.44×10^{-04}	5.03×10^{-04}	0.0195	0.0250
	Dedicated 35 mph	0.0055	9.06×10^{-05}	1.00×10^{-03}	5.88×10^{-04}	0.0228	0.0300

Table 14. Stop Dose by Population Type (person-rem)

Route	Service/Speed	General Population (Yard Stops)	General Population (Interchange Stops)	General Yard Workers	Classification Yard Workers	Crew	Escorts	Total
Route 1	Key 50 mph	0.0179	0.0009	0.0061	0.0269	2.39×10^{-06}	0.0495	**0.1013**
	Regular 50 mph	0.0179	0.0009	0.0061	0.0269	2.39×10^{-06}	0.0495	**0.1013**
	Regular 35 mph	0.0179	0.0009	0.0061	0.0269	2.39×10^{-06}	0.0495	**0.1013**
	Dedicated 50 mph	0.0077	0.0027	0.0026	0.0056	9.48×10^{-05}	0.0226	**0.0413**
	Dedicated 35 mph	0.0077	0.0027	0.0026	0.0056	9.48×10^{-05}	0.0226	**0.0413**
Route 2	Key 50 mph	0.0139	0.0046	0.0056	0.0598	4.25×10^{-06}	0.0484	**0.1323**
	Regular 50 mph	0.0139	0.0046	0.0056	0.0598	4.25×10^{-06}	0.0484	**0.1323**
	Regular 35 mph	0.0139	0.0046	0.0056	0.0598	4.25×10^{-06}	0.0484	**0.1323**
	Dedicated 50 mph	0.0064	0.0069	0.0026	0.0124	1.76×10^{-04}	0.0258	**0.0543**
	Dedicated 35 mph	0.0064	0.0069	0.0026	0.0124	1.76×10^{-04}	0.0258	**0.0543**
Route 3	Key 50 mph	0.0155	0.0024	0.0061	0.0425	3.45×10^{-06}	0.0505	**0.1169**
	Regular 50 mph	0.0155	0.0024	0.0061	0.0425	3.45×10^{-06}	0.0505	**0.1169**
	Regular 35 mph	0.0155	0.0024	0.0061	0.0425	3.45×10^{-06}	0.0505	**0.1169**
	Dedicated 50 mph	0.0066	0.0047	0.0026	0.0088	1.35×10^{-04}	0.0242	**0.0472**
	Dedicated 35 mph	0.0066	0.0047	0.0026	0.0088	1.35×10^{-04}	0.0242	**0.0472**
Route 4	Key 50 mph	0.0131	0.0029	0.0056	0.0516	3.72×10^{-06}	0.0474	**0.1206**
	Regular 50 mph	0.0131	0.0029	0.0056	0.0516	3.72×10^{-06}	0.0474	**0.1206**
	Regular 35 mph	0.0131	0.0029	0.0056	0.0516	3.72×10^{-06}	0.0474	**0.1206**
	Dedicated 50 mph	0.0061	0.0050	0.0026	0.0107	1.49×10^{-04}	0.0247	**0.0493**
	Dedicated 35 mph	0.0061	0.0050	0.0026	0.0107	1.49×10^{-04}	0.0247	**0.0493**
Route 5	Key 50 mph	0.0158	0.0048	0.0061	0.0613	4.25×10^{-06}	0.0521	**0.1402**
	Regular 50 mph	0.0158	0.0048	0.0061	0.0613	4.25×10^{-06}	0.0521	**0.1402**
	Regular 35 mph	0.0158	0.0048	0.0061	0.0613	4.25×10^{-06}	0.0521	**0.1402**
	Dedicated 50 mph	0.0068	0.0072	0.0026	0.0127	1.76×10^{-04}	0.0258	**0.0554**
	Dedicated 35 mph	0.0068	0.0072	0.0026	0.0127	1.76×10^{-04}	0.0258	**0.0554**
Route 6	Key 50 mph	0.0175	0.0010	0.0053	0.0308	2.92×10^{-06}	0.0432	**0.0978**
	Regular 50 mph	0.0175	0.0010	0.0053	0.0308	2.92×10^{-06}	0.0432	**0.0978**
	Regular 35 mph	0.0175	0.0010	0.0053	0.0308	2.92×10^{-06}	0.0432	**0.0978**
	Dedicated 50 mph	0.0086	0.0041	0.0026	0.0064	1.08×10^{-04}	0.0232	**0.0451**
	Dedicated 35 mph	0.0086	0.0041	0.0026	0.0064	1.08×10^{-04}	0.0232	**0.0451**

2.2.3 Results for Individual Populations

General Wayside Population

Persons who are located near rail routes could receive very low-level exposures when shipments containing HLRW and SNF casks move past. These doses are referred to as in-transit off-link doses. The total general population dose for all route/service type/speed combinations evaluated ranged from 0.0170 to 0.0452 person-rem. In-transit doses are speed dependent (see Figure 12 and Table 15). For both speed cases, dedicated train service doses were lower than for regular or key train service. In addition to the in-transit dose, general population doses are derived from stops. The total dose for all stops (yard and interchange) for regular and key service are higher than for dedicated due to increased number of stops and longer stop durations.

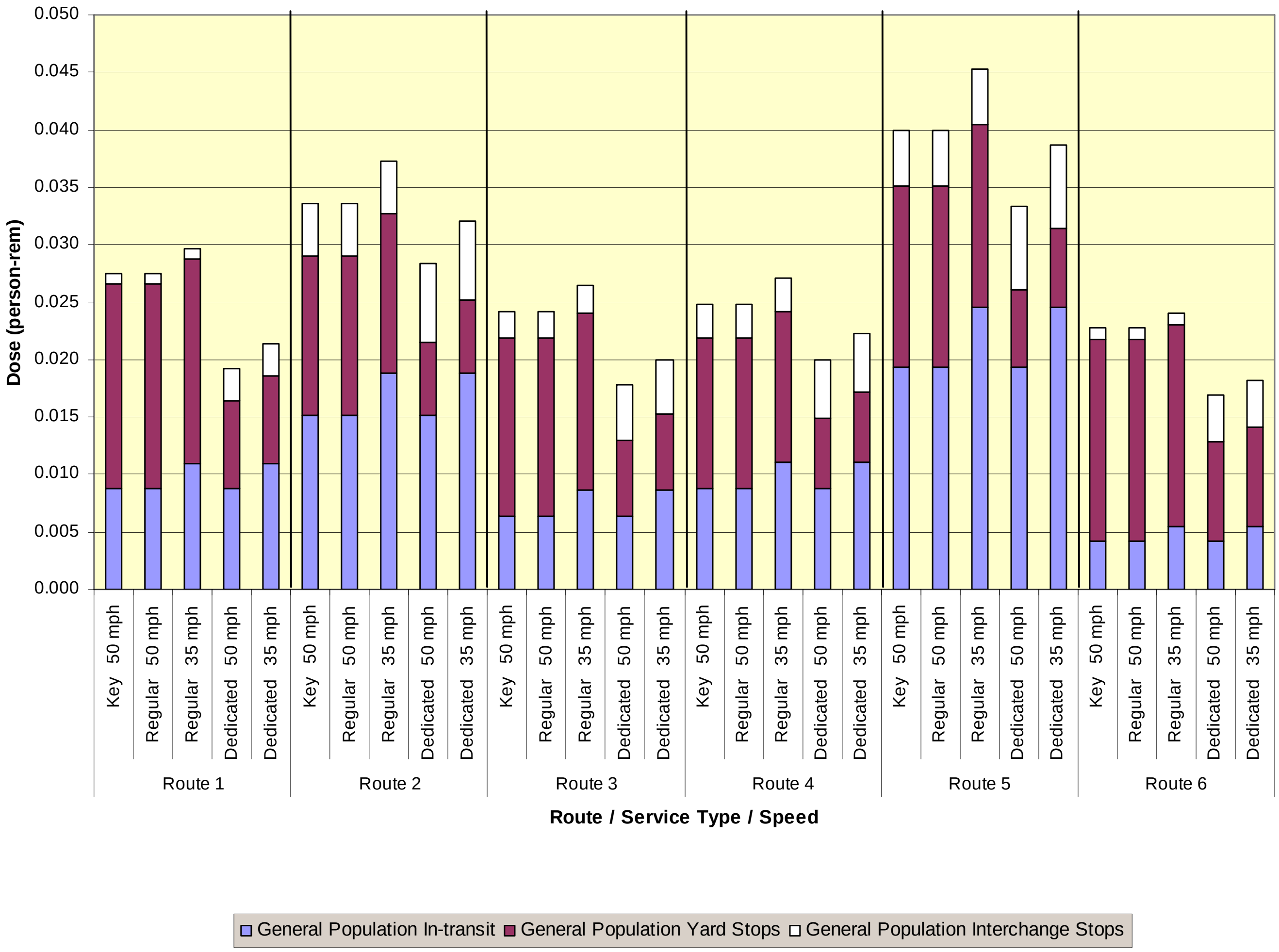


Figure 12. General Population Dose

RADTRAN calculates an individual in-transit dose received by a person standing 98.5 ft (30 m) from a train as it passes at 15 mph (24 km/hr). This dose, calculated to represent a maximum dose to a single person in the general population, is calculated to be 4.32×10^{-04} mrem (4.32×10^{-07} rem). At this rate, a single individual would have to be exposed to over 6,000 cask shipments for the individual to receive a dose equivalent to the total received during a typical 4-hour jet flight.

Table 15. General Population Dose

Route	Service	General Population Dose (person-rem)			
		General Population In-Transit	General Population Yard Stops	General Population Interchange Stops	Total
Route 1	Key 50 mph	0.0087	0.0179	0.0009	**0.0275**
	Regular 50 mph	0.0087	0.0179	0.0009	**0.0275**
	Regular 35 mph	0.0109	0.0179	0.0009	**0.0297**
	Dedicated 50 mph	0.0087	0.0077	0.0027	**0.0192**
	Dedicated 35 mph	0.0109	0.0077	0.0027	**0.0213**
Route 2	Key 50 mph	0.0151	0.0139	0.0046	**0.0335**
	Regular 50 mph	0.0151	0.0139	0.0046	**0.0335**
	Regular 35 mph	0.0188	0.0139	0.0046	**0.0372**
	Dedicated 50 mph	0.0151	0.0064	0.0069	**0.0284**
	Dedicated 35 mph	0.0188	0.0064	0.0069	**0.0321**
Route 3	Key 50 mph	0.0064	0.0155	0.0024	**0.0242**
	Regular 50 mph	0.0064	0.0155	0.0024	**0.0242**
	Regular 35 mph	0.0086	0.0155	0.0024	**0.0265**
	Dedicated 50 mph	0.0064	0.0066	0.0047	**0.0178**
	Dedicated 35 mph	0.0086	0.0066	0.0047	**0.0200**
Route 4	Key 50 mph	0.0088	0.0131	0.0029	**0.0247**
	Regular 50 mph	0.0088	0.0131	0.0029	**0.0247**
	Regular 35 mph	0.0111	0.0131	0.0029	**0.0270**
	Dedicated 50 mph	0.0088	0.0061	0.0050	**0.0199**
	Dedicated 35 mph	0.0111	0.0061	0.0050	**0.0222**
Route 5	Key 50 mph	0.0193	0.0158	0.0048	**0.0399**
	Regular 50 mph	0.0193	0.0158	0.0048	**0.0399**
	Regular 35 mph	0.0246	0.0158	0.0048	**0.0452**
	Dedicated 50 mph	0.0193	0.0068	0.0072	**0.0333**
	Dedicated 35 mph	0.0246	0.0068	0.0072	**0.0386**
Route 6	Key 50 mph	0.0043	0.0175	0.0010	**0.0228**
	Regular 50 mph	0.0043	0.0175	0.0010	**0.0228**
	Regular 35 mph	0.0055	0.0175	0.0010	**0.0240**
	Dedicated 50 mph	0.0043	0.0086	0.0041	**0.0170**
	Dedicated 35 mph	0.0055	0.0086	0.0041	**0.0182**

Passing Train Passengers

Passengers on passing trains receive very low-level in-transit exposures (these are referred to as on-link doses). Doses for the total passenger population range from 6.44×10^{-04} to 2.25×10^{-03} person-rem per shipment. On-link dose levels are speed sensitive and vary by route depending on the amount of train traffic (see Figure 13 and Table 16).

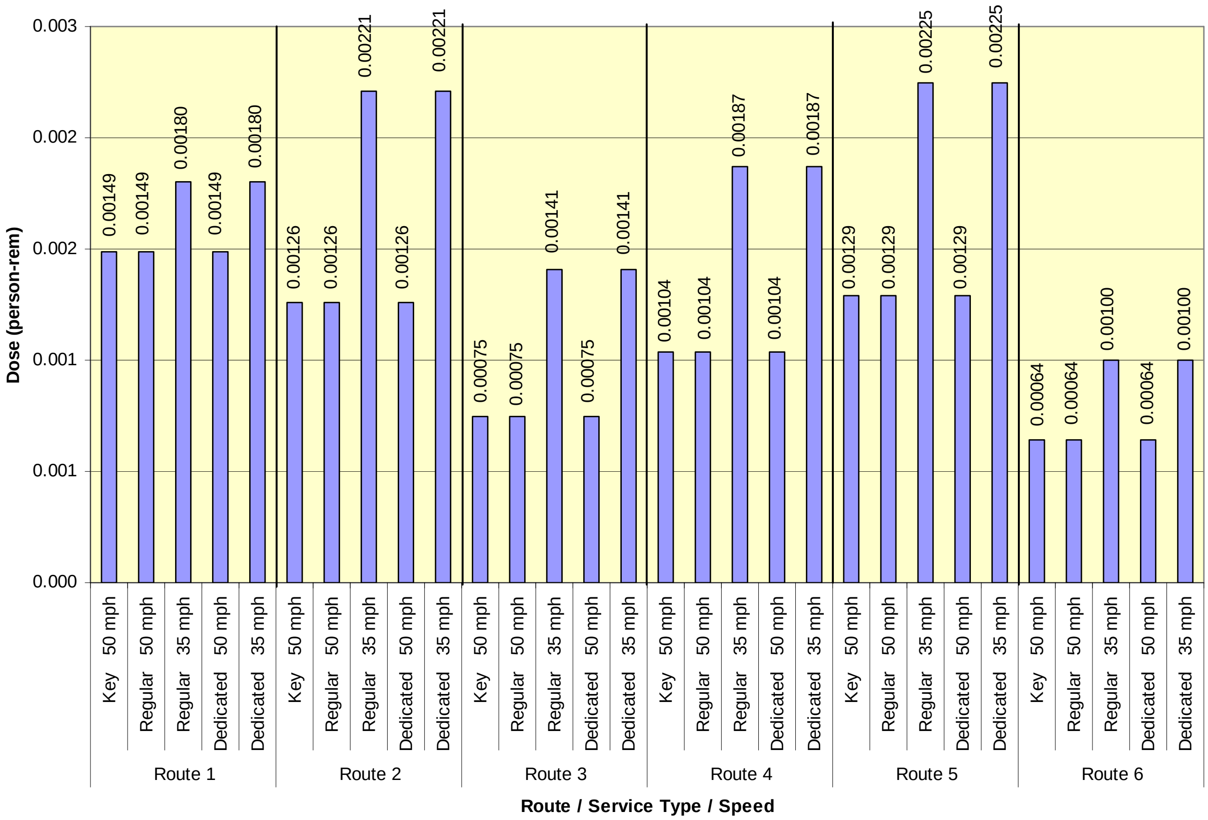


Figure 13. Train Passenger On-Link Dose

Table 16. Train Passenger On-Link Dose

Route	Service	On-Link Dose (person-rem)
Route 1	Key 50 mph	1.49×10^{-03}
	Regular 50 mph	1.49×10^{-03}
	Regular 35 mph	1.80×10^{-03}
	Dedicated 50 mph	1.49×10^{-03}
	Dedicated 35 mph	1.80×10^{-03}
Route 2	Key 50 mph	1.26×10^{-03}
	Regular 50 mph	1.26×10^{-03}
	Regular 35 mph	2.21×10^{-03}
	Dedicated 50 mph	1.26×10^{-03}
	Dedicated 35 mph	2.21×10^{-03}
Route 3	Key 50 mph	7.47×10^{-04}
	Regular 50 mph	7.47×10^{-04}
	Regular 35 mph	1.41×10^{-03}
	Dedicated 50 mph	7.47×10^{-04}
	Dedicated 35 mph	1.41×10^{-03}
Route 4	Key 50 mph	1.04×10^{-03}
	Regular 50 mph	1.04×10^{-03}
	Regular 35 mph	1.87×10^{-03}
	Dedicated 50 mph	1.04×10^{-03}
	Dedicated 35 mph	1.87×10^{-03}
Route 5	Key 50 mph	1.29×10^{-03}
	Regular 50 mph	1.29×10^{-03}
	Regular 35 mph	2.25×10^{-03}
	Dedicated 50 mph	1.29×10^{-03}
	Dedicated 35 mph	2.25×10^{-03}
Route 6	Key 50 mph	6.44×10^{-04}
	Regular 50 mph	6.44×10^{-04}
	Regular 35 mph	1.00×10^{-03}
	Dedicated 50 mph	6.44×10^{-04}
	Dedicated 35 mph	1.00×10^{-03}

Vehicle Occupants at Grade Crossings

Occupants in automobiles at grade crossings were evaluated in this analysis as a distinct population since they would be adjacent to passing trains carrying HLRW and SNF. This analysis considered only urban crossings, where the highest traffic volumes are experienced and where off-peak scheduling would be unlikely. Since the FRA Highway-Railway Crossing Inventory estimates that an average of greater than 2,000 vehicles per day traverse each urban public crossing, it was assumed that vehicles would be queued at each urban crossing. As discussed in Section 2.1.5, cars within 98.5 ft (30 m) of the track centerline were considered. A queue of five 14-foot-long cars on each side of the track was assumed to be the maximum possible within the 98.5-ft (30-m) distance. This results in a total of 10 cars per crossing considered in estimating the dose to vehicle occupants. The number of crossings per route was estimated by multiplying the total urban distance for each route by 4.42 crossings per mi (2.74/km), a typical value for urban freight corridors [ADL, 1999]. To calculate the maximum dose at these urban grade crossings for each route and for each speed restriction, the train speed used was the distance-weighted average speed for all urban links on each route. It was assumed that at any point in time 10 vehicles would be at each crossing at the time the cask passes, as well as an average vehicle occupancy of 1.63 persons per vehicle. Figure 14 and in Table 17 show the calculated dose results. The dose to vehicle occupants at grade crossings is train-speed specific and is not impacted by the type of train service.

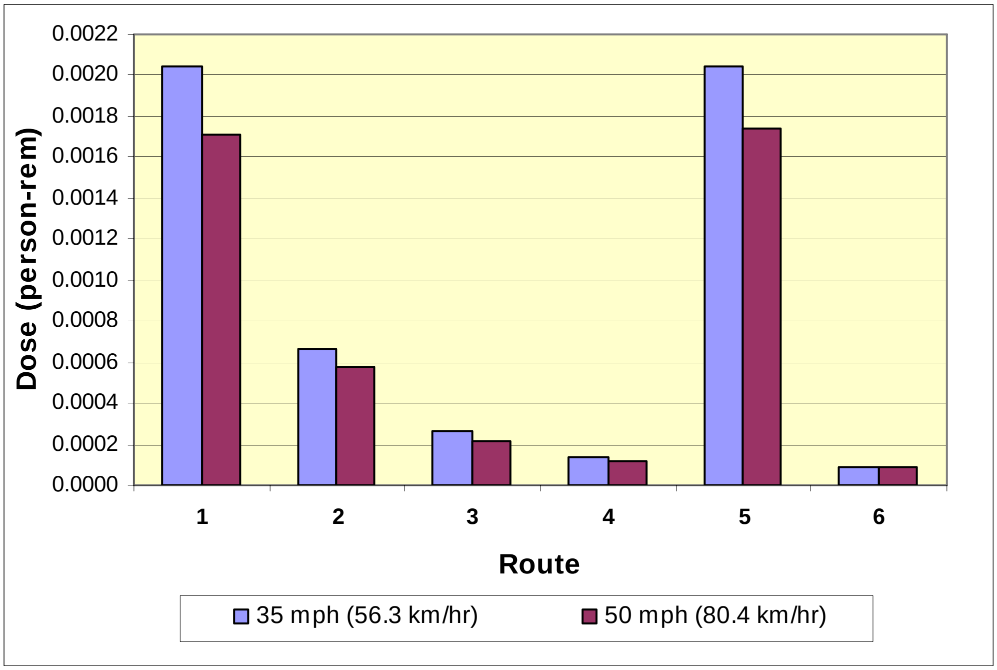


Figure 14. Dose to All Vehicle Occupants at Grade Crossings by Route and Weighted-Average Speed

Table 17. Total Dose to Vehicle Occupants at Grade Crossings

Route	**(person-rem)** 35 mph (56.3 km/hr)	**(person-rem)** 50 mph (80.4 km/hr)
1	2.04×10^{-03}	1.71×10^{-03}
2	6.60×10^{-04}	5.73×10^{-04}
3	2.61×10^{-04}	2.20×10^{-04}
4	1.34×10^{-04}	1.15×10^{-04}
5	2.04×10^{-03}	1.74×10^{-03}
6	9.06×10^{-05}	8.55×10^{-05}

Train Crew and Escorts

For train crews, dedicated train doses are higher than for the regular and key trains (assuming no special shielding provisions), primarily because of the closer proximity of the crew to the cask in the dedicated train. In-transit results are also speed dependent, with higher train speeds generating lower doses. Train crews could receive between a 1.17×10^{-05} and 1.62×10^{-03} person-rem dose per shipment (see Table 18).

For shipment escorts, dedicated train case doses are lower than regular and key train cases for both speed scenarios because of the shorter stop durations. Stop doses are higher than the in-transit doses for regular and key train cases. Escorts could receive between a 0.108 and 0.041 person-rem dose per shipment (see Table 18).

Table 18. In-Transit and Stop Dose to Train Crew and Escorts (person-rem)

Route	Service	Crew			Escorts		
		In-Transit	Stops	Total	In-Transit	Stops	Total
Route 1	Key 50 mph	9.26×10^{-06}	2.39×10^{-06}	1.17×10^{-05}	0.0184	0.0495	0.0679
	Regular 50 mph	9.26×10^{-06}	2.39×10^{-06}	1.17×10^{-05}	0.0184	0.0495	0.0679
	Regular 35 mph	1.10×10^{-05}	2.39×10^{-06}	1.34×10^{-05}	0.0218	0.0495	0.0713
	Dedicated 50 mph	3.01×10^{-04}	9.48×10^{-05}	3.96×10^{-04}	0.0184	0.0226	0.0410
	Dedicated 35 mph	5.62×10^{-04}	9.48×10^{-05}	6.57×10^{-04}	0.0218	0.0226	0.0444
Route 2	Key 50 mph	2.31×10^{-05}	4.25×10^{-06}	2.74×10^{-05}	0.0457	0.0484	0.0941
	Regular 50 mph	2.31×10^{-05}	4.25×10^{-06}	2.74×10^{-05}	0.0457	0.0484	0.0941
	Regular 35 mph	2.73×10^{-05}	4.25×10^{-06}	3.16×10^{-05}	0.0541	0.0484	0.1025
	Dedicated 50 mph	1.18×10^{-03}	1.76×10^{-04}	1.36×10^{-03}	0.0457	0.0258	0.0715
	Dedicated 35 mph	1.39×10^{-03}	1.76×10^{-04}	1.57×10^{-03}	0.0541	0.0258	0.0799
Route 3	Key 50 mph	1.44×10^{-05}	3.45×10^{-06}	1.79×10^{-05}	0.0285	0.0505	0.0790
	Regular 50 mph	1.44×10^{-05}	3.45×10^{-06}	1.79×10^{-05}	0.0285	0.0505	0.0790
	Regular 35 mph	1.71×10^{-05}	3.45×10^{-06}	2.06×10^{-05}	0.0339	0.0505	0.0844
	Dedicated 50 mph	7.33×10^{-04}	1.35×10^{-04}	8.68×10^{-04}	0.0285	0.0242	0.0527
	Dedicated 35 mph	8.71×10^{-04}	1.35×10^{-04}	1.01×10^{-03}	0.0339	0.0242	0.0581
Route 4	Key 50 mph	1.91×10^{-05}	3.72×10^{-06}	2.28×10^{-05}	0.0378	0.0474	0.0852
	Regular 50 mph	1.91×10^{-05}	3.72×10^{-06}	2.28×10^{-05}	0.0378	0.0474	0.0852
	Regular 35 mph	2.26×10^{-05}	3.72×10^{-06}	2.63×10^{-05}	0.0447	0.0474	0.0921
	Dedicated 50 mph	9.73×10^{-04}	1.49×10^{-04}	1.12×10^{-03}	0.0378	0.0247	0.0625
	Dedicated 35 mph	1.15×10^{-03}	1.49×10^{-04}	1.30×10^{-03}	0.0447	0.0247	0.0694
Route 5	Key 50 mph	2.36×10^{-05}	4.25×10^{-06}	2.79×10^{-05}	0.0469	0.0521	0.0990
	Regular 50 mph	2.36×10^{-05}	4.25×10^{-06}	2.79×10^{-05}	0.0469	0.0521	0.0990
	Regular 35 mph	2.82×10^{-05}	4.25×10^{-06}	3.25×10^{-05}	0.0559	0.0521	0.1080
	Dedicated 50 mph	1.21×10^{-03}	1.76×10^{-04}	1.39×10^{-03}	0.0469	0.0258	0.0727
	Dedicated 35 mph	1.44×10^{-03}	1.76×10^{-04}	1.62×10^{-03}	0.0559	0.0258	0.0817
Route 6	Key 50 mph	9.85×10^{-06}	2.92×10^{-06}	1.28×10^{-05}	0.0195	0.0432	0.0627
	Regular 50 mph	9.85×10^{-06}	2.92×10^{-06}	1.28×10^{-05}	0.0195	0.0432	0.0627
	Regular 35 mph	1.15×10^{-05}	2.92×10^{-06}	1.44×10^{-05}	0.0228	0.0432	0.0660
	Dedicated 50 mph	5.03×10^{-04}	1.08×10^{-04}	6.11×10^{-04}	0.0195	0.0232	0.0427
	Dedicated 35 mph	5.88×10^{-04}	1.08×10^{-04}	6.96×10^{-04}	0.0228	0.0232	0.0460

Car Inspectors and Close Proximity Yard Workers

Car inspectors/classification workers could receive stop doses between 0.0056 and 0.0613 person-rem per shipment. Since the exposures to this population group are for stops only (no in-transit), results are not speed dependent but are driven by the number and duration of stops, which are route-specific. In all cases, doses for dedicated trains are less than for regular and key trains (see Figure 15).

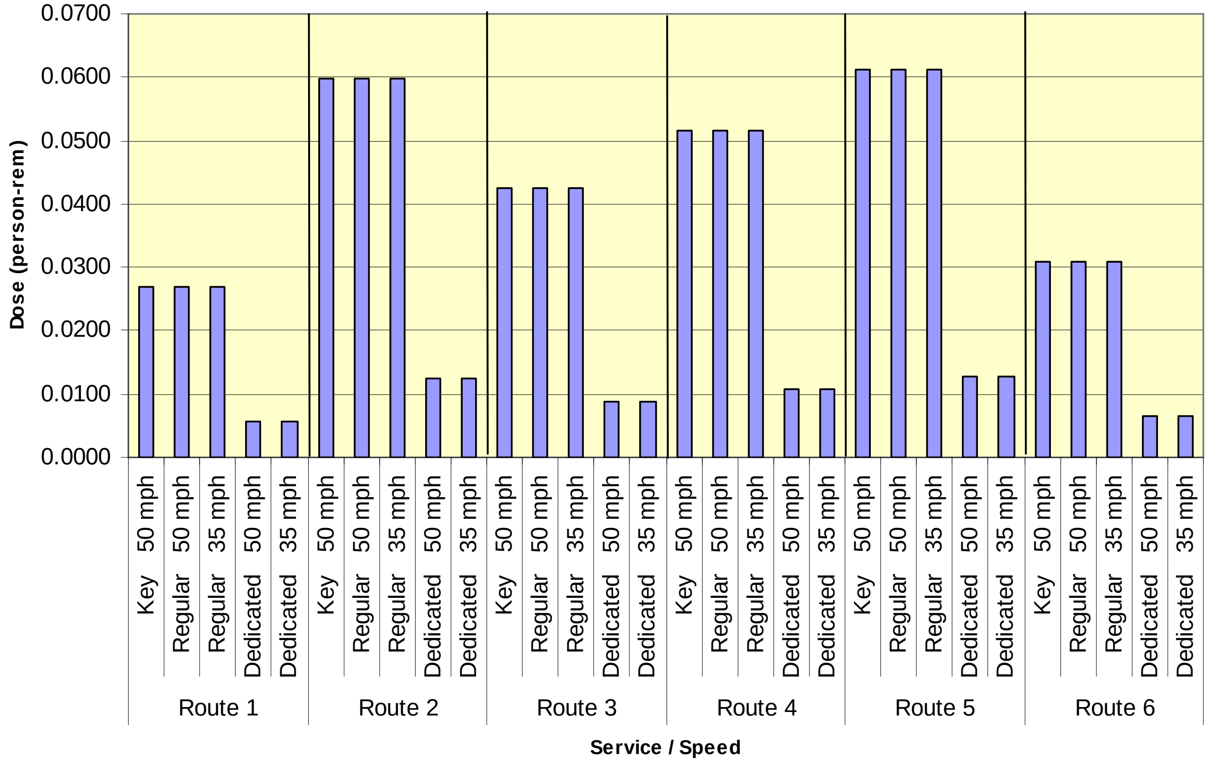


Figure 15. Inspector/Classification Yard Worker Dose

Rail Yard Workers

Rail yard workers (other than classification workers) could receive stop doses between 2.62×10^{-03} and 6.09×10^{-03} person-rem per shipment. Since the exposure for this population is for stops only (excludes in-transit), results are driven by the number and duration of stops that are route-specific. In all cases, doses for the dedicated train cases are less than the regular and key train cases (see Figure 16).

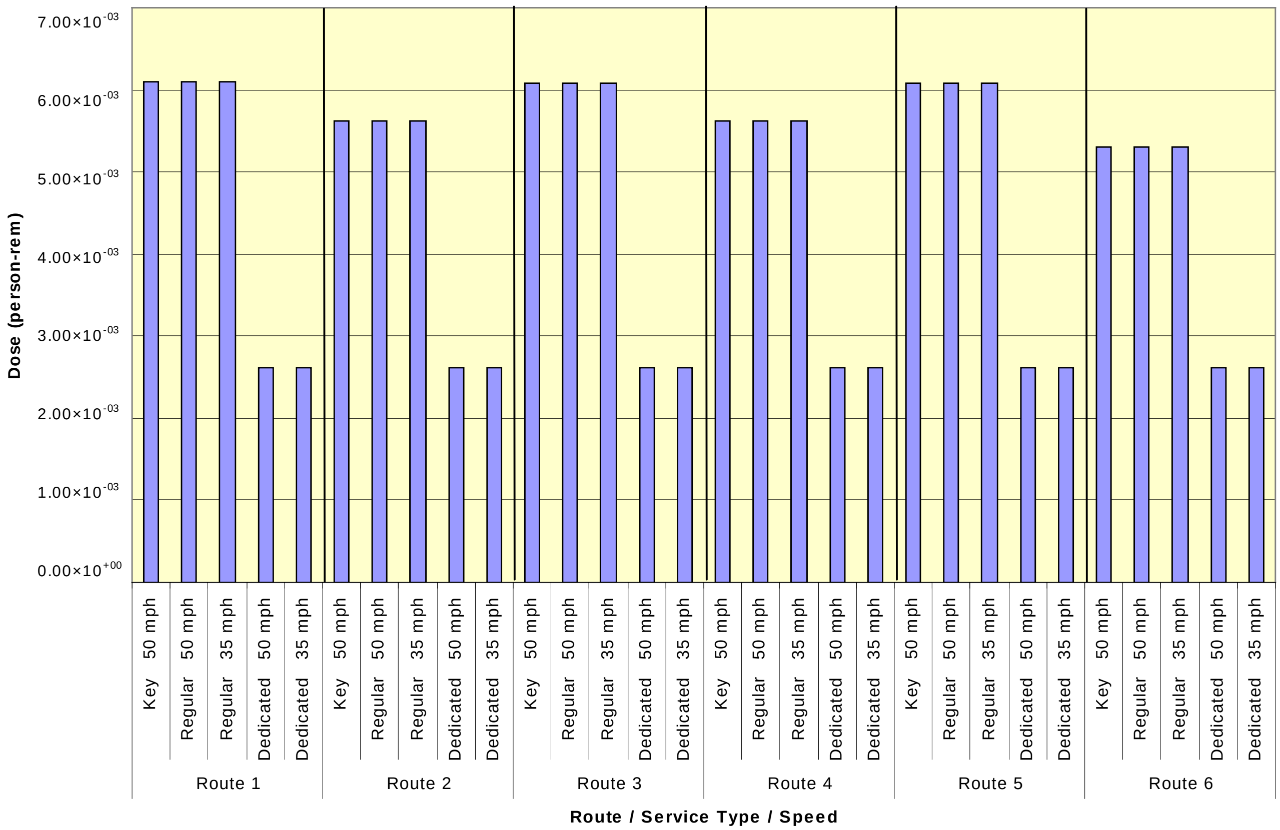
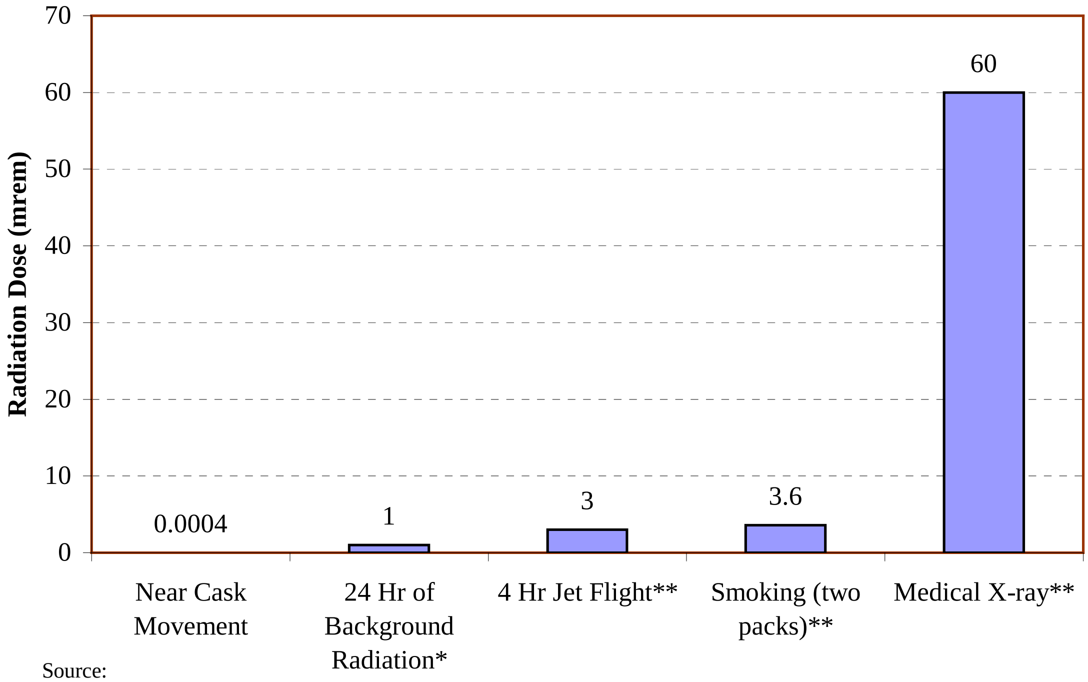


Figure 16. General Rail Yard Worker (Non-Classification) Dose

As reported earlier, the maximum individual dose for a single SNF cask shipment is 4.32×10^{-04} mrem (4.32×10^{-07} rem). This value is compared to exposures from other sources in Figure 17.



Source:
* www.ocrwm.doe.gov
** National Council on Radiation Protection (NCRP)

Figure 17. Comparison of Incident-Free Exposure Rate Versus Other Common Exposures

2.2.4 Relationship Between Incident-Free Transportation Dosage and the Resulting Health Impacts (LCFs)

According to NCRP [NCRP, 1993], the average annual natural background exposure in the United States is 360 mrem (0.36 rem) per year per person.

The radiological impacts are first expressed as the total calculated exposure for the effected population. The total calculated exposure is then used to estimate the hypothetical health effects, expressed in terms of estimated LCFs. The dose-to-risk conversion factors used in this analysis to relate radiation exposures to LCFs are based on the recommendations of NCRP [NCRP, 1993]. These conversion factors are consistent with those used by NRC [56 CFR 233.63 (CFR 1991a)]. The factor used to convert a radiation dose to its effect is 0.0004 LCFs per person-rem for workers and 0.0005 latent cancer fatalities per person-rem for individuals among the general population. The latter factor is slightly higher because there are individuals in the general public, such as the children and elderly (less than 18 and greater than 65 years of age), who may be more sensitive to radiation than workers.

The health effects are determined by multiplying the population dose (person-rem) by the appropriate conversion factor. Although conversion factors exist which relate population dose cancer incidence and genetic effects, this assessment considered only cancer fatalities.

The numbers of fatalities calculated were for single movements with a single cask per movement. For the general population, impacts of multiple cask movements can be estimated by multiplying the single cask dose times the number of casks in the movement.

The number of individuals exposed, the duration of their exposure and the resulting LCF was estimated for each service type. The exposure level differs for each service type since many variables, such as train speed and stop time, vary between the two (see Table 19 and Figure 18).

Table 19. Incident-Free Transportation LCFs

Route	Service/Speed	Total Dose (person-rem)			LCFs		
		Workers	Public	Total	Worker	Public	Total
Route 1	Key 50 mph	0.1009	0.0307	0.1316	4.04×10^{-05}	1.54×10^{-05}	**5.57×10^{-05}**
	Regular 50 mph	0.1009	0.0307	0.1316	4.04×10^{-05}	1.54×10^{-05}	**5.57×10^{-05}**
	Regular 35 mph	0.1043	0.0335	0.1378	4.17×10^{-05}	1.68×10^{-05}	**5.85×10^{-05}**
	Dedicated 50 mph	0.0496	0.0224	0.0720	1.98×10^{-05}	1.12×10^{-05}	**3.10×10^{-05}**
	Dedicated 35 mph	0.0533	0.0252	0.0784	2.13×10^{-05}	1.26×10^{-05}	**3.39×10^{-05}**
Route 2	Key 50 mph	0.1596	0.0354	0.1949	6.38×10^{-05}	1.77×10^{-05}	**8.15×10^{-05}**
	Regular 50 mph	0.1596	0.0354	0.1949	6.38×10^{-05}	1.77×10^{-05}	**8.15×10^{-05}**
	Regular 35 mph	0.1680	0.0401	0.2081	6.72×10^{-05}	2.01×10^{-05}	**8.72×10^{-05}**
	Dedicated 50 mph	0.0879	0.0302	0.1181	3.52×10^{-05}	1.51×10^{-05}	**5.03×10^{-05}**
	Dedicated 35 mph	0.0965	0.0350	0.1315	3.86×10^{-05}	1.75×10^{-05}	**5.61×10^{-05}**
Route 3	Key 50 mph	0.1276	0.0252	0.1528	5.10×10^{-05}	1.26×10^{-05}	**6.36×10^{-05}**
	Regular 50 mph	0.1276	0.0252	0.1528	5.10×10^{-05}	1.26×10^{-05}	**6.36×10^{-05}**
	Regular 35 mph	0.1330	0.0281	0.1611	5.32×10^{-05}	1.41×10^{-05}	**6.73×10^{-05}**
	Dedicated 50 mph	0.0650	0.0187	0.0838	2.60×10^{-05}	9.36×10^{-06}	**3.54×10^{-05}**
	Dedicated 35 mph	0.0706	0.0217	0.0922	2.82×10^{-05}	1.08×10^{-05}	**3.91×10^{-05}**
Route 4	Key 50 mph	0.1425	0.0259	0.1684	5.70×10^{-05}	1.30×10^{-05}	**7.00×10^{-05}**
	Regular 50 mph	0.1425	0.0259	0.1684	5.70×10^{-05}	1.30×10^{-05}	**7.00×10^{-05}**
	Regular 35 mph	0.1494	0.0290	0.1784	5.98×10^{-05}	1.45×10^{-05}	**7.43×10^{-05}**
	Dedicated 50 mph	0.0770	0.0211	0.0980	3.08×10^{-05}	1.05×10^{-05}	**4.13×10^{-05}**
	Dedicated 35 mph	0.0840	0.0242	0.1083	3.36×10^{-05}	1.21×10^{-05}	**4.57×10^{-05}**
Route 5	Key 50 mph	0.1665	0.0430	0.2094	6.66×10^{-05}	2.15×10^{-05}	**8.81×10^{-05}**
	Regular 50 mph	0.1665	0.0430	0.2094	6.66×10^{-05}	2.15×10^{-05}	**8.81×10^{-05}**
	Regular 35 mph	0.1755	0.0495	0.2250	7.02×10^{-05}	2.48×10^{-05}	**9.49×10^{-05}**
	Dedicated 50 mph	0.0894	0.0364	0.1258	3.58×10^{-05}	1.82×10^{-05}	**5.40×10^{-05}**
	Dedicated 35 mph	0.0987	0.0429	0.1416	3.95×10^{-05}	2.15×10^{-05}	**6.09×10^{-05}**
Route 6	Key 50 mph	0.0988	0.0235	0.1223	3.95×10^{-05}	1.17×10^{-05}	**5.13×10^{-05}**
	Regular 50 mph	0.0988	0.0235	0.1223	3.95×10^{-05}	1.17×10^{-05}	**5.13×10^{-05}**
	Regular 35 mph	0.1021	0.0251	0.1272	4.08×10^{-05}	1.25×10^{-05}	**5.34×10^{-05}**
	Dedicated 50 mph	0.0523	0.0177	0.0700	2.09×10^{-05}	8.85×10^{-06}	**2.98×10^{-05}**
	Dedicated 35 mph	0.0557	0.0193	0.0750	2.23×10^{-05}	9.66×10^{-06}	**3.19×10^{-05}**

Note: LCF rates for worker population: 0.0004; for general population: 0.0005 (source: NCRP 1993).

When applied to an individual, units are lifetime probability of LCFs per rem (or 1,000 mrem) of radiation dose. When applied to a population of individuals, units are excess number of cancers per person-rem of radiation dose.

The difference between the worker risk and the general public risk is attributable to the fact that the general population includes more individuals in sensitive age groups (that is, less than 18 years of age and over 65 years of age).

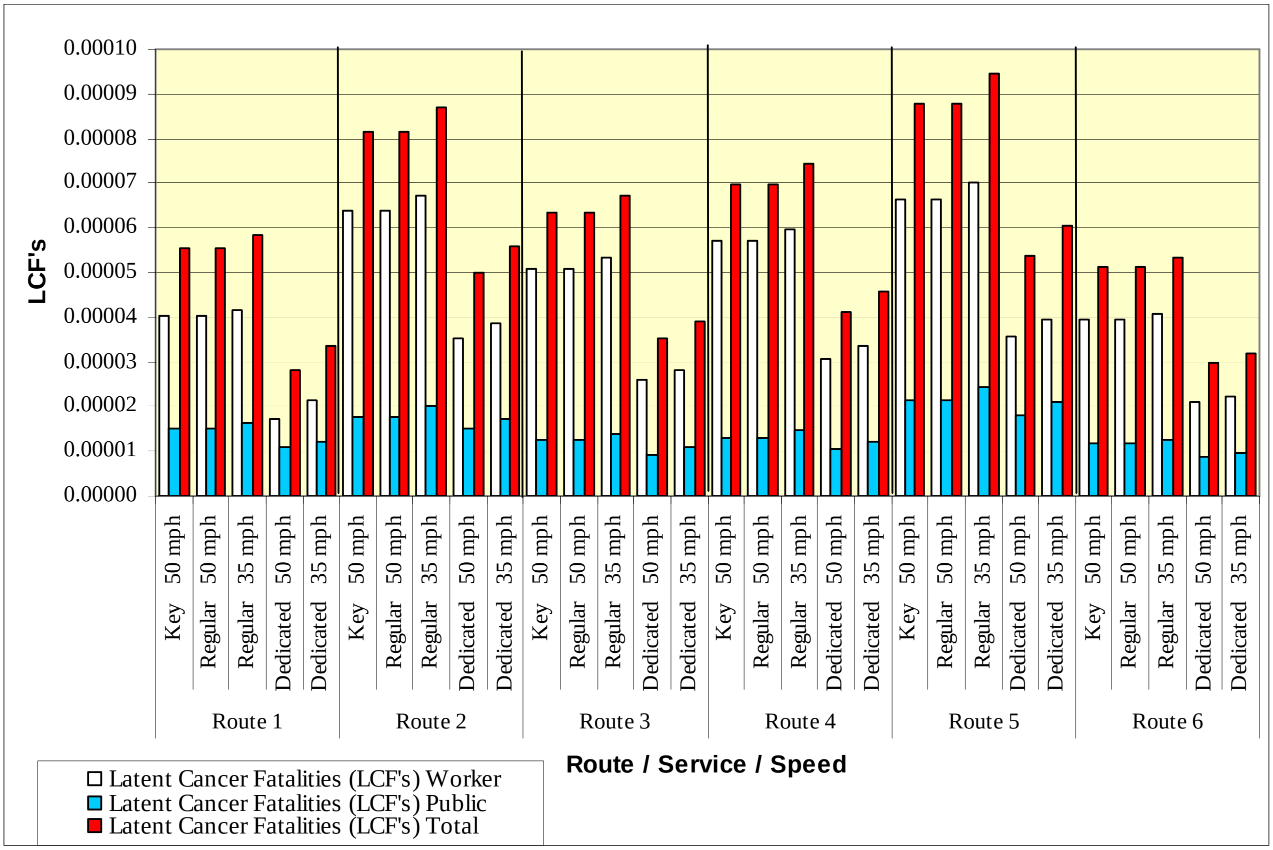


Figure 18. Latent Cancer Fatalities by Route, Service Type, and Speed

The in-transit results presented above relate to the movement of a single train with a single SNF cask. The DOE plans for SNF movements to Yucca Mountain may include movements of multiple casks on a single train. As an example of the impact multiple casks have on radiation dose, Figure compares the total dose to the general public and to rail workers for both a single cask and double cask movement for Route 6. The general public dose for a double-cask movement is two times that of a single-cask movement. The total rail worker dose, however, does not double due primarily to the more distant position of the crew and escorts relative to the second cask. Table 20 shows the resulting LCFs calculated from the doses shown in Figure 19.

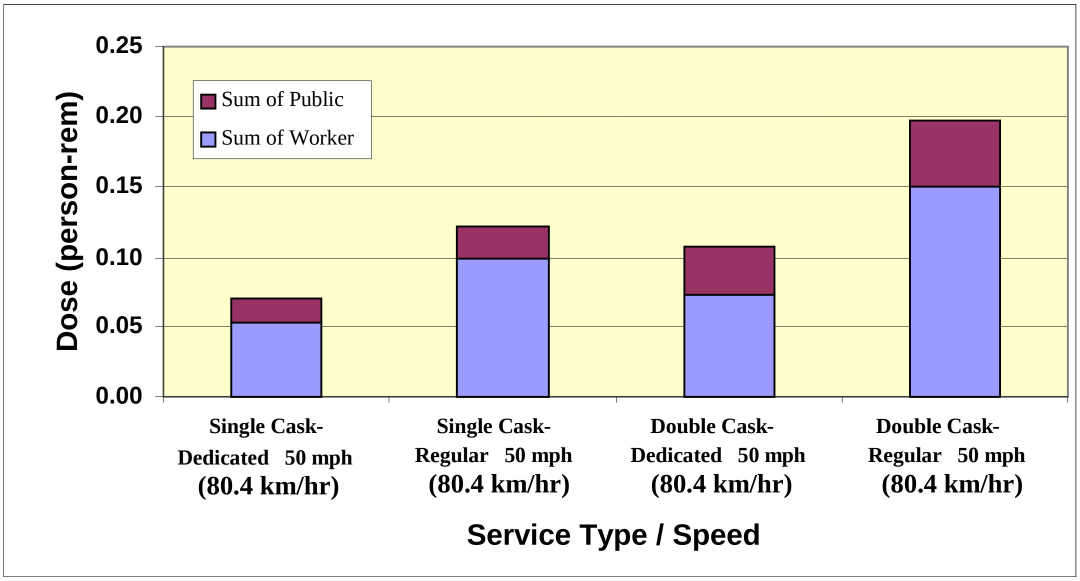


Figure 19. Comparison of Single- and Double-Cask Shipment Dose–Route 6

Table 20. Average LCFs–
Single and Double Cask Movements–Route 6

Route 6 Service Type/Speed		LCFs Worker	LCFs Public	LCFs Total
Single Cask Movement	Dedicated 50 mph (80.4 km/hr)	2.09×10^{-05}	8.85×10^{-06}	2.98×10^{-05}
	Regular/Key 50 mph (80.4 km/hr)	3.95×10^{-05}	1.17×10^{-05}	5.13×10^{-05}
Double Cask Movement	Dedicated 50 mph (80.4 km/hr)	2.92×10^{-05}	1.77×10^{-05}	4.68×10^{-05}
	Regular/Key 50 mph (80.4 km/hr)	6.05×10^{-05}	2.34×10^{-05}	8.40×10^{-05}

Note: LCF rates for worker population: 0.0004; for general population: 0.0005 (source: NCRP 1993).

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3. Accident Risk Analysis

In the previous chapter, the difference in population exposure to radiation due to transportation of SNF or HLRW by dedicated, key, or regular train service was calculated. It was assumed, in that chapter, that no accidents occurred during shipment. This chapter examines the possibility of accident-related exposure by describing the likelihood of accidents involving trains carrying SNF or HLRW and the typical magnitude of radiological consequences for those accidents. The baseline accident probability is calculated for unrestricted regular train service and adjusted to reflect the special constraints of key and dedicated train service.

In the previous chapter, complete characterizations of radiological exposure for populations along six typical rail shipping routes were calculated. A calculation of aggregate radiological exposure under incident-free conditions was necessary to make a comparison between dedicated, key, and regular train service in that case, since no specific event, such as an accident, was involved in the shipment.

In this chapter, aggregate accident-related radiation exposures are not calculated. Instead, aggregate accident probabilities (not specific to routes) are calculated, and the typical radiological consequences of those accidents are characterized. This is because this chapter addresses the difference in accident involvement and severity for the three types of service independent of the route along which the transportation will take place.

For the purposes of this report, accidents have been classified into four categories with respect to severity and potential for content release:

- *Category I* Delay event–accident well within the HAC modeled by the cask packaging test criteria of 10 CFR Part 71; dose rate assumed equivalent to the non-exclusive use transport rate of 10 mrem/hr at 3.3 feet (1 m) from the cask surface. Accidents in Category I could result in an increased duration of exposure to certain individuals (such as crew and nearby population) due to the extended time required to clear the wreck scene and resume transport.
- *Category II* Serious accident–an accident close to the HAC, which could result in a hundredfold increase in radiation levels, but no release of radioactive material occurs. The surface dose rate is assumed equal to 1 rem/hr (1,000 mrem/hr) at 3.3 feet (1 m) from the cask surface.
- *Category III* Major accident–an accident that exceeds the HAC. A greater loss of shielding occurs, but no release of radioactive material occurs. The surface dose rate is assumed equal to 4.3 rem/hr (4,300 mrem/hr) at 3.3 feet (1 m) from the cask surface. Accidents in Category III could expose populations to higher doses of radiation for extended time periods.
- *Category IV* Severe accident–an accident well in excess of the HAC. A significant loss of shielding with the release of some radioactive material occurs.

The consequences of any of these four types of accidents are determined by two factors: the environment in which the accident occurred, including bystander and general population, and the potential for a second event, such as a fire, puncture, or fall following the impact that constituted the initial accident.

The time required to respond to the accident, implying the time spent onsite by emergency responders and crew, results in longer duration and possibly higher intensity exposure.

The radiological consequences of Category I, II, and III accidents are examined here. Category IV accidents are not described in detail in this report because the consequences of these accidents would not vary by type of service. The probability of involvement in such an event is the only variable.

The potential population radiation exposure due to accidents involving the cask are characterized for cases where consequences vary with the type of train service. Differences in the position of the crew with respect to the cask, the duration of the response to the accident (such as time needed to re-rail a derailed car), and the accident forces that might impact the cask have effects on the total radiation doses that people will experience in accidents. The resulting emission rates for an accident of a given severity are the same for either service. The duration of the incident and the probability of occurrence are different.

3.1 Methodology

The methodology employed in comparing the relative safety of dedicated train service to regular and key train service for the transport of SNF and HLRW included the following salient features:

- Historical accident data are employed for structuring the event trees for each type of service.
- Regular trains are assumed to operate at allowable track speed with no restrictions with respect to consist, content, or passing rules. This report assumes that regular trains are 70 cars in length, and the cask consist is positioned in the middle of the train.
- Dedicated trains are assumed to operate with several restrictions, including a no-passing rule, a speed limit of 50 mph (80.4 km/hr), and a limited frequency of visits to classification yards. Dedicated trains are assumed to be six cars in length, including up to two locomotives, two buffer cars, the cask car, and an escort car. Key train restrictions (per AAR recommendations) suspend the no-passing rule but do impose a speed limit of 50 mph (80.4 km/hr) for the train carrying spent fuel. No limits on the frequency of visits to classification yards are imposed.
- Modifications to operational constraints, suggested by AAR in their recommended practice, are compared to the effects of the most restrictive operational constraints.
- Accident consequences are derived from cask emission rate levels, duration of exposure, and number of persons exposed. Typical consequences for accidents of given severity are calculated, and the probabilities for such are given for each type of service.
- The cask used in the analysis is a prototype 125-ton (113-metric ton) steel-lead-steel cask being considered for certification by NRC. The performance of this cask is specified by several specific tests defined by NRC, and the performance is further extrapolated by NRC and SNL analyses.

The potential radiological risks from accidents are based upon several factors: the design of the cask and its ability to withstand various impact forces or fires; the likely level of radiation resulting from these impacts or fires; and the effect of that radiation on crews, escorts, emergency response personnel, and the general population surrounding an accident site. Figure 20 illustrates the components of the analysis, which are described below:

- NRC Cask Certification Criteria: NRC criteria for cask certification establish the required functional strength of the cask. To meet these requirements, specific cask designs have been proposed (and built).
- Kinetic Model of Crush Force Mitigation: Most accidents involve a collision with a piece of railroad equipment; the initial impact velocity is therefore mitigated by the equipment first impacted. The degree to which accident forces are mitigated are described in this model.
- Finite Element Model: Cask designs were used by NRC and SNL to create finite element models. These models describe likely deformations in casks resulting from impacts. The

resulting force-crush characteristics are employed in this analysis to assess the likely results of collisions between the cask and other rail equipment.

- Equivalent Impact Velocities for Different Surface Hardness: SNL defined an array of impact velocities that are the equivalent of NRC's compliance tests and velocities that would cause cask damage for a given surface hardness. The residual speed at which a cask might impact the wayside surface after the initial collision, which is mitigated due to equipment (locomotive) crush, is compared with the SNL impact velocity. These speeds were employed in the construction of the event tree.

- Accident Scenarios and Damage: Given the information above, scenarios that result in incidents that exceed NRC's drop-test compliance speed of 30 mph (48.2 km/hr) were constructed.

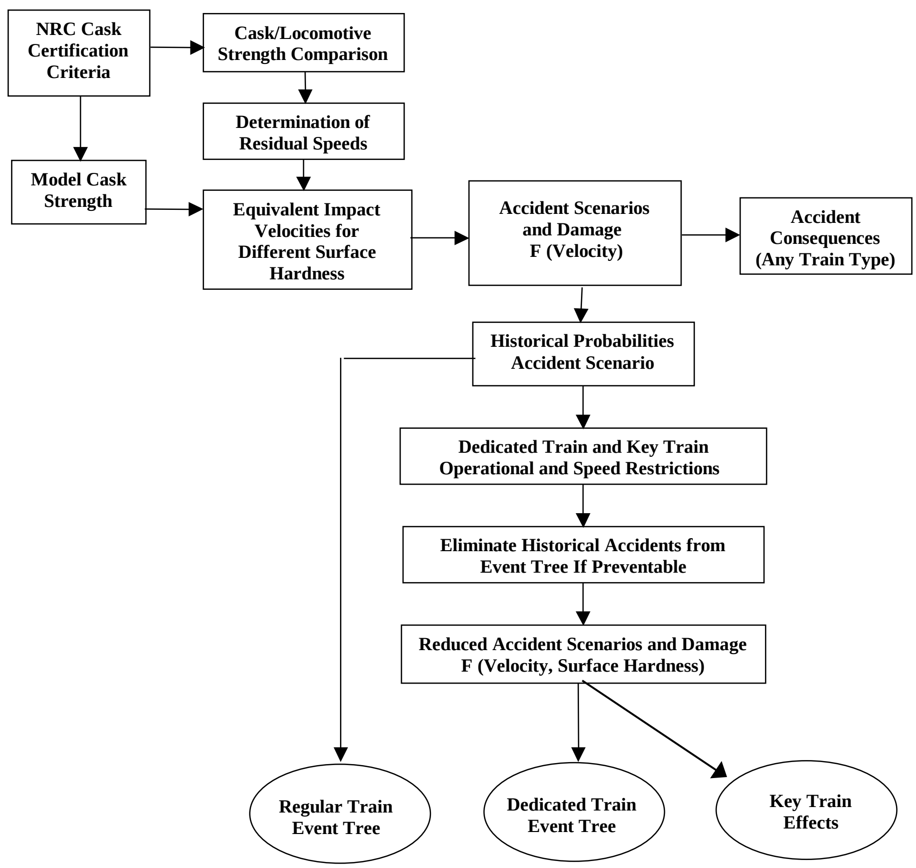


Figure 20. Accident Risk Analysis Methodology Flow Diagram

- Accident Consequences (dedicated, key, and regular trains): Accident consequences, described in terms of cask damage and resulting radiation exposure, were divided into four severity categories. Total radiation emissions were estimated for Category I, II, and III accidents.

- Historical Accident Probabilities Accident Scenarios: Given the conditions required to incur damage (as described in Accident Consequences), historical accident data were sorted into bins based upon the category of the accident severity that were likely to result.

- Regular Train Event Tree: A regular train event tree was constructed for trains operating without operational restrictions. This event tree provides a baseline probability that a regular train would be involved in an accident at or above a velocity required to damage the cask.

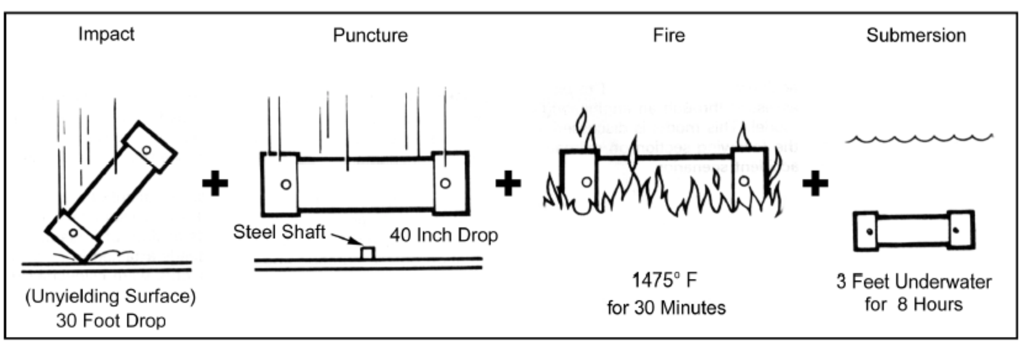
- Dedicated Train Operational and Speed Restrictions: Analyses of the effect on the historical accident probability of train accidents defined on the regular train event tree were conducted to estimate how operational and speed restrictions for dedicated trains would have affected those probabilities.
- Modify Baseline Event Tree to Define Dedicated Train Event Tree: Some accidents were determined to have been preventable (such as raking collisions) if operational restrictions had been imposed. These were therefore removed from the regular train event space for purposes of defining the dedicated train event tree. Some accidents were not thought to have been completely preventable, but accident severity would have been reduced if speed had been restricted. Those accidents could not be removed from the event tree (thereby reducing probability). The probability of an accident in the higher speed range was instead reduced, and the lower speed range probabilities increased.
- Evaluation of key train movements (as recommended by AAR) were conducted to compare safety effects with dedicated and regular trains.

3.2 Accident Severity Factors

3.2.1 NRC Cask Certification Criteria

Accident scenarios were selected for investigation based primarily on the design specifications and compliance tests specified by the NRC. NRC identifies four tests: a drop test, a puncture test, an immersion test, and a fire test. Each of these tests results in a minimum design criterion for cask performance. Figure 21 illustrates the four cask performance tests required by NRC regulations. NRC is responsible for describing the robustness of the cask through design standards and physical testing. These design criteria and results of physical tests and simulations have been used to determine the level of resilience of the cask to various events.

Survival, according to NRC regulations, as defined in 10 CFR Part 71, requires that after the test the cask (1) not release its contents and (2) the emission rate at 3.3 ft (1 m) from the cask is no more than 1,000 mrem/hr [NRC, 1980].



Source: "An Updated View of Spent Fuel Transportation Risk" a Summary Paper for Public Meetings" Office of Nuclear Material Safety and Safeguards, NRC.

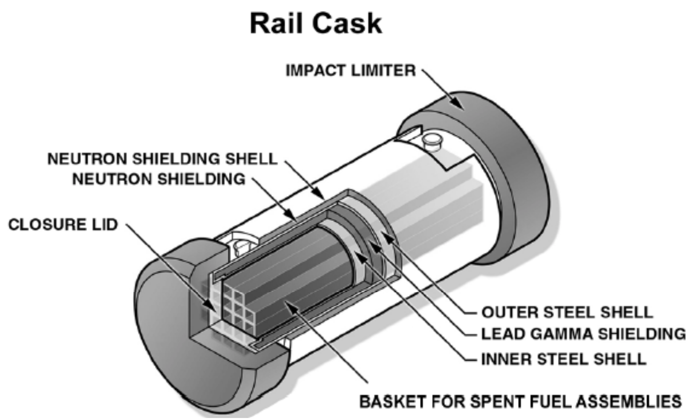
Figure 21. Cask Design Tests

The ability of a cask design to withstand the structural and thermal requirements of these performance tests has been demonstrated by engineering analyses, scale-model, or (in some cases) full-scale testing. Manufacturers and NRC are responsible for verifying that the proposed designs will satisfy the performance test criteria. A hypothetical 125-ton (113-metric ton) steel-lead-steel cask being considered for certification by NRC is assumed for purposes of this study. A description of the design of the cask appears in Chapter 1. Sections 3.2.2 and 3.2.3 describe the structured and thermal characteristics, respectively of the assumed cask in response to various collision scenarios.

3.2.2 Cask Structural Characteristics in Collision Scenarios

The cask used in the analysis is a hypothetical 125-ton (113-metric ton) steel-lead-steel cask being considered for certification by NRC. The performance of this cask is specified by several specific tests defined by NRC, and the performance is further extrapolated by NRC and SNL analyses. SNL defined a generic steel-lead-steel rail cask design after conducting a survey of existing and proposed SNF rail transport cask designs [NRC, 2000].

The actual weight of the generic cask is 225,000 lbs (102,058 kg), and it is constructed using stainless steel for the inner and outer shell linings and lead as the gamma shielding layer. There are 24 closure bolts, each 1.75 inches (4.5 cm) in diameter. The wall thickness variations are a 1.0-inch (2.54-cm) inner shell lining, 4.5 inches (11.4 cm) of lead, and a 2.0-inch (5.08-cm) outer shell lining. The overall outside diameter of the cask is 80 inches (203 cm), and the cavity diameter is 65 inches (165 cm). The cask length is 200 inches (5.08 m). This particular cask design uses an elastomeric seal material. Figure 22 shows a schematic of the cask design envisioned.



Source: NUREG/CR-6672, Vols. 1,2, SAND2000-0234, Figure 4.3 on page 4-4 of Volume 1

Figure 22. Conceptual Design of a Generic Steel-Lead-Steel Rail Cask

SNL analyzed a generic rail transport cask without the impact limiters in NUREG/CR-6672, and the results from a set of those analyses are used in this report. The results used for this report are for various impact orientations into a rigid surface at 30 mph (48.2 km/hr), equivalent to a 30-foot (9.1 m) drop. SNL noted that the impact limiters are typically designed to absorb the full energy associated with a regulatory drop height and hence an equivalent speed for a SNF cask, including the impact limiter of 42 mph (67.2 km/hr). To cover the full range of possible impact orientations, the following procedure was used. For impact angles between 5 degrees and vertical the end-on analysis results are used; for impact angles between 5 degrees and 70 degrees the center of gravity (CG) over the corner results are used; and for angles between 70 degrees from vertical to horizontal the side-on impact results are used. The key results obtained from the large deformation non-linear finite element analyses are the modes of deformation and the force crush characteristics. Figure 23 shows the resulting force crush characteristics, which SNL developed in support of NUREG/CR-6672. These graphical results, however, were not presented in NUREG/CR-6672; instead they were obtained through a private correspondence with SNL.

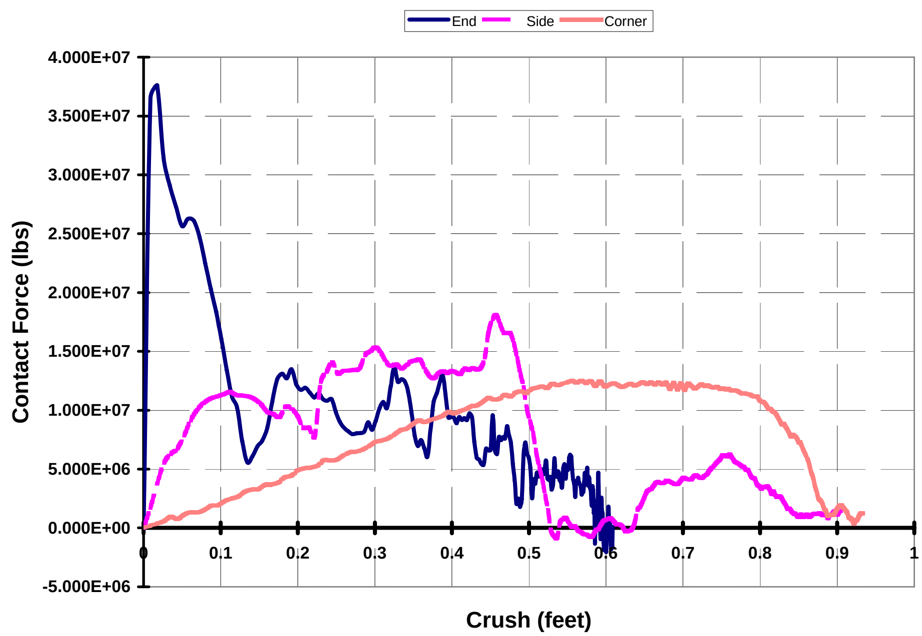


Figure 23. Force Crush Characteristic of Generic Steel-Lead-Steel Rail Transport Cask for Three Impact Orientations at 30 mph (48.2 km/hr) into a Rigid Surface

For the end loading condition into a rigid surface, the peak load experienced by the cask is 38 million lbs (170 MN) at 0.24 in (0.61 cm) of deformation. After the initial peak load, the force required to continue crushing the cask lowers. Between 0.1 and 0.5 ft (3 and 15.2 cm) of deformation, the average force is approximately 8 million lbs (36 MN). The final deformation experienced is 0.6 ft (18.3 cm) of crush. Although 0.6 ft (18.3 cm) of deformation might seem significant, it represents an aggregate accumulation of small strains over the entire 200-in (5 m) length of the cask. No failure of the cask lining at this level of deformation occurs; the cask might experience some bulging near the point of impact. The total reduction in length of the cask is approximately 3.6 percent. The SNL study indicated no failure of the closure bolts under these conditions; however, the minor damage incurred to the cask could result in a small increase in emissions that is still within the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

The side loading condition into a rigid surface initially exhibits a less stiff response with the initial peak load just over 11 million lbs (50 MN), then a stepped force plateau region between 0.1 and 0.22 ft (3 and 6.7 cm) of crush at approximately 11 million lbs (50 MN), and between 0.22 and 0.5 ft (6.7 and 15.2 cm) of crush at approximately 13.5 million lbs (60 MN). Again no failure of the cask occurs. The cask does experience permanent deformations with a number of plastic ripples forming; the reduction in the cask's height in the sidewise position is approximately 7.5 percent. Similar to the end loading condition, the SNL study indicated no failure of the closure bolts under these conditions; however, the minor damage incurred to the cask could result in a small increase in emissions that is still within the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

The least stiff orientation is that for the corner impact loading condition into a rigid surface. A much lower initial slope exists between the point of contact and the first initial peak load of 12 million lbs (53 MN). The force plateaus at approximately 12 million lbs (53 MN) between approximately 0.55 and 0.8 ft (16.8 and 24.4 cm) of deformation with a final crush distance of 0.9 ft (27.4 cm). The deformation of the cask in this loading condition is greater than that of the longitudinal loading condition because the cask impact area is more localized. Even so, the final reduction in length on one side of the cask is approximately 5.4 percent, which does not cause a breach to form. Again, the SNL study indicated no failure of the closure bolts under these conditions; however, the minor damage incurred to the cask could result in a small increase in emissions that is still within the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

In summary, substantial kinetic energy is associated with SNF casks and the rest of the train consist during transport. If an accident occurs, SNF casks could be subjected to impacts against a variety of objects and in various orientations. For the purpose of this analysis, it is assumed that an SNF cask involved in an accident could be subjected to the following two types of collisions:

1. A primary impact against other freight equipment.
2. A secondary impact against the surrounding infrastructure or environment.

Sections 3.2.2.1 and 3.2.2.2 discuss the analyses conducted to determine any potential damage to the cask, under various operating conditions, for these two collision scenarios, respectively.

3.2.2.1 Primary Collisions with Rail Equipment

Freight locomotives are the stiffest freight or passenger rail equipment that a rail transport SNF cask would typically encounter. In general, freight locomotives are constructed with a heavy platform underframe. A lighter superstructure is mounted to the underframe, along with the engine and other equipment. The underframe is designed to withstand the large buff and draft loads the vehicle is subjected to during regular operation, so it is very stiff. The heaviest six-axle locomotives weigh between 415,000 lbs (1850 kN) and 440,000 lbs (1,960 kN). The force-crush behavior for one of these vehicles is highly dependent on the manner in which it is loaded during a collision [FRA, 1995].

Figure 24 is a schematic of the key structural elements on a typical road locomotive. The coupler is attached to the draft gear support structure. During a head-on collision, these items are loaded before any other key structural elements on the locomotive. Above the coupler and striker plate is the anti-climber. The purpose of this element is to prevent material from climbing above the underframe where it could penetrate the short hood structure.

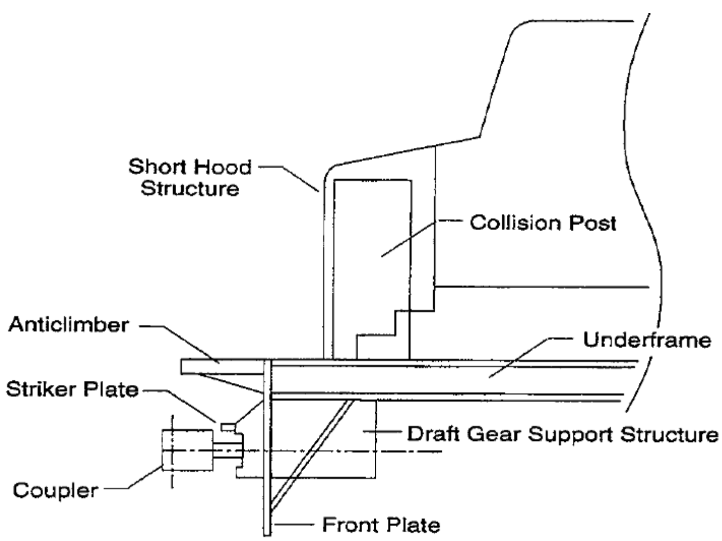


Figure 24. Schematic of Front End of Freight Locomotive

The two key structural elements above the underframe that act in concert with the short hood to resist penetration of foreign objects into the cab area of the locomotive are the collision posts. Once an object has cleared the collision posts and entered into the cab area, a relatively low uniform load level is required to clear the deck of the locomotive.

A number of calculations have been conducted on the crush characteristic of each specific member shown in Figure 24, and composite force crush curves were developed. The force crush curve is dependent on the load path during crush. Since every event is slightly different, a pair of representative crush paths were chosen and used to develop a set of composite force crush curves. The first curve presented in Figure 25, Loading A, is associated with the central longitudinal loading of the underframe at the level of the neutral axis. The second curve developed, Loading B, accounts for crush of the coupler and draft gear support structure, followed by hinge formation in the underframe with subsequent failure of the short hood and collision posts with full penetration above the deck. Both curves exhibit an initial high peak load followed by softened behavior. The results presented show crush to be between 17 to 80 in (43 to 200 cm) of longitudinal deformation. To date, no analyses or tests have been conducted that provide information on the crush strength for larger crush distances. For the purposes of this report, therefore, the force level experienced in the plateau region is extrapolated out at the same level for very large crush distances. The uncertainty associated with the shape of the curve does not affect the final qualitative comparison of risk because the same curves are applied to both types of consists.

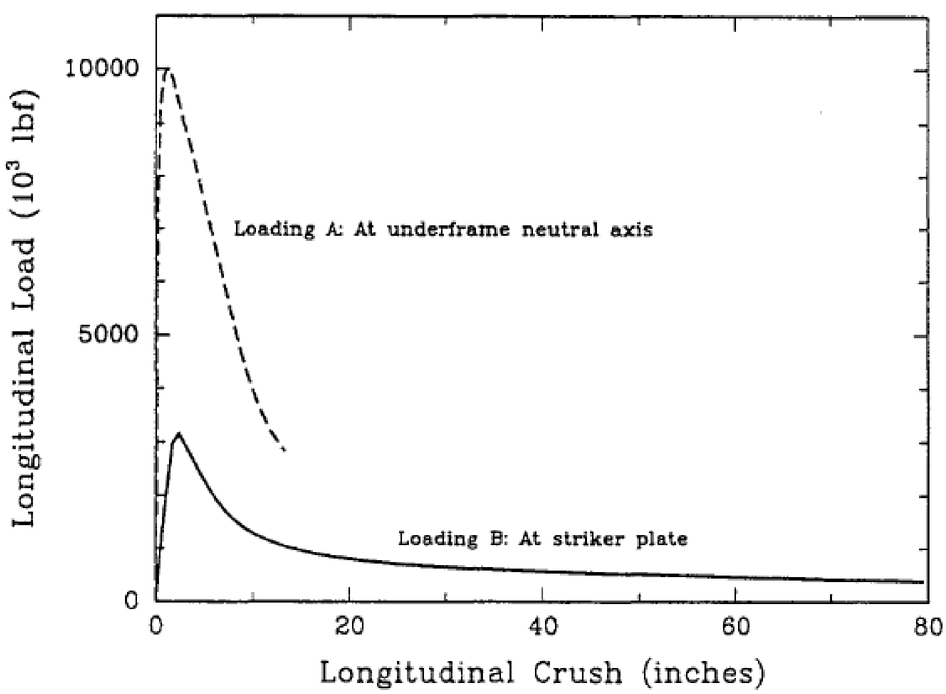


Figure 25. Force Crush Characteristic for Generic Freight Locomotive

Figure 23 and Figure 25 depict the force crush characteristics for the generic rail steel-lead-steel transport cask (analyzed by SNL in NUREG/CR 6672) and a typical locomotive. The crush characteristics for the cask are developed for three loading orientations: end-on, side-wise, and the cask CG over the corner. The locomotive force crush characteristics are for head-on type loading conditions either at the level of the underframe neutral axis or for a climbing contact condition with initial contact occurring at the striker plate. Figure 26 shows a plot of these characteristics.

A one-dimensional collision dynamics model, discussed further in Section 3.2.2.2 and Appendix G, was developed to analyze SNF cask deformations resulting from collisions with a generic freight locomotive for several different cask orientations. The end-on loading condition for the transport cask is significantly stiffer than that of the locomotive in either Loading A or Loading B. For a collision between a rail SNF cask and a locomotive in a head-on collision, the locomotive will deform and be unable to generate sufficiently high forces to cause significant deformation to the rail SNF cask.

The side-wise and corner loading conditions for the cask, compared to the loading of the locomotive at the underframe level, suggests that some shared crush would exist between the cask and the locomotive. For the side-wise loading case, 0.1 ft (3 cm) of cask deformation is predicted; for the corner loading condition, 0.45 ft (13.7 cm) of cask deformation is predicted. For the climb loading condition of the locomotive, cask deformations on the order of 0.1 ft (3 cm) are predicted only for the cask corner over the CG loading case. Based on the results of SNL tests and analyses, none of these loading conditions would breach the cask or cause a seal failure. There is the possibility of lead slump, and hence, a loss of shielding, which would result in a small increase in emissions still within the regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

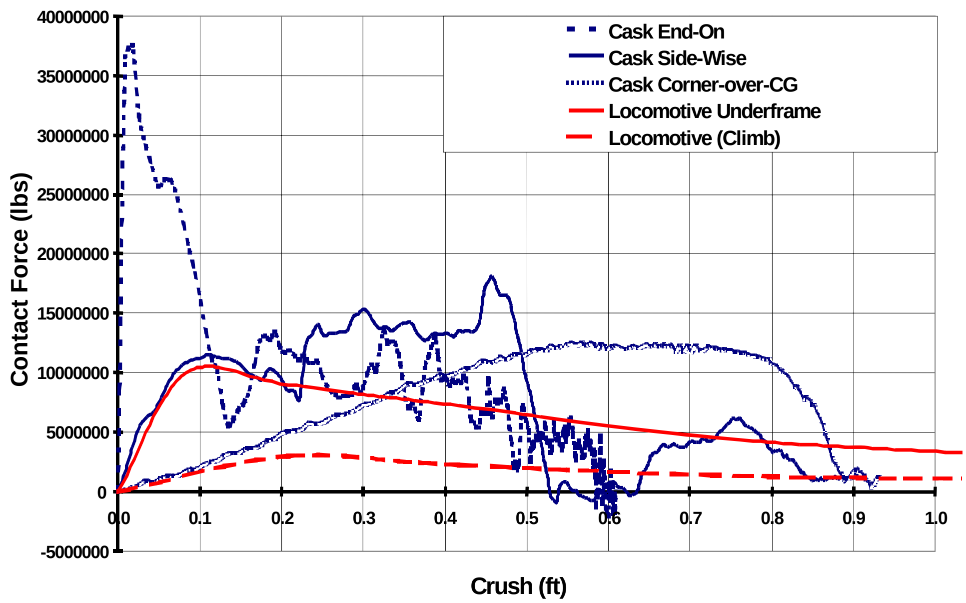


Figure 26. Comparison of Force Crush Characteristics: Generic Rail SNF Transport Cask and Typical Locomotive

3.2.2.2 Secondary Collisions with Surrounding Infrastructure or Environment

This section discusses a procedure about how to obtain an estimate of the residual speed that an SNF cask is traveling at after a primary collision with a freight locomotive. The residual speed is the metric used to compare a collision scenario result to the regulatory drop height requirement to determine whether the potential damage to the cask exceeds regulatory limits. Four scenarios are discussed: head-on and rear-end collisions between a rail SNF cask and a locomotive, a side impact collision at a rail-rail crossing, and a raking collision where the rail SNF cask is overhanging a second track and fouls the oncoming locomotive's rail right-of-way (ROW).

In the event of a collision between two trains or a train and an object fouling the ROW, kinetic energy is consumed in a variety of ways. A significant energy absorption mechanism is plastic deformations of the striking vehicle and whatever is struck. Momentum is conserved, and some energy is absorbed in the speeding up/slowing down of the struck object. Additional energy is absorbed by the compression of draft gears along the length of the consist. If cars derail, additional kinetic energy is consumed as the cars tear up the track and slide along ballasted surfaces. The amount of kinetic energy that is absorbed is extremely dependent on the specifics of the event.

The approach taken is to account for some energy absorption in the event of a collision between a locomotive and a rail SNF cask through the application of a simplified one-dimensional collision dynamics model. A collision dynamics model is used to calculate the transfer of momentum of two objects striking each other at prescribed speeds, as well as the energy consumed due to plastic deformations. The requisite information to exercise the model is a description of the force displacement behavior of the cask and of the object that the cask strikes.

The key assumptions of this approach include the following:

- The cask is bare (the force limiters have been removed, consistent with analyses conducted by SNL in NUREG/CR 6672).
- The cask has been released from the transport car (hence no additional energy absorption due to the rail transport car crush or breaking of the tie-downs) and is traveling at the speed of the SNF consist at the time of the accident.
- The rail SNF cask strikes a generic freight locomotive head-on, is struck side-wise by the freight locomotive, or is involved in a raking collision.
- Two load paths are investigated for the locomotive to ascertain sensitivity of residual speeds or cask damage.
- Depending on the collision scenario, separate force crush responses are used for the rail SNF cask (end-wise, side-wise, and corner over the cask CG).
- Both the cask and the locomotive remain in-line during the complete event (enforces the one-dimensional response).
- The final speed at which the cask is traveling is called the cask residual speed.

This approach, using these assumptions, provides a reasonable manner to estimate the energy absorption and final cask residual speed for the three collision scenarios developed. The scenarios developed are then mapped into the cask response in the accident severity and probabilities section of the report. The different consist types and operating rules will determine the likelihood of the scenario. The behavior of the cask in the scenario analyzed is independent of the type of consist involved in the accident.

The following steps were used to develop the required input for the collision dynamics model:

- Estimate force crush characteristic of a generic rail SNF cask in the appropriate orientation.
- Estimate force crush characteristic of a generic freight locomotive.
- Develop a one-dimensional collision dynamics model.
- Define initial collision scenarios of concern.

The previous sections described the force crush characteristics for both the generic rail steel-lead-steel rail SNF cask and a typical locomotive. A one-dimensional collision dynamics model is used to calculate the exchange of linear momentum and the absorption of energy due to plastic deformations occurring in either the rail SNF cask or the generic freight locomotive. This is a lumped mass modeling approach where the non-linear spring characteristics are the force crush characteristics developed for either the rail SNF cask or the locomotive. Figure 27 shows a schematic of the one-dimensional lumped mass system. The system equations of motion are developed and solved in a MathCAD worksheet using the Runge-Kutta differential equation solver. Using the information obtained in the previous sections along with the model developed, a series of collision conditions are modeled and scenarios of concern are reported (see Appendix G for a more detailed discussion of these analyses).

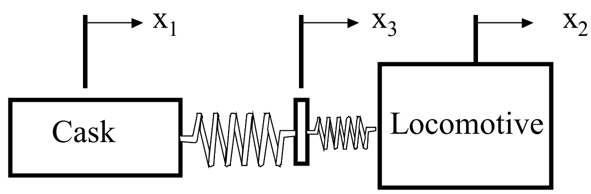


Figure 27. Collision Dynamics Model

Head-On Collisions

The first category of collision scenarios analyzed using a collision dynamics lumped parameter approach was that of a head-on collision. In any real head-on collision, most of the energy absorbed would be in the crushing of the leading locomotive. It is assumed that the rail SNF cask becomes free due to breakage of the tie-down straps or the car derailing. As a worst-case scenario, the cask is free to strike a locomotive. In this scenario, the rail SNF cask travels at 50 mph (80.4 km/hr), the original speed of the SNF consist, and then strikes a freight locomotive traveling in the opposite direction (see Figure 28). The analysis investigates this scenario for different locomotive speeds between 30 mph and 70 mph (48.2 and 112.6 km/hr) to bound a range of typical track speeds. Although cask speeds of 50 mph (80.4 km/hr) were investigated in the current analyses, the 30 mph (48.2 km/hr) force deflection diagrams were used. Use of the 30 mph (48.2 km/hr) diagrams was assumed reasonable because they provided a more conservative result (i.e., the 30 mph (48.2 km/hr) diagrams predict failure of the cask at slightly lower impact speeds than the 50 mph (80.4 km/hr) diagrams).

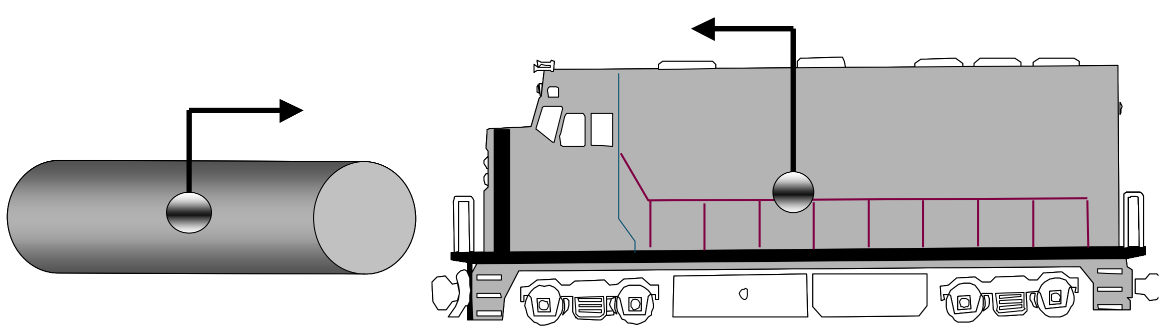


Figure 28. Schematic of Head-On Collision Scenario Between SNF Cask and Freight Locomotive

The force crush characteristics used for the cask are those determined by SNL for an end-on impact into a rigid barrier at 30 mph (48.2 km/hr). Both force crush characteristics presented earlier for the locomotive were used to test the sensitivity of the final residual speed to changes in the locomotive force crush characteristics. Table 21 presents the scenarios investigated. The first two columns in the table show the initial speeds at which the cask and locomotives are traveling. The second two columns are the calculated residual speed that the cask is moving at after the primary collision with the locomotive. These results show that the cask shears completely through the locomotive and continues to travel at the residual speed indicated for all scenarios except the first one (locomotive speed 30 mph (48.2 km/hr), Loading A), where it becomes embedded in the locomotive. This residual speed is the speed that the rail SNF cask can strike the surrounding rail environment, as is compared against the regulatory impact speed, 30 mph (48.2 km/hr). These results indicate that the predicted energy absorbed during the primary collision will slow the cask sufficiently so that a secondary collision could not result in damage to the cask that results in emissions that exceeds the regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

Table 21. Residual Speeds for Various Simplified Head-On Collision Scenarios

Initial Cask Speed mph (km/hr)	Initial Locomotive Speed (in opposite direction) mph (km/hr)	Loading A: Force Crush Cask Residual Speed mph (km/hr)	Loading B: Force Crush Cask Residual Speed mph (km/hr)
50 (80.4)	30 (48.2)	0 (0)	3 (4.8)
50 (80.4)	40 (64.4)	6 (9.7)	12 (19.3)
50 (80.4)	50 (80.4)	12 (19.3)	20 (32.3)
50 (80.4)	60 (96.4)	19 (30.6)	25 (40.2)
50 (80.4)	70 (122.6)	23 (37)	28 (45.1)

If the amount of energy actually consumed during the collision is less than predicted because the cask is ejected from the consist, the residual speed could be greater than that quoted in the table, but it would still be less than the initial cask speed.

Rear-End Collisions

The same analysis procedure used for head-on collisions can be used for rear-end collisions, but, in general, the rear-end collision scenario is more benign when the two consists are moving in the same direction because the amount of energy to be dissipated is related to the closing speed at impact. For the case where the cask is not moving and is struck by the locomotive from behind, however, the loading is similar to that of the rail-rail crossing collision described in the next section. As will be discussed below, scenarios exist where the residual speed could lead to possible secondary impacts that are in excess of 30 mph (48.2 km/hr) with resulting damage to the cask that potentially exceeds regulatory limits. These scenarios include rear impacts by the locomotive with the cask at speeds in excess of 50 mph (80.4 km/hr). For these cases, the cask becomes embedded in the locomotive, and they travel down the track at the same residual speed.

Rail-Rail Crossing Collisions

The second collision scenario occurs at rail-rail 90^{o} crossings where the locomotive is traveling at some speed and impacts the side of the rail SNF cask sitting at the crossing (see Figure 29). The rail transport cask's initial speed is zero, and the locomotive is traveling at a variety of track speeds. In this case, the cask is accelerated from rest as the locomotive is crushed and slows down. The force crush curve used to describe the rail transport cask is the side-wise impact into a rigid surface at 30 mph (48.2 km/hr), developed by SNL in NUREG/CR 6672. Both force crush characteristics presented earlier for the locomotive were used to test the sensitivity of the final residual speed to changes in the locomotive force crush characteristics. Table 22 presents the scenarios investigated.

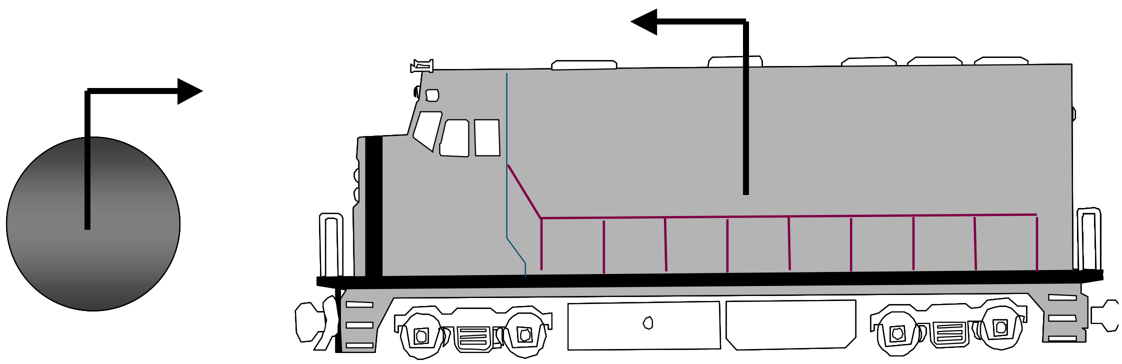


Figure 29. Schematic of the Rail-Rail Crossing Collision Scenario

The first two columns in the table show the initial speeds at which the cask and locomotives are traveling. The second two columns are the calculated residual speed that the cask is moving at after the primary collision with the locomotive. This residual speed is the speed that the rail SNF cask can strike the surrounding rail environment, which is compared against the regulatory impact speed, 30 mph (48.2 km/hr). The slight differences in the residual speeds predicted for the two different force crush curves result from the differences in total energy consumed during crush of the locomotive as momentum is exchanged. A number of scenarios are presented in the shaded cells of Table 22, which are of concern in terms of possible secondary impacts of the cask with the surrounding rail environment at speeds greater than 30 mph (48.2 km/hr) with resulting damage that potentially exceeds regulatory emissions limits of 1,000 mrem/hr at 3.3 ft (1 m). For all scenarios analyzed, the cask becomes embedded in the locomotive. Only one locomotive is included in this analysis. If a train backed up the impacting locomotive, the residual speeds for the rail SNF cask would be even higher.

Table 22. Residual Speeds for Various Simplified Rail-Rail Crossing Collision Scenarios

Initial Cask Speed mph (km/hr)	Initial Locomotive Speed mph (km/hr)	Loading A: Force Crush Cask Residual Speed mph (km/hr)	Loading B: Force Crush Cask Residual Speed mph (km/hr)
0 (0)	40 (64.4)	26 (41.8)	26 (41.8)
0 (0)	50 (80.4)	33 (53.1)	32 (51.5)
0 (0)	60 (96.4)	39 (62.8)	38 (61.2)
0 (0)	70 (122.6)	44 (70.8)	46 (74)

Raking/Corner Impacts

The final impact scenario studied was that of an overhanging rail SNF cask traveling at 50 mph (80.4 km/hr) that was struck on the corner by a passing locomotive going in the opposite direction at a variety of speeds (see Figure 30). The force crush characteristic used for the rail transport cask is that associated with a corner impact into a rigid surface at 30 mph (48.2 km/hr) generated by SNL and presented in Figure 26. Both force crush characteristics presented earlier for the locomotive were used to test the sensitivity of the final residual speed to changes in locomotive force crush characteristics.

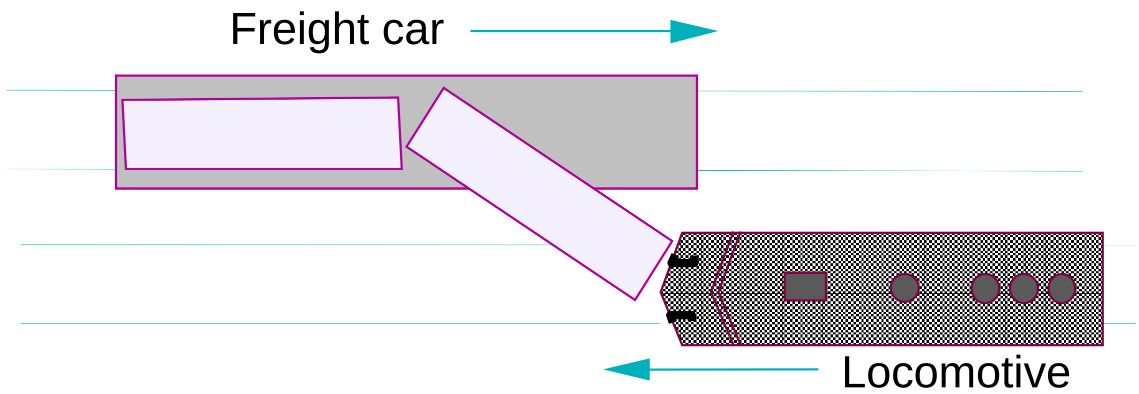


Figure 30. Schematic of Raking Collision Scenario

Table 23 presents the scenarios investigated. The first two columns in the table show the initial speeds at which the cask and locomotives are traveling. The second two columns are the calculated residual speed that the cask is moving at after the primary collision with the locomotive. This is the speed at which it can now strike the surrounding rail environment, which is compared against the regulatory impact speed, 30 mph (48.2 km/hr). If the amount of energy absorbed in this simple scenario occurs for an actual accident, it will not be more severe than a Category II. For raking or cornering collisions where the amount of energy consumed in plastic deformations is less than that calculated, the final cask residual speeds will be higher than those presented.

Table 23. Residual Speeds for Various Simplified Raking/Corner Collision Scenarios

Initial Cask Speed mph (km/hr)	Initial Locomotive Speed mph (km/hr)	Loading A: Force Crush Cask Residual Speed mph (km/hr)	Loading B: Force Crush Cask Residual Speed mph (km/hr)
50 (80.4)	30 (48.2)	0 (0)	1 (1.6)
50 (80.4)	40 (64.4)	6 (9.7)	12 (19.3)
50 (80.4)	50 (80.4)	8 (12.9)	20 (32.3)
50 (80.4)	60 (96.4)	16 (25.7)	25 (40.2)
50 (80.4)	70 (122.6)	20 (32.3)	28 (45.1)

3.2.2.3 Equivalent Impact Velocities for Different Surface Hardness

Impact velocity and surface hardness are critical determinants of the resulting damage from any accident involving the spent fuel cask. The effect of a 30-ft (9.1 m) drop onto an unyielding surface is not the equivalent of the same drop onto yielding (soft) surfaces. Table 24 provides an example of this type of trade off for the generic steel-lead-steel rail cask analyzed by SNL in NUREG/CR 6672. It also illustrates that the translation from impact velocity and surface hardness to damage is not linear; damage depends upon the orientation of the impact and the type of surface that the cask hits. The equivalent impact velocities shown in Table 24 assume that the impact limiter normally attached to the cask during transport is not on the cask at the time of impact. For the purposes of this study, only the values reported for a 30-mph (48.2-km/hr) impact speed into a rigid surface are used. The 60, 90, and 120 mph (96.4, 144, and 192 km/hr) speeds (shaded columns) are not used as they represent cases that exceed the regulatory compliance limits. When reviewing Table 24, results in the shaded columns for yielding surfaces while based on results in the 30 mph (48.2 km/hr) column, necessitated using a slightly different set of assumptions regarding the properties of the yielding surfaces. [NRC, 2000].

Table 24. Impact Speeds onto Real Yielding Surfaces–Type B Steel-Lead-Steel Spent Fuel Rail Cask

Impact Surface	Impact Orientation	Impact Speed (mph)			
		30	**60**	**90**	**120**
Hard Rock	End	30	60	90	120
	Corner	30	60	90	120
	Side	30	60	90	120
Soft Rock/Hard Soil/Concrete Slab (abutment)	End	38	319	391	509
	Corner	35	640	990	>990
	Side	32	207	289	>289
Clay/Silt	End	84	>386	>480	>635
	Corner	58	>133	>208	>223
	Side	32	>180	>256	>262
Railbed/Roadbed	End	38	386	480	635
	Corner	35	133	208	>223
	Side	32	180	256	>262
Water	End	78	∞	∞	∞
	Corner	150	∞	∞	∞
	Side	42	∞	∞	∞

Source: Table 7.23 Impact Speeds (mph) onto Real Yielding Surfaces that are Equivalent to 30-, 60-, 90-, and 120-mph (48.2-, 96.4-, 144-, and 192-km/hr) Impacts onto an Unyielding Surface. Type B Steel-Lead-Steel Spent Fuel Rail Cask (p 7-59), [NRC, 2000].

3.2.2.4 Summary of Cask Structural Characteristics

The analyses in this section led to the identification of potential final impact velocities for several simplified generic collision scenarios using force crush characteristics for a generic steel-lead-steel rail SNF cask and for two different locomotive crush paths. The results indicate that the residual speeds for head-on and raking collisions for the scenarios studied are less than 30 mph (48.2 km/hr) and will not result in accidents more severe than Category II. For the rail-rail crossing scenario, however, possible speed combinations are predicted to allow a secondary impact velocity greater than the regulatory allowed speed of 30 mph (48.2 km/hr), resulting in a Category III accident. Any collision where the locomotive strikes the rail SNF cask from the side at a speed in excess of 50 mph (80.4 km/hr) will result in residual speeds greater than 30 mph (48.2 km/hr) and damage to the cask that potentially results in a Category III accident. In no event is a Category IV accident expected, provided the striking locomotive initial speed is less than 70 mph (112.6 km/hr). This is based upon the results presented in NUREG/CR 6672; results of this study indicate that the highest residual speeds calculated are between 44 and 46 mph (70.8 and 74 km/hr).

Several caveats exist:

- For all the scenarios studied, it is possible that either a greater or lesser amount of energy will actually be consumed during a collision depending on very event-specific variables.

- The actual bounds of possible secondary impact speeds that a cask may experience lie between zero and the initial speed of the cask or locomotive.

Using the force crush characteristics presented, a generic steel-lead-steel rail transport cask is sufficiently stiff such that direct collisions with a locomotive, for the speeds investigated, will not result in Category III accidents. The analyses presented by SNL in NUREG/CR 6672 also show that the bare cask will survive even higher impact speeds into a rigid planar surface without causing a breach or seal failure. Additional energy consumption mechanisms exist if the force limiters remain attached during the collision, as they are designed to absorb the complete energy from a 30-ft drop (9.1-m).

3.2.3 Cask Thermal Characteristics in Collision Scenarios

The 1987 Modal Study [NRC, 1987a],[26] conducted for NRC by Lawrence Livermore National Laboratory, established baseline parameters for estimating risk of cask failure under varying transportation accident scenarios. Response to severe thermal loads was identified as an important component of such an estimate. It has been recognized in research [NRC, 2000] and certification standards for hypothetical accident conditions (in Subpart F, 10 CFR Section 71.73) that cask immersion in fires of over 1,475° F (800° C) for times in excess of the NRC compliance test parameters can melt lead shielding, thermally degrade and fail elastomeric seals, and burst-rupture spent fuel rods–resulting in elevated source emission levels, secondary vapor leaks, and dangerous releases of dispersing radioactive materials.

The Modal Study focused on modeling the physical cask response to thermal loads, to evaluate impacts on cask structural integrity in various fires. It did not go so far as to predict associated radioactive levels and releases. In its most recent analysis NUREG CR-6672 [NRC, 2000], SNL established that lead slump (occurring due to impacts or melting of lead used as an interior cask layer) could significantly reduce the shielding provided by the cask and result in elevated surface emission levels. SNL's analytical discussion concluded that at 662° F (350° C) the elastomeric seals of the steel-lead-steel rail cask would begin to fail.[27] SNL calculated that it would take 1.06 hours for this temperature to be reached in an optically dense, fully engulfing fire at 1,475° F (800° C) [NRC, 2000].[28] SNL further assumed that at 1,382° F (750° C) the spent fuel rods could fail by burst rupture. The time required for this event in the same type of fire was calculated to be 2.91 hours [NRC, 2000].

3.3 Accident Severity and Probabilities

3.3.1 Accidents of Interest

Train accident scenarios were analyzed to identify the possible scenarios involving a spent fuel cask that could result in an impact, a fire, or both. These accident scenarios were assigned probabilities based upon whether the accident would happen at impact velocities that could exceed an equivalent compliance test impact velocity for a hard surface. The probability of each of the accident scenarios was estimated for a regular train with no operational restrictions. Once a complete accident event tree was calculated, accidents that would be reduced or eliminated due to speed restrictions, train consist limits, or other operational restrictions (such as a no-passing rule or reduction of yard entries) were also reduced or eliminated from the event tree.

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[26] NRC is currently revisiting part of this study and is presently in Phase 2 of a four-phase study known as the Package Performance Study (PPS).

[27] "7.2.5.2 Thermal Failure of Cask Seals and Spent Fuel Rods. During normal transport under ambient conditions, the peak temperature of spent fuel in a Type B spent fuel cask is about 572° F (300°C) [7-22]. Because the average temperature of free burning hydrocarbon fuel fires is about 1,832° F (1,000° C) [7-23], elastomeric cask seals and spent fuel rods can both fail if the cask that contains them is heated long enough by a hot fire. …Nevertheless, it is here assumed that elastomeric cask seals begin to leak when heated to 662° F (350° C)." When heated to elevated temperatures, spent fuel rods fail by burst rupture. During the experiments of Lorenz, et al. [7-26], sections of spent fuel rods that had been heated to 1,652° F (900° C) failed by burst rupture when rod pressures reached 275 psig."

[28] Ibid., Chapter 6, pp 6-7.

3.3.2 Historical Accident Probabilities

The likelihood of accidents during future spent fuel shipments in the United States can be estimated based upon the past experiences in shipments of many types of goods. Some peculiarities about the shipment of spent fuel, most especially shipments of large casks (the 125-ton (113-metric ton) MPC), may increase additional accident probability.

Accident probabilities were based upon 14 years of accident data from the Railroad Accident/Incident Reporting System (RAIRS) database, from 1988 to 2001 (see Table 25). This extended time period provides an ample basis to assess accident probabilities and account for any short-term fluctuations in accident rates. Normalized accident rates were calculated by dividing total accidents by reported train miles for each year using the data that appear in Table 26.

3.3.3 Accident Speed Evaluations

Each accident type has been examined to identify the potential hazard to the cask in the event of that accident. Casks may be damaged due to impacts with surrounding surfaces (the ground, railbed), or other rail equipment (car-couplers, pieces of rail equipment), or cars themselves, such as in collisions with locomotives. In each scenario, the potential harm to the cask is the crucial element in defining the event tree. Potential impact velocities with the cask and whatever it encounters is, at its maximum, defined in terms of the speed of the train carrying the cask. In some accident scenarios, however, the cask velocity may be reduced by intermediate, but non-damaging, collisions with rail equipment before encountering a potentially damaging final collision. The initial velocity for each of the accident types, defined in Table 27 is used to estimate the final cask impact velocity for that scenario. Estimated damage, given these initial velocities, is defined only in terms of whether the final impact velocity is less than, equal to or greater than NRC's compliance value. Table 27 describes the definitions of these accident types and the method of selecting the initial impact velocity of concern.

Table 25. Reported Train Accidents 1988-2001

RAIRS Accidents 1988-2001	Total Main and Yard		Main Only		Yard Only	
	Accident Count	Probability	Accident Count	Probability	Accident Count	Probability
Derailment	23,219	0.6634	10,672	0.6681	12,547	0.6594
Head-On Collision	246	0.007	149	0.0093	97	0.0051
Rear-End Collision	312	0.0089	237	0.0148	75	0.0039
Side Collision	1,889	0.054	219	0.0137	1,670	0.0878
Raking Collision	510	0.0146	163	0.0102	347	0.0182
Broken Train Collision	84	0.0024	45	0.0028	39	0.002
Highway-Rail Crossing*	2,393	0.0684	2,365	0.1481	28	0.0015
Rail-Rail Crossing	16	0.0005	14	0.0009	2	0.0001
Obstruction	763	0.0218	605	0.0379	158	0.0083
Explosive	9	0.0003	2	0.0001	7	0.0004
Fire/Violent Explosion	337	0.0096	245	0.0153	92	0.0048
Other Impacts**	4,388	0.1254	880	0.0551	3,508	0.1844
Other in Narrative	834	0.0238	377	0.0236	457	0.024
Total	**35,000**		**15,973**		**19,027**	

* RAIRS data contains only a portion of highway-rail crossing accidents.
** Other: Acts of God, or other events involving the operation of on-track equipment (standing or moving) that result in reportable casualty/damages (e.g., humping accidents, switch damage).
Source: RAIRS.

Table 26. Reported Train Miles

Year	Total Train Miles	Mainline Train Miles	Yard Train Miles
1988	609,334,435	504,008,966	105,325,469
1989	620,598,940	516,268,837	104,330,103
1990	608,837,284	510,685,897	98,151,387
1991	576,834,890	488,315,540	88,519,350
1992	593,703,777	509,274,174	84,429,603
1993	613,973,971	526,852,215	87,121,756
1994	655,083,056	565,307,012	89,776,044
1995	669,823,264	579,931,398	89,891,866
1996	670,923,960	583,100,706	87,823,254
1997	676,716,407	591,842,608	84,873,799
1998	682,894,841	599,202,777	83,692,064
1999	712,452,725	624,993,727	87,458,998
2000	722,876,632	633,957,546	88,919,086
2001	709,758,198	624,198,248	85,559,950
Total	9,123,812,380	7,857,939,651	1,265,872,729

Source: RAIRS.

Table 27. Accident Scenarios and Equivalent Velocities for the NRC Compliance Test

Accident Type	Equivalent Velocity
Derailment	For train derailments where the cask car does not derail (assigned an 80 percent probability), it is assumed that the cask may impact other rail equipment. The resulting damage from such an impact is assumed not to exceed the regulatory limit of 30 mph (48.2 km/hr), which corresponds to a Category I/II event. For train derailments where the cask car does derail (assigned a 20 percent probability), it is assumed that the cask impacts a hard object in the surrounding environment. Any train speed in excess of 30 mph (48.2 km/hr) will result in damage to the cask that exceeds regulatory limits. Refer to Table 24 for velocity equivalents. This corresponds to a Category III event.
Head-On Collision	For head-on train-to-train collisions, the worst-case assumptions applied are the cask train speed is 50 mph (80.4 km/hr), the cask breaks free of its car, and the cask collides head-on with the second train's locomotive. For speeds of the second locomotive below 70 mph (112.6 km/hr), Category I/II events can occur. For speeds of the second locomotive above 70 mph (112.6 km/hr), it is assumed that the cask impacts a hard object in the environment and damage that exceeds regulatory limits occurs, which corresponds to a Category III event (see Table 21).
Rear-End Collision	The worst-case rear-end scenario assumed is that a stationary cask is struck by the second train's locomotive and derails. After impact, the cask and locomotive continue to move at a residual velocity. For striking locomotive speeds under 40 mph (64 km/hr), the residual velocities do not exceed 30 mph (48.2 km/hr), which corresponds to a Category I/II. For striking locomotive speeds greater than 40 mph (64 km/hr), the cask impacts a hard object in the environment, and damage that exceeds regulatory limits occurs, which corresponds to a Category III event (see Table 22).
Side Collision	The side-collision scenario assumes the cask is hit broadside by a train and derails. After impact, the cask and locomotive continue to move at a residual velocity. For striking locomotive speeds under 40 mph (64 km/hr), the residual velocities do not exceed 30 mph (48.2 km/hr), which corresponds to a Category I/II. For striking locomotive speeds greater than 40 mph (64 km/hr), the cask impacts a hard object in the environment, and damage that exceeds regulatory limits occurs, which corresponds to a Category III event (see speeds defined in Table 22).
Raking Collision	For raking collisions, it is assumed that the cask is struck on the corner by another piece of rail equipment and derails. For speeds of the second locomotive below 70 mph (112.6 km/hr), Category I/II events can occur. For speeds of the second locomotive above 70 mph (112.6 km/hr), it is assumed that the cask impacts a hard object in the environment, and damage that exceeds regulatory limits occurs, which corresponds to a Category III event (see Table 23).
Broken Train Collision	In the broken train collision scenario, a section of a train rolls into the path of a moving train or rolls into another stopped train. The speeds of concern are assumed to be the same as in the raking collision. The broken train must be traveling at a speed below 70 mph (112.6 km/hr) for a Category I/II event to occur. The broken train must be traveling at a speed above 70 mph (112.6 km/hr) for a Category III event to occur (see Table 23).
Highway-Rail Crossing	For a highway-rail crossing scenario, the worst case occurs when the train derails. The derailment logic is then applied.
Rail-Rail Crossing	For the rail-rail crossing scenario, the cask is impacted broadside by a locomotive and derails. After impact, the cask and locomotive continue to move at a residual velocity. For striking locomotive speeds under 40 mph (64 km/hr), the residual velocities do not exceed 30 mph (48.2 km/hr), which corresponds to a Category I/II. For striking locomotive speeds greater than 40 mph (64 km/hr), the cask impacts a hard object in the environment, and damage that exceeds regulatory limits occurs, which corresponds to a Category III event (see Table 22).
Obstruction	These collisions are assumed to be similar to highway-rail crossing accidents discussed above.
Explosion/Fire	These events are evaluated independently in terms of potential fire hazard.

3.3.4 Baseline Event Trees–Regular Trains

Based upon nationally available historical train accident data for 1988-2001, three event trees were constructed. One representing regular trains involving all manners of movement on the mainline, the second representing regular trains in yards, and the third describing fire events. Fires are treated independently because they can be initiating events, or a secondary event following one of the other accident scenarios.

An event tree is a useful representation of the likelihood of accidents of various types. This is a summary of the distribution of "types" of accidents given their rate of occurrence. The baseline event tree represents accidents that have occurred at all speeds on the mainline. The base rate is calculated by summing the total reported accidents during the period and normalizing by train miles in both yards and on the mainline (see Figure). This probability is the accident rate per train mile in the U.S. for 1988-2001. The probability of each of the accident types is based upon the fraction of those accidents that fell into one of the accident categories using the Railroad Accident Information Reporting System (RAIRS) data for this time period. FRA defines a reportable train accident as:

> Any collision, derailment, fire, explosion, act of God, or other event involving the operation of on-track equipment (standing or moving) that results in total damages to all railroads involved in the event that is greater than the current reporting threshold to railroad on-track equipment, signals, track, track structures, and roadbed.
>
> Note: The classification of a train accident by type (collision, derailment, other) is determined by the first reportable event in the accident sequence. All reports for a single accident are to use the same designation. For example, if following a derailment a train strikes a consist on an adjacent track, the report for this additional consist will indicate that the accident type was a derailment, not a collision [FRA, 2000].

Accidents that are reported are determined by a reporting threshold:

> The amount of total reportable damage resulting from a train accident which, if exceeded, requires the preparation and forwarding of form FRA F 6180.54 by the railroads involved. For accidents occurring in calendar years 1991-1996, the reporting threshold is $6,300. For accidents that occur in calendar year 1997, the reporting threshold is $6,500. See 61 Fed. Reg. 60632 (Nov. 29, 1996). Pursuant to § 225.19(e), the reporting threshold will be revised annually according to the formula set forth in Appendix B to Part 225 [FRA, 2000].

Due to the substantial difference in the frequency of accidents in yards versus mainline (nearly 50 percent of U.S. mainline accidents), a separate yard event tree was constructed. Figure 32 shows a representation of the event tree for yard accidents. The yard event tree is identical in structure to the mainline tree, but the probabilities are different due to the different distribution of accident types and speeds in yards. The probability of a train accident being either on the mainline or in a yard is distinguished in the event trees. The distinction between mainline and yard accidents is made first because of the significant difference in the number of yard entries made by a regular versus dedicated train and the resulting significant decrease in accident exposure (not accounting for severity) that results from this operational distinction. Given that the accident happens in one or the other environment, five further accident type scenario characteristics are described, including the probability of a collision; derailment, highway-rail grade crossing accident; fire or explosion; or some other type of accident.

Each event tree begins with the overall train accident rate per train mile, based upon the historical RAIRS accident data. These are subdivided into types of accidents (e.g., grade crossings, collisions), and the probabilities of those types are reflected in the initial nodes. Some of each of those types of accidents result in derailments, and the probability of a subsequent derailment following each initiating event is also calculated. These derailments pose scenarios in which a secondary impact with another piece of railroad equipment, the ground, or an object on the wayside may occur and damage the cask as discussed in Section 3.2.2. The frequency of derailments was assessed using the accident report account of the number of cars that derailed in the event. The RAIRS report indicates whether any car derailed independent of whether the initiating event classified the accident as a derailment.

Severity of the derailment is a crucial component of this analysis. Since the surface hardness of the final surface impacted by the cask is unknown, an approach to estimating the possibility of cask damage or release was constructed based upon impact velocity and the distribution of final velocities after secondary impacts that could result in cask damage. The probabilities have been categorized into impact velocities that would represent exceeding regulatory compliance limits for impacts with hard surfaces. This is a very conservative approach. The nodes that describe speed distributions follow the accident type nodes on the trees and summarize the probability that the accident will occur at or above the threshold speed that is the equivalent of the NRC's 30-ft (9.1-m) drop compliance test for a hard surface impact.

Several categories of collisions are grouped into two scenarios, those where the initial impact velocity must equal or exceed 70 mph (112.6 km/hr) to result in a 30 mph (48.2 km/hr) (NRC compliance speed equivalent) impact and those for which that speed is 50 mph (80.4 km/hr). Head-on, raking, and broken train collisions are in the former category, and rear-end and side collisions are in the latter. Rail-highway crossing, rail-rail, and obstruction collisions are analyzed separately in the event trees. In all cases involving derailments, it is assumed that the probability that the cask car is one of the derailing cars is 0.2. This is based upon the analysis of derailment characteristics presented in Section 3.4.2.

To illustrate use of the mainline event tree in calculating accident probabilities (see Figure 31), an example is provided here. The example calculates the probability that obstruction collisions of regular trains operating on mainline will result in cask impacts that exceed regulatory compliance limits. In this example, the obstruction accident type branch of the tree is of interest. From the event tree, the overall mainline regular train accident rate is 2.0327×10^{-6}; the probability of an obstruction collision is 0.03788; and the probability of a derailment following an obstruction collision is 0.13223. Furthermore the following distribution of train speeds for obstruction derailments is noted: less than 30 mph, 0.64969; 30 mph to 50 mph (48 km/hr to 80.4 km/hr), 0.28355; 50 mph to 70 mph (80.4 km/hr to 112.6 km/hr), 0.06614; and greater than 70 mph (112.6 km/hr), 0.00061. Finally, for all train derailments, the cask car has a 0.20 probability of actually derailing. As discussed in Section 3.2.2 and in Table 28, it was determined that, for obstruction derailments, the critical speed is 30 mph (48 km/hr); that is, obstruction derailments with initial train speeds greater than 30 mph (48 km/hr) will result in cask damage that exceeds regulatory compliance limits. The train speed probabilities of interest in the event tree will therefore be the sum of those above 30 mph (48 km/hr). Given the above, the calculation for the probability of obstruction collisions resulting in damage to casks that exceeds regulatory limits is:

Pr (Obstruction collision > limits) = $(2.03272\times10^{-6}) \times (0.03788) \times (0.13223) \times (0.28355 + 0.06614 + 0.00061) \times (0.20) = 7.13278\times10^{-10}$

The calculation of similar probabilities using the yard event tree is performed in the same manner as with the mainline tree, except that the 0.20 probability factor for cask car derailment does not apply to yard accidents.

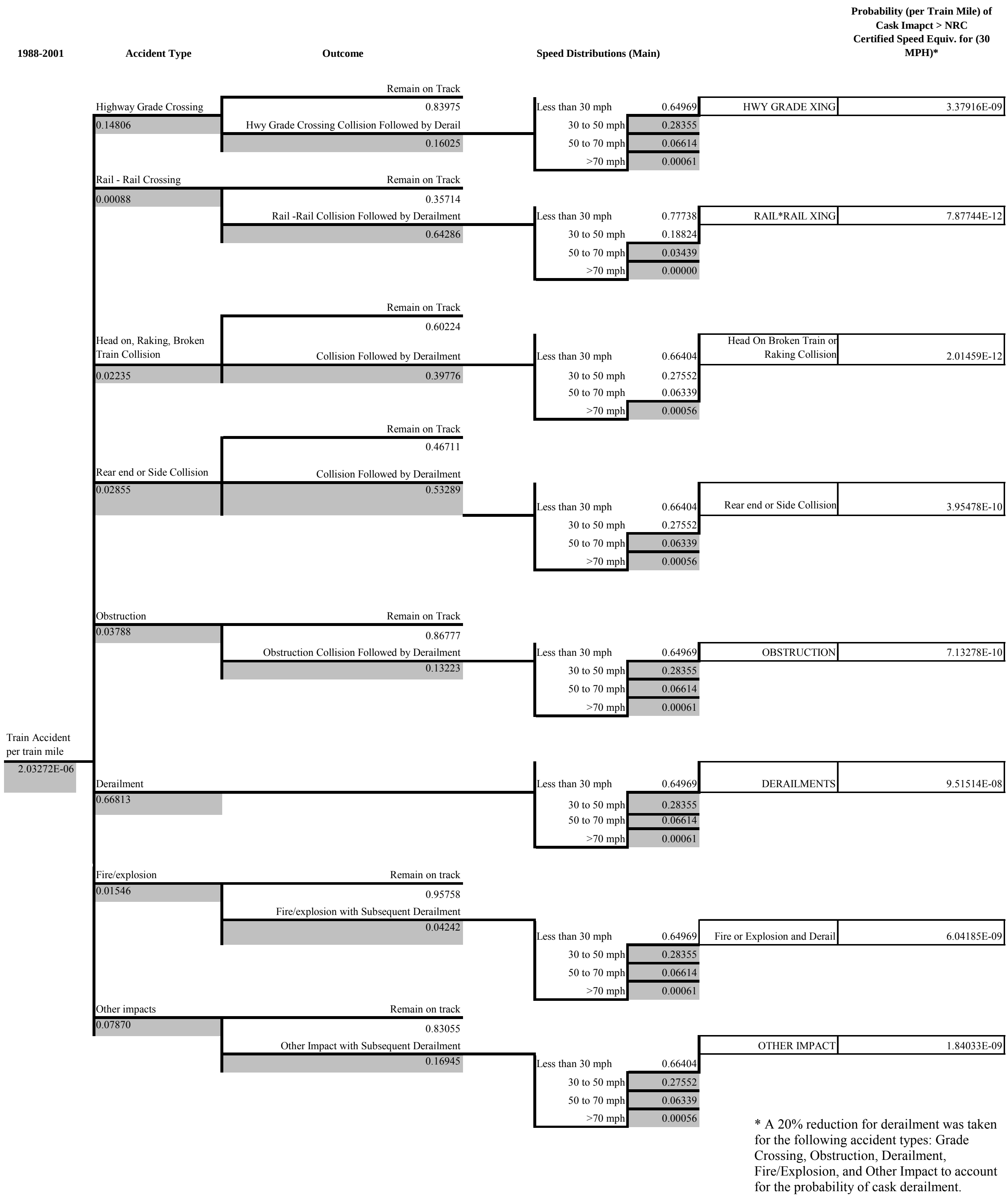

Figure 31. Main-Line Event Tree

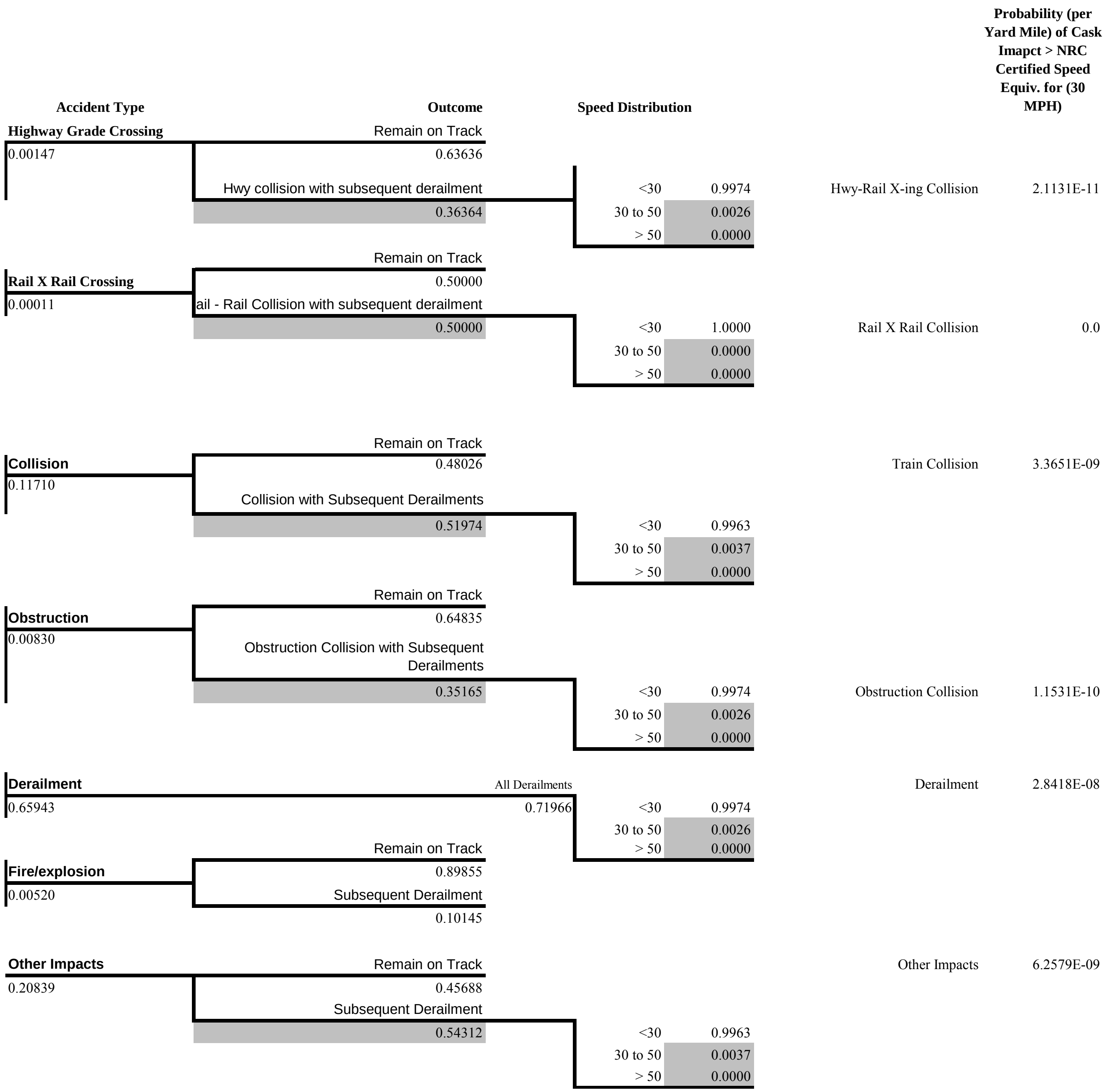

Figure 32. Yard Event Tree

3.3.5 Fire Event Trees

Fires are similar to other major accident events on the event tree in that they, like collisions or derailments, may occur as an initiating event or, like derailments, may occur as an aftermath of the initial event. Both the probability that an initial fire occurs and that a fire results from another incident are of concern in this analysis. Since a fire may result from any node on the event tree, a separate analysis was constructed to represent its overall risk.

The framework for analysis of fire risk combines the assessment of fire probability for mainline or yard events, as initiating or secondary events, with a measure of the likely severity of the fire. The fire analysis is concerned with fire intensity (temperature) and duration. Intensity is governed by the type of fuel available to the fire, while duration is governed by the quantity of fuel and/or the accessibility of the accident site to emergency mitigation.

The major contributory factors toward cask involvement (in the hypothetical fire) must be identified. The initial assumption is that a train fire is a type of accident, independent of other types, and occurs at a fixed frequency for mainline and yard environments. The fire accident probability is 4.11×10^{-08} per train mile on the mainline and 7.74×10^{-08} per yard mile. The probability of a fire as an initiating event on the mainline is 2.8×10^{-08} per train mile.[29] Fires as initiating events in rail yards occur 6.95×10^{-08} per yard mile. The probability of a fire as a secondary event at either location type has been estimated by reviewing accident report narrative descriptions in which a fire is noted. The probability of fire, given an accident, is 1.47×10^{-02} per train mile on the mainline and 4.99×10^{-03} per yard mile for yards.

The next determining factor in whether the fire is likely to exceed the certified cask performance standard is the presence of flammable hazardous material (hazmat) cargo in either the train transporting the cask or in other involved train consists. The presence of potentially flammable hazmat and particularly high levels of flammables and combustibles near the cask car is the foremost consideration in determining whether the cask can be compromised by fire in an accident. The estimate of the probability of exposure to flammable hazmat was based upon two inputs: first, the historical accident record of hazmat involvement in accidents where fires occurred, and second, the probability that the hazmat involved in any future accident will be flammable, based upon an analysis of waybill flow data. The RAIRS database for years 1998-2001 indicates that hazmat was carried in 48 out of 340 fire incidents and hence have a heightened potential for flammable release necessary for a large engulfing pool fire. This yields a probability of hazmat given a fire of 48/340 or 0.14. The probability that the hazmat is highly flammable is based upon an analysis of the Waybill Sample for 2001 [STB, 2001]. An assessment of flammability of the hazardous commodities reported in the waybill was based upon the National Fire Protection Association (NFPA) flammability rating. Using this standard, flammable hazmat consisted of approximately 610 of 1,017 commodities (60 percent). This estimate of flammability is based upon flashpoint and interactive chemical properties. NFPA ratings for all hazmat commodities reported in the waybill sample could not be found, so this estimate of exposure is a likely underestimate of the total flammable commodities shipped in the United States. Based upon the available information, however, these data showed that in addition to fuel not carried as cargo, about 60 percent of all hazmat tons shipped are flammable (rated 1 or above on the NFPA rating scale) and could contribute to a high-temperature fire.[30]

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[29] These rates are based upon 1988-2001 RAIRS data, including all accident reports in which fires or explosions are described as the initial accident event.

[30] The NFPA rates commodities in five categories: (4) will rapidly or completely vaporize at normal pressure and temperature, or is readily dispersed in air and will burn readily; (3) liquids and solids that can be ignited under almost all ambient conditions;

The probability of a flammable material release can be estimated for any train involved in an accident, based upon whether it is carrying hazmat. This release estimate is the percentage of hazmat cars releasing given an accident (3.94 percent according to FRA accident records from 1988-2001) multiplied by the fraction of hazmat carloads with flammables (60 percent), as estimated based on the 2001 waybill sample. Without hazmat, only a small probability (0.001) to (0.00001) of a small flammable release remains because the type of volatile material in the consist that may be available to contribute to a fire event is limited to locomotive fuel. In yards specific data on the volume of hazmat available for ignition cannot be constructed from available data. Given the presence of many more tracks, trains, and consists that may contain hazmat that may be in the process of switching and therefore exposed to the cask, however, an estimate of the likelihood of exposure is 25 percent higher than on the mainline.

Fire events that can achieve the temperature and durations described in SNL's analysis were identified based upon the reported volume of flammable hazmat shipped in the 2001 Waybill sample and an estimate of the duration of fires resulting from involvement of a single carload. Reported weights for a single carload of flammable hazmat ranged from 8 to 89 tons (7.3 to 80.7 metric tons) per carload. On average, a carload of flammable hazmat contains 23,000 gallons (87,0656 liters) of material. Based upon this assumption, the cargo will be fully consumed in a 30-ft (9-m) diameter pool fire within at least 4.5 hours of ignition.

The final steps in establishing a framework for comparing the likelihood of a fire that exceeds NRC's cask fire certification requirement are estimating the probabilities of: (a) exposure of the cask to a pool fire and (b) engulfment of the cask to the required levels of intensity and duration. A statistical basis for estimating the frequency of these three components is not easily available. Distinguishing factors, however, can be described for mainline versus yard environments and on the basis of the content of the consist of the train carrying SNF. The assumptions used to construct the final nodes on the fire event tree (see Figure 33) are described below.

Exposure of Cask to Fire. The cask could be exposed if a fire is initiated on the train or results from an explosion or an impact (resulting from a collision or derailment), and a car(s) carrying flammable cargo released its contents and caught fire. The contents of one or more hazmat cars would: (1) have to release and then collect, forming a fully engulfing pool fire which must equal the dimensions of the cask and (2) the cask would have to come to rest within that pool. Although no empirical data is available, exposure likelihood given an accident and a flammable hazmat cargo release is estimated to be 0.01 for the mainline. In yards, because more directional opportunities exist for the fire spreading from adjacent tracks or facilities, the estimate is four times that of the mainline (0.04).

Cask Engulfment. Engulfment, given cask exposure, is assumed to be even more rare than cask exposure, perhaps as low as 1/1,000 times (0.001), but it is not dependent upon mainline or yard environments. There is no known parametric data to confirm this figure. This estimate is based primarily on judgment regarding the scenario from which a pool fire and cask engulfment could result. This scenario is difficult to achieve since it involves the release, subsequent pooling (into a 30-ft (9.1-m) diameter or greater pool), and ignition of the contents of one or more flammable hazmat carrying cars directly underneath the cask. Accident reports and descriptions were evaluated to determine whether lengthy fire events involving sufficient material could result in this type of fire. However, historically only a few fire events have resulted in multi-hour, high temperature fires involving enough material to create a pool fire. Lacking more detailed data on specific consists' configurations and fire events, the analysis has focused on the presence of a flammable material in the consist as a potential contributor to the initiating event, not upon

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(2) must be moderately heated or exposed to relatively high temperature before ignition can occur; (1) must be preheated before ignition can occur; (0) materials that will not burn. See http://www.ilpi.com/msds/ref/nfpa.html.

the likelihood that the fire will result in a fully engulfing fire. Therefore, this probability is uniformly applied to yard and mainline accident events.

To illustrate use of the fire event tree in calculating fire probabilities (see Figure 33), this report provides an example here. The example calculates the probability of a fully engulfing cask fire for regular and key trains for combined operations on mainlines and in yards that will result in cask damage exceeding NRC compliance limits. Starting at the root node of the fire event tree, the overall accident rates for regular/key trains is 2.03272×10^{-6} and 1.50307×10^{-5} on mainlines and in yards, respectively. The next two branches of the tree indicate the probability of different types of accidents occurring on mainlines and in yards, given an accident, and the probability that each of these accident types results in a fire. For example, the probability of a mainline derailment, given an accident, is 0.668127465, and the probability that this type of accident results in a fire is 0.004029235. These two probabilities are multiplied together for each accident type and summed over all accident types to yield the overall probability of a fire, given an accident on mainlines and in yards. The results are shown in the next node of the tree as 0.0245427 and 0.0136757 for mainlines and yards, respectively. The following node probabilities are noted in subsequent branches of the tree:

- The probability of hazmat being present in the consist is approximately 0.155 and 0.0714 for mainline and yard accidents, respectively.

- The probability of a flammable hazmat release, given the presence of hazmat, is 0.0280 and 0.0145 for mainline and yard accidents, respectively.

- The probability of a pool fire being ignited, given a flammable hazmat release, is 0.0394 for mainline and yard accidents.

- The probability of cask exposure to the pool fire is 0.01 and 0.04 for mainline and yard accidents, respectively.

- The probability of the cask being engulfed in the pool is 0.001 for mainline and yard accidents.

The overall probability of a fully engulfing cask fire for combined regular and key train operations on mainlines and in yards will be the sum of their separate mainline and yard probabilities. The mainline probability will be the product of the mainline accident rate times the probability of a fire, given an accident, times the probability of hazmat being present in the consist, given an accident, times the probability of a flammable hazmat release, given the presence of hazmat, times the probability of a pool fire being ignited, given a flammable hazmat release, times the probability of the cask being exposed, given a pool fire, times the probability of the cask being engulfed, given that it is exposed to the pool fire:

$\Pr(\text{Fire/Mainline} > \text{limits}) = (2.03272 \times 10^{-6}) \times (0.0245427) \times (0.154798762) \times (0.028015564) \times (0.0394) \times (0.01) \times (0.001) = 8.5244 \times 10^{-16}$

The corresponding probability for yard fire accidents, Pr (Fire/Yard > limits), is 3.3455×10^{-15}.

The combined probability for regular and key train operations on mainlines and in yards of accidents resulting in fires that will damage the cask in excess of NRC compliance limits is 4.1979×10^{-15}, which is the sum of the two probabilities above.

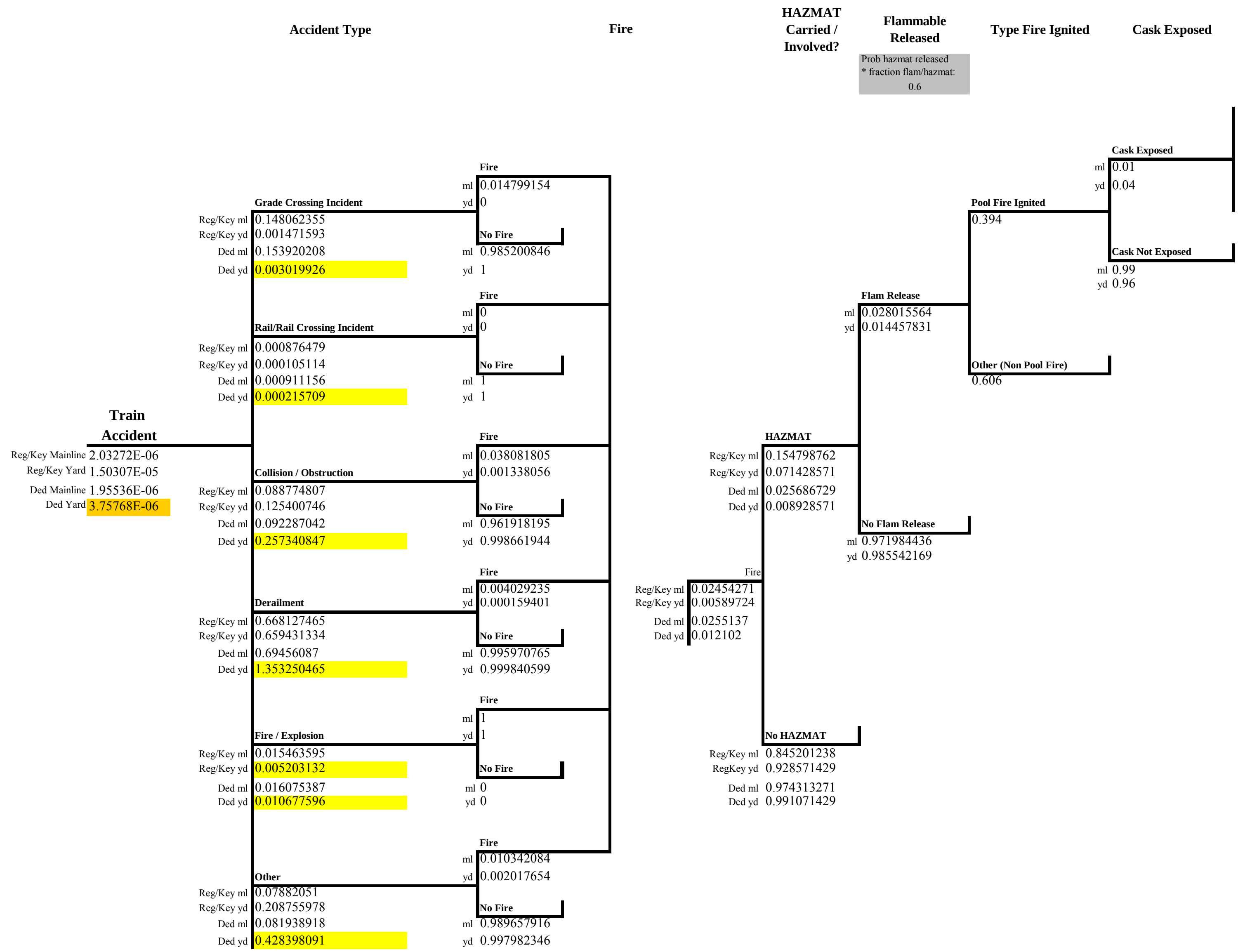


Figure 35. Fire Event tree

3.4 Modified Event Tree–Dedicated Trains

An event tree based upon 14 years of rail accident history was constructed, to describe the probability of an accident. The event tree provides a basis for the probability assessment of accident likelihood involving the shipment of spent fuel by regular trains and can be used to predict how changes in train configurations or operational rules might affect accident likelihood. This event tree describes how likely it is that any train, independent of train makeup or environment, might be involved in an accident. The event trees are limited to a historical view of accidents, and in that sense, fail to reflect how trends in the use of different equipment, changes in operational factors (such as train density), and introduction of different train sets might affect future risk. The long time period included in the dataset, however, helps to compensate for historical trends in accident frequency. Some factors cannot be accounted for, such as the implementation of high-speed rail in many of the highest population density corridors of the country, which exposes trains to accidents that are of a higher velocity than most of those experienced in the accident time period of estimation. The deployment of 110 mph (177 km/hr) trains in corridors that may also experience spent fuel shipments poses a concern for risks of a high-speed collision, passenger exposure, and other significant consequences; this risk should therefore be included in this analysis. A list of proposed high-speed rail corridors appears in Appendix F.

Dedicated and regular trains are expected to operate in different manners. Operational restrictions primarily affect the likelihood that a train is exposed to particular scenario, such as a collision or derailment, and the environment in which the accident might happen (and therefore its likely speed and severity). The baseline event tree (based on historical accident rates) was modified to reflect operational restrictions, consist content limits, speed limits, and other special constraints to be applied to the shipment, as well as differences in the lengths of regular and dedicated trains. This was accomplished by recalculating the probability that a particular type of accident might occur, that an accident would occur in a specific environment, or that the severity of the accident would be affected. In general, these operational restrictions and consist constraints reduce the accident probability. Each of these adjustments to the event tree was made to reflect how the accident probability for individual shipments might vary. Since the total number of additional trains generated by using dedicated trains represents a small fraction of total train volume, no specific adjustment for increases in train density was made in this analysis.

Table 28 lists the adjustments to the accident rate that have been made for each section of the event tree in order to reflect these estimates of how the combination of operational restrictions and the dedicated consist contributes to overall accident risk.

The methodology for estimating the non-catastrophic accident analysis involved a comparison of accident probability due to changing five aspects of service:

- Yard entries
- Train consist length or configuration
- No pass rule for dedicated trains (not key trains as defined by AAR)
- Speed limit
- Other hazmat in consist (not in dedicated trains but possible in key trains as defined by AAR)

Table 28. Adjustments to Baseline Accident Rate for Dedicated Train Service

Accident Type	Factors that Affect Accident Rate	Dedicated Train Rate Adjustment Factor (Probability or Severity)	Change in Probability (Increase Decrease No Change)
Single Train Derailment	Consist Length	Reduces derailment rate	Decrease
	Consist Configuration Effects on Train Handling	Significantly reduces train handling accidents.	Decrease
Collision/ Obstruction	Speed Factor	Change in accident severity by reducing accident frequency for high-speed collisions. Reduction in expected accident severity in all scenarios depending upon route.	Decrease
	Yard Entry Rate	Yard entry rate reduced or eliminated	Decrease
	No Passing Rule	Reduction in raking collision rate in double track territory if dedicated train holds the main in other meets/passes, reduces derailment probability.	Decrease
Highway-Rail Grade Crossing or Rail-Rail	Train Frequency (no passing rule)	Increase frequency of trains may increase number of accidents. Improved stopping distances, train handling, pre-inspection, and use of escorts may, however, reduce accident probability.	No Change
	Train Length	Reduction in derailment probability, improvement in braking capability.	Decrease
	Speed Factor	Improvement in braking capability, severity reduction.	Decrease
Fire	Train Length	Reduction in derailment probability.	Decrease
	No Hazmat in Consist	Reduction in fire probability.	Decrease
Other	Train Handling	Reduction in derailment probability.	Decrease

3.4.1 Yard Entry Modifications

The greatest difference in terms of operational behavior between a regular and dedicated train is the ability to conduct run-through service. This is because the required regular train entries in yards for reclassification adds time and risk to transportation. For that reason, and because the accident rates in yards and on the mainline are so dramatically different, the analysis of the accident rates has been subdivided into two categories, mainline and yard.

Many previous analyses have assumed that accident probability, severity, and consequences are independent of the environments in which they occur. This assumption leads to the blanket application of a general or universal accident rate to all environments and all trains. It can easily be demonstrated, however, that accident involvement of trains can be affected by train makeup, track environment, and operational constraints. The significant differences between dedicated and regular trains with respect to the accident rate lie in the differences attributable to these three characteristics. Environmental and spatial factors were examined for a typical route (see Figure 34). The grouping of accidents around yards on the Humboldt route illustrates the tendency of accidents to cluster spatially, especially in higher traffic areas.

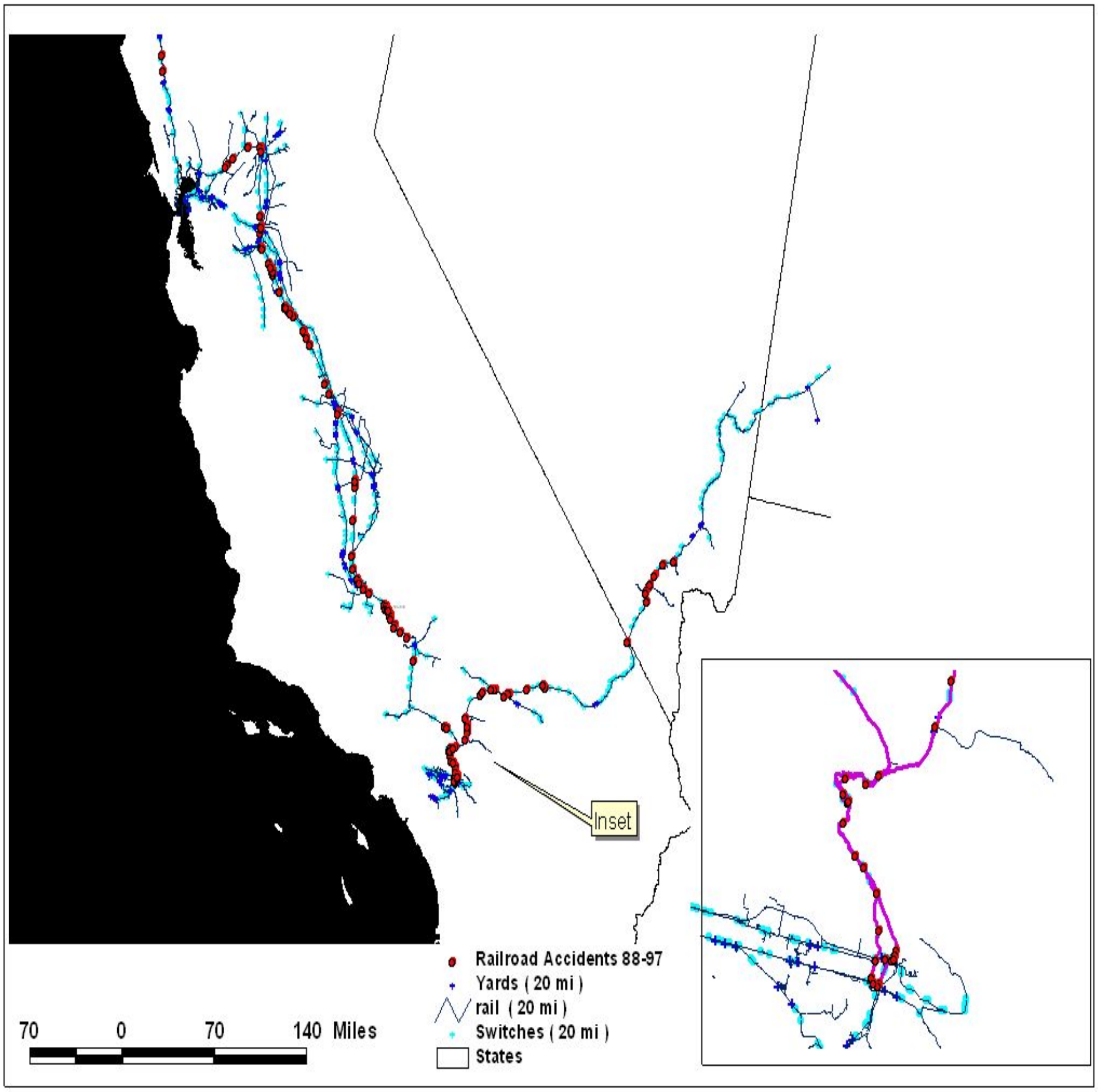


Figure 34. Humboldt, CA, to Yucca, NV, Rail Route Illustrating Accident Locations (1988-1997)

Table 28 illustrates a comparison of the effect of train environment on the accident rate. This table categorizes the total reported train accidents for 1988-2001 that were described with respect to the location of their occurrence into five accident categories.

The total train miles in yards and on the mainline have also been calculated for those years. These sums reveal that the accident rate per train mile in yards is over seven times the rate on the mainline. Accident rates on the mainline are roughly 2.03 per million train miles (see Figure 31), while the rate for yards is 15 per million yard miles (see Figure 32). This information is significant in comparing methods of shipment that would avoid yard entries or limit classification stops in yards. Reduction of yard entries by conducting run-through service will significantly affect accident probability by reducing exposure to one of the highest accident rate environments during shipment. If a train were able to avoid certain environments, the exposure to situations where accidents could occur would similarly decrease. This analysis assumes that although dedicated trains will have to stop in some yards, they will not have to stop in all yards or their stops will not involve classification activities within the yard. Based upon a hypothetical analysis of the six representative routes described in the incident-free analysis using the

BNSF's logistics planning model [BNSF, 2000], therefore the number of yard entries might be cut by 7 percent, and the time spent in yards is cut by 75 percent compared to regular train service. Applying this 75 percent reduction results in a reduction in the yard accident portion of the event tree due to yard exposure from 1.50×10^{-05} yard miles to 3.76×10^{-06} yard miles for dedicated trains.

3.4.1.1 Train Consist Length/Configuration Modifications

Train stability is enhanced when the arrangement of cars in the train minimizes dynamic instability due to load positioning. Trains in which the loads are inappropriately arranged can be dangerously unstable in transport. Even in the absence of incorrect load arrangement, dynamic instability is an issue when oversized or unusually heavy freight cars are included in train consists. Three factors are used to describe the stability of a train, the ratio of the weight of the cars to the locomotives, number of axles, and distribution of weight within the train consist. Simulations of train makeup comparing dedicated train configurations and regular train configurations with the cask consist at the rear of the train illustrate the unfavorable train-track dynamics resulting from the regular train configuration. A comparison of train forces exerted on different cars in a train for specific maneuvers and on particular routes was made. The results were used to compare how the configuration of the train (including position of the cask car and buffer cars) and train length, contribute to forces that may influence derailment risk. Figure illustrates the difference in forces exerted on the car in the middle of a 70-car train versus within the consist of a six-car dedicated train in a situation where an emergency brake application has been made. Forces on the car in the cask position when braking from 50 mph (80.4 km/hr) are significantly higher in the longer train consist than would be experienced in a shorter, dedicated train. These unfavorable forces could contribute to an increased derailment risk.

Train handling related incidents and accidents occur when either the individuals responsible for constructing trains in a yard fail to properly position the cars in the train so as to minimize dynamic instability in transit or the train operator fails to properly control the train during transit. The frequency of these events can be calculated based upon RAIRS accident data, which report accidents caused by improper train makeup or handling. On mainline track, 592 of these accidents (8.6 percent of total derailments) were reported in RAIRS between 1988-2001. If accident rates reflect the risk experienced by properly built trains not carrying oversized loads, it is possible to adjust that rate to reflect how the oversized loads might increase accident potential. This adjustment was made in the analysis to forecast what the specific effects of shipping the 125-ton (113-metric ton) cask may be as a worst case. Train accident involvement rates for collisions, grade crossing accidents, fires, and obstructions are not likely to be affected by train makeup. The most significant likely effect is in the derailment rate. Therefore, this analysis has assumed that the derailment accident rate should be augmented to reflect factors affected by the 125-ton (113-metric ton) cask. It is reasonable to assume that 50 percent of these train-handling accidents would be significantly reduced or eliminated in short trains with six or fewer cars.

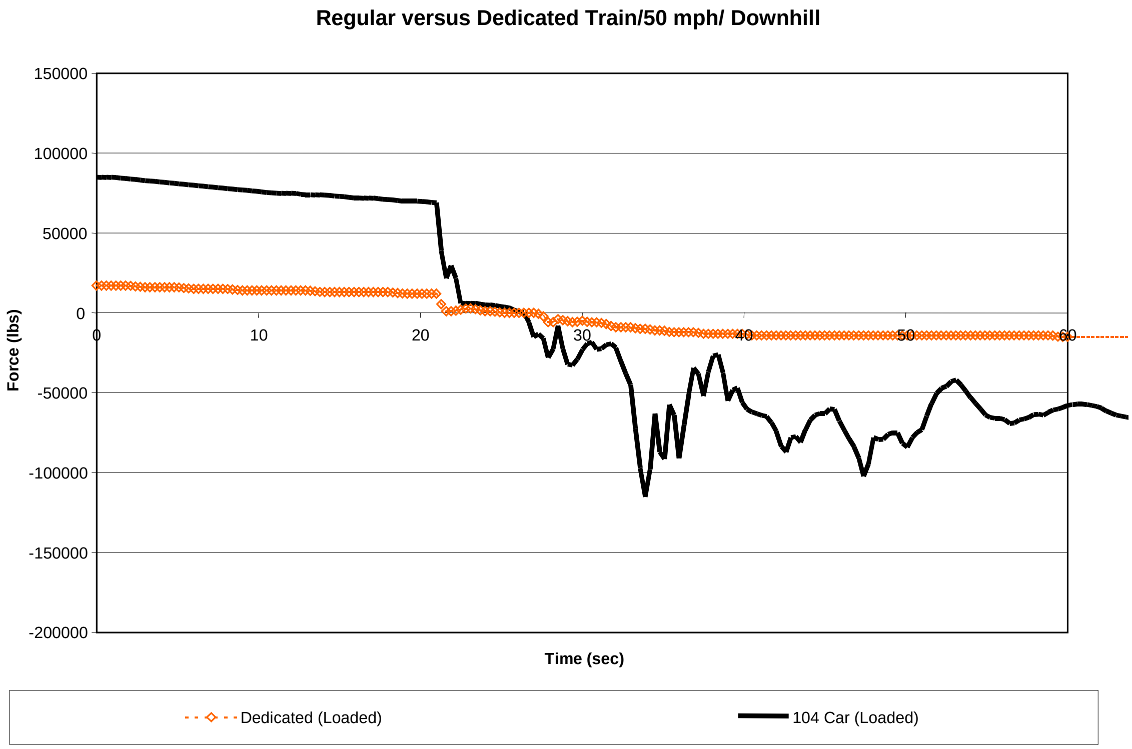


Figure 35. Train Simulation of Railcar Forces Under Emergency Brake Application–50 mph (80.4 km/hr)

3.4.1.2 No-Pass Rule Modifications

Accident involvement in raking collisions may be reduced if a no-passing rule is imposed. The effect of this operational constraint should be to reduce the probability of raking collisions between train consists on the mainline. This rule would not necessarily affect other raking collisions, such as train consist impacts with bridges. In this analysis, the estimated effect of the no-passing rule on the mainline was the elimination of all raking collisions, which account for approximately 20 percent[31] of all mainline collisions.

3.4.1.3 Speed Limit Modifications

An examination of speed factors in determining the likelihood and severity of accidents was conducted using the same 1988-2001 dataset of accidents. A comparison of the likelihood of a derailment at a given speed for collisions and single train derailment accidents, as well as the number of cars derailing given a derailment, was made for accidents in the seven speed categories defined for the accident severity analysis shown in Table 29.

This approach shows that increased speed does not factor significantly in the frequency of accidents, since more accidents occur at lower speeds. Determination of accident rates by speed categories would require mileage data for these categories. Since these detailed data are not available for this analysis, a reduction in accident probability (per train mile) at higher speeds could not be assumed. The most conservative

[31] Based upon RAIRS data, total raking collisions were 163 of 813 mainline collisions during the study period (1988-2001).

assumption is that the accident rate remains constant and that only accident severity decreases with speed restrictions. The table illustrates that, on average, nearly 66 percent of reported mainline accidents in RAIRS occur at less than 35 mph (56.3 km/hr). Therefore, imposition of speed limits on dedicated trains is unlikely to reduce the overall frequency of accidents. This does not mean that accident severity (and therefore overall risk) is also unaffected. The speed effects are reflected in the event trees only by reducing the probability that the accident event will happen at speeds above the constrained limit, not by reducing accident probabilities overall.

Table 29. Speed Distribution of Mainline Accidents (1988-2001)

	SPEED CATEGORIES						
Accident Type	**Less than 35 mph** (56.3 km/hr)	**35 to 55 mph** (56.3 to 88.5 km/hr)	**55 to 65 mph** (88.5 to 104.6 km/hr)	**65 to 70 mph** (104.6 to 112.6 km/hr)	**70 to 75 mph** (112.6 to 120.7 km/hr)	**75 to 106 mph** (120.7 to 170.5 km/hr)	**Greater than 106 mph** (170.5 km/hr)
Collisions	85.80%	10.57%	1.48%	0.34%	0.07%	0.94%	0.61%
Obstructions	58.09%	22.68%	8.15%	2.42%	1.91%	6.11%	0.64%
Derailments	79.54%	17.76%	2.12%	0.36%	0.06%	0.16%	0.00%
Grade Crossing	40.17%	38.18%	9.87%	4.33%	1.40%	6.05%	0.00%
Average by Speed Categories	65.90%	17.50%	0.60%	0.60%	0.40%	1.20%	0.40%

A second issue with respect to speed is the question of how speed contributes to accident severity and whether that contribution changes depending upon train length. This is important because the likelihood of cask involvement in a derailment given an accident is of concern, as well as the likely duration of the response to the incident. The fewer the number of derailing cars, the shorter the response duration and derailment recovery time required. Therefore, both questions are addressed in this analysis. Measuring severity in terms of the number of cars that derailed in accidents that involved either collisions or non-collision related derailments at given speeds and for given train lengths provides insights into both of these questions.

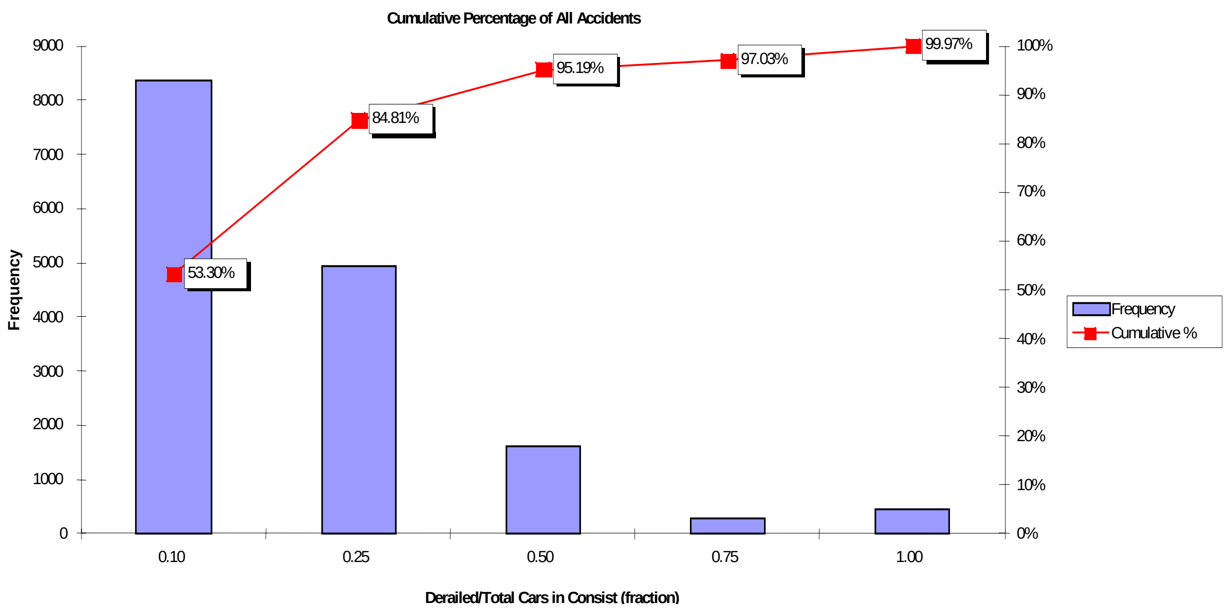
3.4.2 Train Length, Speed, and Accident Severity

The relationship between train length and reported accident speed on derailments was examined for the accidents included in this analysis since both of these factors would be constrained in dedicated trains (compared to regular or key trains). The reason to constrain either of these factors is the expected reduction in risk, either by reducing the likelihood of accident involvement or reducing the expected severity of accidents. This section attempts to understand how train length and speed affect the expected severity of the derailment. Using RAIRS accident reports from 1988-2001, the accident type and number of derailing cars for accidents that had been classified as either derailments or collisions were analyzed. Derailments also occur in many collisions. Since the accident initiates with a train collision, however, it is classified in that category in RAIRS. By inspecting fields in the accident record that describe the number of derailed cars, it is possible to determine whether a subsequent derailment occurred after a train collision. Likewise, it is possible to determine (based upon other fields in the accident record) how many cars were in the train consist and how many of those derailed (referred to here as the derailment fraction).

Derailment-only and collision-related derailment accidents differ in the number of cars that typically derail. In derailment-only accidents, 66.5 percent of all accidents result in a derailment of five cars or less. In collision-related derailments, that number is 94.2 percent. To provide a more normalized comparison, the fraction of the number of cars that typically derail in accidents was also calculated. In derailment-only accidents, 53.3 percent of all accidents result in a derailment of 10 percent of the consist or less (see Figure 36), while 79.36 percent of all collision-related accidents result in a derailment of 10 percent of the consist or less (see Figure 37).

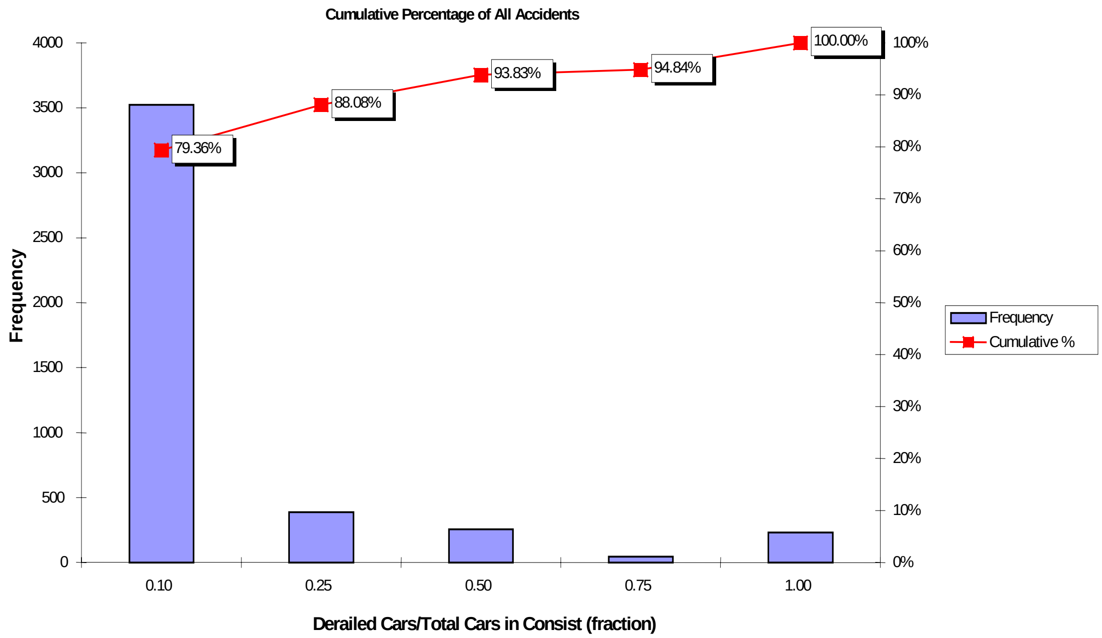
These data suggest that in both types of accidents it is most probable for the number of derailed cars to be less than 10 percent of the train consist, in a six-car train, about one car. The rest of this analysis focuses on how the two factors potentially affected by dedicated train requirements, train length and speed, could affect the derailment outcome.

Dedicated trains are assumed to be short, six cars or less. Key trains and regular trains are not constrained with respect to length. To make a comparison between the three types of service, the data have been disaggregated by train length and grouped into the following categories: 6 cars or less, 7 to 50 cars, 51 to 100 cars, and over 100 cars. Some differences between derailment-only and collision-related derailments exist; therefore, Figure 38 presents the data for each type of accident separately.



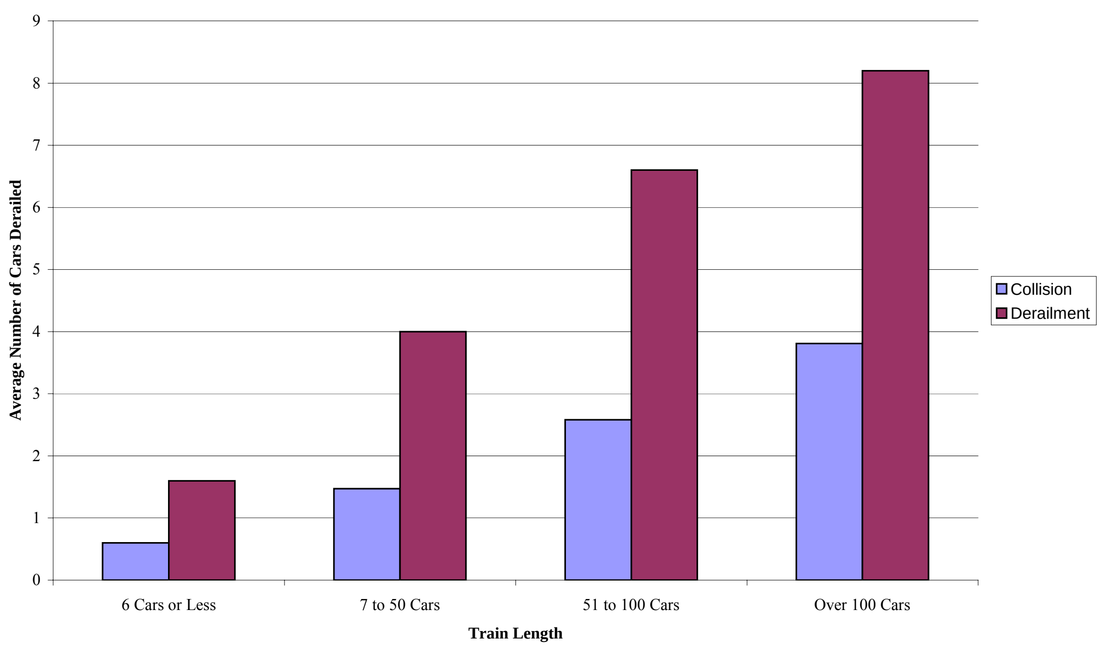
Source: RAIRS

Figure 36. Fraction of Total Number of Cars in Consist Derailed in Derailment-Only Accidents (1988-2001)



Source: RAIRS

Figure 37. Fraction of Total Number of Cars in Consist Derailed in Collision-Related Derailments (1988-2001)

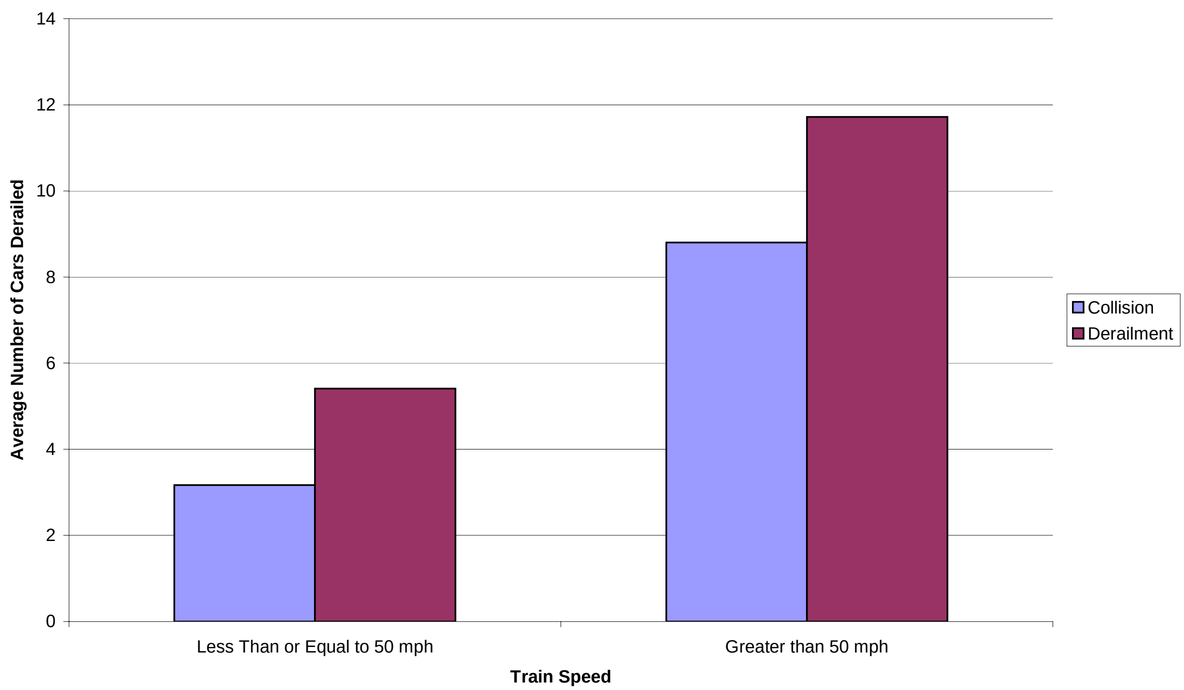


Source: RAIRS

Figure 38. Average Number of Cars Derailed in All Derailments by Train Length (1988-2001) (Derailment-Only and Collision-Related Derailments)

This comparison is interesting since the number of cars derailed in each case increases with train length. This suggests that in derailment accidents, the risk associated with an accident may also increase with train length. This increase in risk may be the result of changes in the likely consequences of the accident. In derailments, the probability that the cask-carrying car will be the car that derails in the accident does not increase with train length, since the fraction of cars that derail decreases in both collisions and derailments as train length increases. Since the total number of cars derailed increases on average, however, the time to clear the wreck after the event will increase due to the increase in the total number of derailed cars. Since the duration of the wreck clearing time affects the total population exposure to radiation associated with each event, the risk also increases.

The second factor evaluated in this analysis was the potential effect of the 50-mph speed limit on risk. In this analysis, the number of collision-related derailments and derailment-only accidents in each speed category were compared. The two speed categories evaluated were 50 mph and less and greater than 50 mph. On average, three or fewer cars derailed in collision-related derailment accidents at less than 50 mph, and the average was five in derailments in the same speed category (see Figure 39). In accidents at speeds greater than 50 mph, the averages were around 8 and nearly 12, respectively. The severity of derailment accidents is different than collision-related derailments; in this case, the fraction of the consist that derails, given a derailment, goes from 15 percent of trains of six cars or less to 23 percent in derailments at greater than 50 mph. The percentage of the consist that derails in collision-related derailments remains about the same for those categories (ranging from 12 percent in the lower speed category to about 10 percent in the higher speed category). The data suggest that high-speed derailments are likely to result in more derailed cars, per derailment, and result in higher risk for transportation of the spent-fuel cask.



Source: RAIRS

Figure 39. Average Number of Cars Derailed by Train Speed (1998-2001) (Derailment-Only and Collision-Related Derailments)

3.5 Modified Event Tree for Dedicated Trains–Results

In Section 3.3, the probability of an accident for regular trains was estimated. This section compares that result with the accident probability for dedicated trains, calculated by applying operational restrictions and carrying a short consist that includes only locomotive(s), buffer cars, and the cask car accompanied by a caboose or escort car. The resulting event tree illustrates the probability that the dedicated train has an accident and that the accident is at a velocity sufficient to exceed the equivalent compliance requirement velocity. The only known speed in historical accident records is the reported train speed at the time of the accident; this is not necessarily the impact velocity of every car in the consist. Absent a better measure of the velocity, however, all accidents have been categorized with respect to this reported velocity, and appropriate reductions applied where speed limits, speed mitigation, or other factors are expected to apply. The result of this is a new event tree, identical in form to the regular train event tree but with different probabilities to reflect the operational restrictions placed on the dedicated train (see Figure 40).

Table 30 shows the cumulative effects on the event trees of the modifications in event probabilities. The effect of reducing the speed of the dedicated train, using operational restrictions that eliminate passing trains, and using consist arrangements that eliminate train-handling accidents would be to reduce the overall probability of a train-to-train collision by approximately 20 percent, and the probability of a train-to-train collision that exceeds regulatory compliance is reduced by about 50 percent. This reduction in train-to-train collisions is due to the combined effects of the dedicated train being limited to 50 mph (80.4 km/hr), the elimination of raking collisions since dedicated trains are not allowed to pass other moving trains, and the avoidance of 50 percent of all train-to-train collisions above 50 mph (80.4 km/hr). This 50 percent factor reflects the assumption that, since only one of the two train speeds is recorded in accident reports, a 50 percent probability exists that the speed not reported could be above 50 mph (80.4 km/hr), even though the dedicated train speed is less than 50 mph (80.4 km/hr). The reduction in overall derailment probability by using dedicated trains is about 4 percent, while the reduction in the probability of a high-speed derailment that could result in an impact that exceeds regulatory compliance is approximately 23 percent.

The cumulative effect of the operational restrictions described in this section is reflected in a small reduction in the mainline accident rate from 2.03×10^{-06} per train mile to 1.96×10^{-06} per train mile or roughly 3.8 percent. The further expected reduction in yard accidents due to a 75 percent reduction in time spent in yards reduces the yard accident rate from 1.50×10^{-05} per yard mile to 3.76×10^{-06} per yard mile.

To illustrate use of the mainline event tree in calculating accident probabilities for dedicated trains (see Figure 40), an example is provided here. The example calculates the probability that collisions of dedicated trains operating on mainlines will result in cask impacts that exceed regulatory compliance limits. In this example, the rear-end or side accident type branch of the tree is of interest. From the event tree, the overall mainline dedicated train accident rate is 1.9554×10^{-6}; the probability of a rear-end or side collision is 0.02968; and the probability of a derailment following a rear-end or side collision is 0.53289. Furthermore, the following distribution of train speeds for rear-end or side derailments exists: less than 30 mph, 0.66404; 30 mph to 50 mph, 0.27552; 50 mph to 70 mph, 0.06339; and greater than 70 mph, 0.00056. As discussed above, for train-to-train collisions, a 0.50 probability exists that collisions above 50 mph will be avoided. Finally, for all train derailments, including those that result from initial collisions, the cask car has a 0.20 probability of actually derailing. As discussed in Section 3.2.2 and in Table 28, it was determined that, for rear-end or side derailments, the critical speed is 50 mph; that is, rear-end or side derailments with initial train speeds greater than 50 mph will result in cask damage that exceeds regulatory compliance limits. The train speed probabilities of interest in the event tree will therefore be the sum of those above 50 mph. Given the above, the calculation for the probability of rear-end or side collisions resulting in damage to casks that exceeds regulatory limits is as follows:

Pr (rear end or side collision > limits) = $(1.9554\times10^{-6}) \times (0.02968) \times (0.53289) \times (0.06339 + 0.00056) \times (0.50) \times (0.20) = 1.9778\times10^{-10}$.

Minor differences between these results and the event tree result from round-off errors.

Table 30. Regular versus Dedicated Train Results–Probability per Train Mile

Accident Type	**Probability per Train Mile (Main and Yard)**	
	Regular Train	**Dedicated Train**
Mainline Accident Rate	2.03×10^{-06}	1.96×10^{-06}
Train-Train Collision	1.05×10^{-07}	8.45×10^{-08}
Train-Train Collision at Greater than NRC Cask Certification Equivalent Velocity	4.05×10^{-10}	2.02×10^{-08}
Derailment	1.36×10^{-06}	1.30×10^{-06}
Derailment at Greater than NRC Cask Certification Equivalent Velocity	9.52×10^{-08}	7.37×10^{-08}
Highway-Rail Grade Crossing	3.01×10^{-07}	3.01×10^{-07}
Highway-Rail Grade Crossing Impact at Greater than NRC Cask Certification Equivalent Velocity	3.38×10^{-09}	2.74×10^{-09}
Other	2.37×10^{-07}	2.37×10^{-07}
Other Accidents at Greater than NRC Cask Certification Equivalent Velocity	2.55×10^{-09}	2.07×10^{-09}
Fire	3.14×10^{-08}	3.14×10^{-08}
Engulfing Fire at Greater than NRC Cask Certification Duration and Intensity	4.20×10^{-15}	4.66×10^{-16}
Yard Accidents (per yard switching mile)	1.50×10^{-05}	3.76×10^{-06}
Yard Accidents at Greater than NRC Cask Certification Equivalent Velocity	3.82×10^{-08}	9.54×10^{-09}
Regular versus Dedicated Train Effect	**Difference Regular versus Dedicated**	
Collision Difference	-2.07×10^{-08}	
Collision at Greater than NRC Cask Certification Speed (Difference)	-2.03×10^{-10}	
Derailment Difference	-5.84×10^{-08}	
Derailment at Greater than NRC Cask Certification Speed (Difference)	-2.14×10^{-08}	
Highway-Rail Grade Crossing Difference	0	
Highway-Rail Grade Crossing at Greater than NRC Certification Speed (Difference)	-6.44×10^{-10}	
Yard Difference	-1.13×10^{-05}	
Yard at Greater than NRC Certification Speed (Difference)	-2.86×10^{-08}	
Fire Involvement Difference	0	
Engulfing Fire (Difference)	-3.73×10^{-15}	

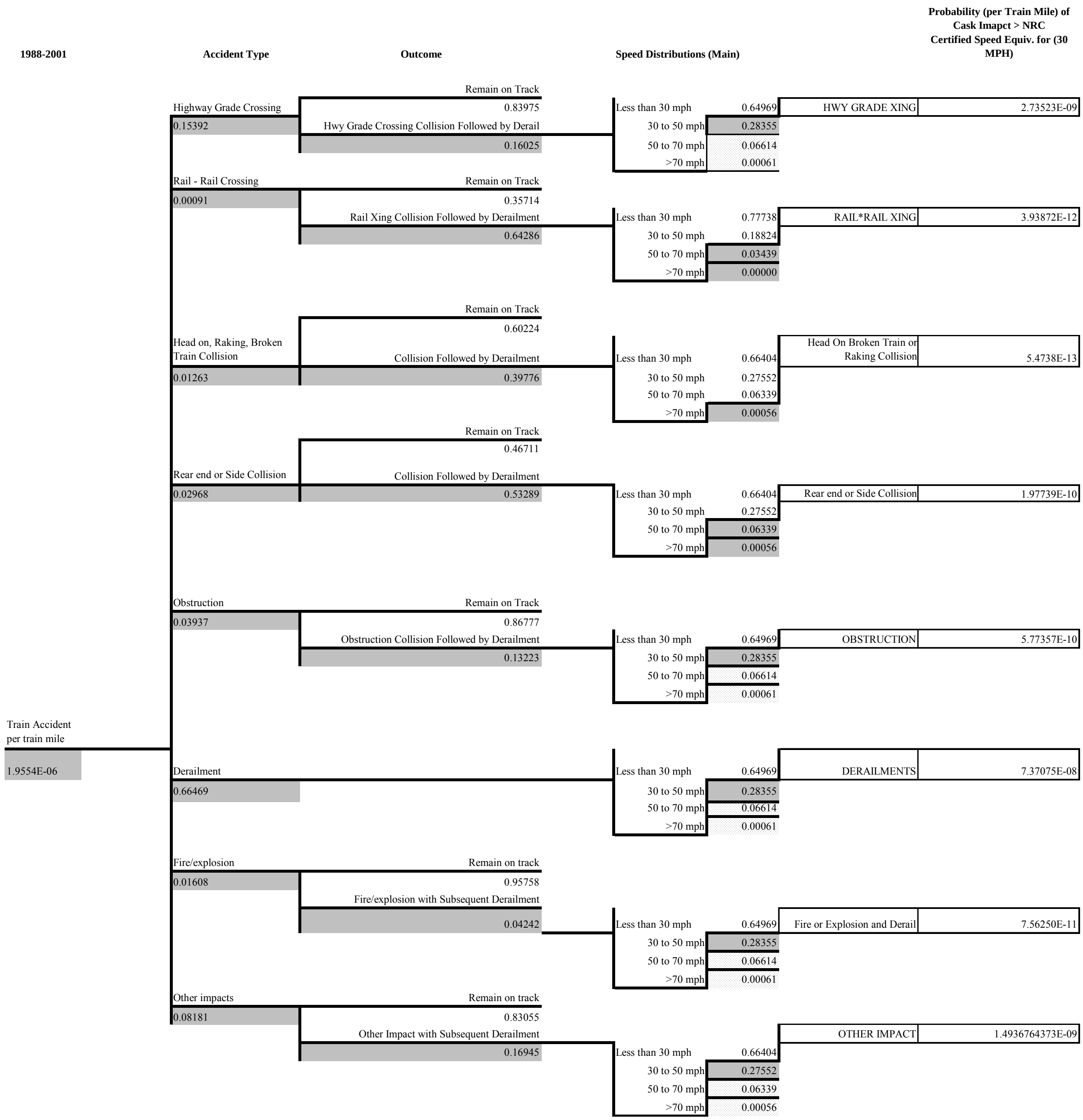


Figure 40. Modified Event Tree--Dedicated Trains on Mainline

3.6 Effect of AAR Circular no. OT-55-D, Recommended Railroad Operating Practices for Transportation of Hazardous Materials

When this study was initiated, AAR had not issued the recommended practice described in this section. The operational restrictions and definitions of dedicated train service included all of those factors described in the previous sections.

In August 2001, AAR issued OT-55-D, which refers to trains that carry one or more carloads of SNF as key trains. Their recommended operational restrictions for this type of service are described in this excerpt from OT-55-D:

Key Trains

> Definition: Any train with five tank car loads of Poison Inhalation Hazard (Hazard Zone A) or 20 car loads or intermodal portable tank loads of a combination of PIH (Hazard Zone A) or flammable gas, Class 1.1 or 1.2 explosives, and environmentally sensitive chemicals, or one or more car loads of spent nuclear fuel (SNF) or high level radioactive waste (HLRW) shall be called a "key train." Attached as Appendix A is a list of PIH (Hazard Zone A or B) and environmentally sensitive chemicals with 49 Hazmat Codes.
>
> Restrictions:
> 1. Maximum speed–key train - 50 mph (80.4 km/hr).
> 2. Unless siding or auxiliary track meets FRA Class 2 standards, a key train will hold main track at meeting or passing points, when practicable.
> 3. Only cars equipped with roller bearings will be allowed in a key train.
> 4. If a defect in a key train bearing is reported by a wayside detector, but a visual inspection fails to confirm evidence of a defect, the train will not exceed 30 mph (56.3 km/hr) until it has passed over the next wayside detector or delivered to a terminal for a mechanical inspection. If the same car again sets off the next detector or is found to be defective, it must be set out from the train.[32]

The effect of these new operational restrictions on the risk of shipping HLRW can be analyzed in terms of their reduction in accident probability or severity relative to regular trains. Table 31 shows the assumptions used as a basis for comparing the effect of using key trains versus dedicated or regular trains. Key trains have only a few specific operational restrictions, and the recommended practice does not specifically require that they be short trains. Therefore, the impact on derailment accident probability due to consist length or configuration is expected to be unchanged relative to the rate for regular trains, including train-handling effects. The rail car used to transport spent fuel is expected to be a special car, designed to provide better handling than standard fleet cars. It is conservatively assumed, however, that the effect of this special car design does not reduce the derailment accident probability for the train since other cars in the consist might also derail.

The speed restriction for key trains affects the expected severity of accidents in the same way that it would affect dedicated train accident severity. It is assumed that this speed restriction would also improve the ability of the key train to respond to emergencies where rapid braking would be required. The braking improvement resulting from the speed restriction should also reduce the likely severity of highway grade-crossing accidents similar to dedicated trains.

Since the content of the train consist is not restricted, the possibility of yard entries at a frequency equal to regular trains must be assumed. Therefore, the expected accident rate in yards is estimated to be equal to that of regular trains.

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[32] AAR, August 30, 2001.

Key trains allow passing on the main with the exception of passes where the track class is less than Class 2. The frequency of key train exposure to this type and condition of track on the main railroad line is expected to be infrequent, by comparison to higher quality (Class 3 or above) track. Since the exposure is low, it is assumed that the restriction on Class 2 track affects only a small number of the total number of train passes that the key train might make during a shipment. It is assumed, therefore, that the raking collision probability, and thus the overall train-to-train collision probability for key trains, is equal to that of regular trains.

The impact of the key train recommended practice on the number of trains, and therefore the frequency of highway grade-crossing accidents, is assumed to be equal to that of regular trains since it is not clear how many (if any) additional trains would be generated under a key train requirement.

Fire risk (probability and severity) for key trains is assumed to be equal to that of regular trains since the recommended practice does not require a limitation on the placement of other hazmat in the consist in excess of hazardous materials shipping regulations. It does not restrict yard entries, and it does not hold oncoming traffic in a train-meet or pass. Therefore, all of the scenarios that could result in a fire involving a regular train could also occur with a key train. Since one of the criteria for key train designation is 20 car loads or intermodal portable tank loads of a combination of PIH (Hazard Zone A or B), flammable gas, Class 1.1 or 1.2 explosives, and environmentally sensitive chemicals, this assumption is conservative since the likely number of key trains with 20 or more cars of flammable gas is significant.

Table 32 summarized the numerical results of applying these assumptions for key trains compared to regular trains. The differences in results between key trains and regular trains are due solely to speed restrictions placed on key trains. The overall mainline and yard accident rates for key trains and regular trains are the same since speed is not assumed to influence overall rates. The overall accident rates for key trains for the specific categories of accidents investigated (train-to-train, derailments, highway-rail crossing, other, and fire) are also the same as for regular trains. The likelihood that these accidents will exceed NRC compliance limits for mainline operations, however, is less for key trains than regular trains since key trains are restricted to speeds less than 50 mph. The likelihood of yard accidents exceeding NRC compliance limits is the same for key and regular trains since their speeds are similar in yards.

Table 31. Assumptions for Service Type–Key Train

Accident Type	Factors that Affect Accident Rate	Key Train Rate Adjustment Factor (Probability or Severity)	Change in Probability (Increase, Decrease, No Change)
Single Train Derailment	Consist Length Effect	Consist length might remain the same as regular train.	No Change
	Consist Configuration	Consist configuration not affected.	No Change
Collision/Obstruction	Speed Factor	Speeds held to 50 mph (80.4 km/hr) for key train.	Decrease
	Yard Entry Rate	Yard entries could equal regular train.	No Change
	Train Frequency	Key trains allow passing on the main. Key train holds main where track class is <2.	No Change
Highway-Rail or Rail-Rail Crossing	Train Frequency	Number of trains generated by key train rules could be equal to, less than, or greater than with regular trains.	No Change
	Train Length	Key train lengths are not necessarily shorter.	No Change
	Speed Factor	Speed reduction should improve braking.	Decrease
Fire	Train Length	Length of train not necessarily shorter than regular train.	No Change
	No Hazmat in Consist	Other hazmat (including flammables) might be in consist.	No Change
Other	Train Handling	Train makeup not necessarily different.	No Change

Table 32. Regular Train versus Key Train Results–Probability per Train Mile

Accident Type	Probability per Train Mile (Main and Yard)	
	Regular Train	**Key Train**
Mainline Accident Rate	2.03×10^{-06}	2.03×10^{-06}
Train-Train Collision	1.05×10^{-07}	1.05×10^{-07}
Train-Train Collision at Greater than NRC Cask Certification Equivalent Velocity	4.05×10^{-10}	2.03×10^{-10}
Derailment	1.36×10^{-06}	1.36×10^{-06}
Derailment at Greater than NRC Cask Certification Equivalent Velocity	9.52×10^{-08}	7.70×10^{-08}
Highway-Rail Crossing	3.01×10^{-07}	3.01×10^{-07}
Highway-Rail Crossing Impact at Greater than NRC Cask Certification Equivalent Velocity	3.38×10^{-09}	2.74×10^{-09}
Other	2.37×10^{-07}	2.37×10^{-07}
Other Accidents at Greater than NRC Cask Certification Equivalent Velocity	2.55×10^{-09}	2.07×10^{-09}
Fire	3.14×10^{-08}	3.14×10^{-08}
Engulfing Fire at Greater than NRC Cask Certification Compliance Duration and Intensity	4.20×10^{-15}	4.20×10^{-15}
Yard Accidents (per yard switching mile)	1.50×10^{-05}	1.50×10^{-05}
Yard Accident at Greater than NRC Cask Certification Equivalent Velocity	3.82×10^{-08}	3.82×10^{-08}
Regular versus Key Train Effect	**Difference Regular versus Key**	
Collision Difference	0	
Collision at Greater than NRC Cask Certification Speed (difference)	-2.03×10^{-10}	
Derailment Difference	0	
Derailment at Greater than NRC Cask Certification Speed (difference)	-1.81×10^{-08}	
Highway-Rail Grade Crossing Difference	0	
Highway-Rail Crossing at Greater than NRC Cask Certification Speed (difference)	-6.44×10^{-10}	

Table 33 summarizes a comparison of the resulting accident rates for regular, key, and dedicated trains. The overall mainline accident rates for all categories of accidents, as well as yard accident rates, for regular and key trains are the same. The overall mainline accident rate for dedicated trains is slightly less (about 3.8 percent) than the rates for key trains and regular trains. The overall yard accident rate for dedicated trains is significantly less (75 percent) than the rates for key and regular trains. The overall dedicated train accident rates for highway-rail crossing, other, and fire accidents are the same as for regular and key trains; however, dedicated train accident rates are lower for train-to-train collisions (about 20 percent) and derailments (about 4.3 percent) than for key and regular trains.

The rates of accidents that will exceed NRC compliance limits are the same for regular and key trains for fire and yard accidents. For all other categories of accidents that will exceed NRC compliance limits, dedicated and key trains will have a lower expected accident rate than for regular trains. The rate of train-to-train collisions that will exceed NRC compliance limits for dedicated and key trains is approximately 50 percent less than for regular trains (key trains have a slightly higher rate than dedicated trains). The rate of derailments that will exceed NRC compliance limits for dedicated and key trains is about 23 percent less and 19 percent less, respectively, than for regular trains. The rate of highway crossing accidents that will exceed NRC compliance limits for dedicated and key trains is approximately 19 percent less than for regular trains. Similarly, the rate of other accidents that will exceed NRC compliance limits for dedicated and key trains is about 42 percent and 19 percent less, respectively, than for regular trains.

Table 33. Regular versus Dedicated versus Key Train Results–Probability per Train Mile

Accident Type	Probability per Train Mile (Main and Yard)		
	Regular Train	Dedicated Train	Key Train
Mainline Accident Rate	2.03×10^{-06}	1.96×10^{-06}	2.03×10^{-06}
Train-Train Collision	1.05×10^{-07}	8.45×10^{-08}	1.05×10^{-07}
Category III Train-Train Collision	4.05×10^{-10}	2.02×10^{-10}	2.03×10^{-10}
Derailment	1.36×10^{-06}	1.30×10^{-06}	1.36×10^{-06}
Category III Derailment	9.52×10^{-08}	7.37×10^{-08}	7.70×10^{-08}
Highway-Rail Crossing	3.01×10^{-07}	3.01×10^{-07}	3.01×10^{-07}
Category III Highway-Rail Crossing Impact	3.38×10^{-09}	2.74×10^{-09}	2.74×10^{-09}
Other	2.37×10^{-07}	2.37×10^{-07}	2.37×10^{-07}
Other Category III Accidents	2.55×10^{-09}	2.07×10^{-09}	2.07×10^{-09}
Fire	3.14×10^{-08}	3.14×10^{-08}	3.14×10^{-08}
Category III Engulfing Fire Accident	4.20×10^{-15}	4.66×10^{-16}	4.20×10^{-15}
Yard Accidents (per yard switching mile)	1.50×10^{-05}	3.76×10^{-06}	1.50×10^{-05}
Category III Yard Accident	3.82×10^{-08}	9.54×10^{-09}	3.82×10^{-08}

3.7 Relative Accident Consequences

3.7.1 Distribution of Accident Severities and Assessment of the Likelihood of Cask Damage

The previous section distinguishes between the probability of an accident, given that one is either in a yard or on the mainline; the probability of a severe accident, given one or the other environments (as described by impact surfaces encountered and train velocity); and how those two distributions differ, depending upon the use of a dedicated versus regular or key train.

Based upon the understanding of the resulting damage from impacts at different velocity ranges, the following accident severity categories were defined with respect to potential emission rates.

- *Category I* Delay event–Accident well within the HAC modeled by the cask packaging test criteria of 10 CFR Part 71; dose rate assumed equivalent to the non-exclusive use transport rate of 10 mrem/hr at 3.3 ft (1 m) from the cask surface. Accidents in Category I could result in an increased duration of exposure to certain individuals (such as crew and nearby population) due to the extended time required to clear the wreck scene and to resume transport.

- *Category II* Serious accident–An accident close to the HAC, which could result in a hundredfold increase in radiation levels, but no release of radioactive material occurs. The surface dose rate is assumed equal to 1 rem/hr (1,000 mrem/hr) at 3.3 ft (1 m) from the cask surface.

- *Category III* Major accident–An accident that exceeds the HAC. A greater loss of shielding occurs but no release of radioactive material. The surface dose rate is assumed to be equal to 4.3 rem/hr (4,300 mrem/hr) at 3.3 ft (1 m) from the cask surface. Accidents in Category III could expose populations to higher doses of radiation for extended time periods.

- *Category IV* Severe accident–An accident well in excess of the regulatory compliance limit. A significant loss-of-shielding with the release of some radioactive material occurs. This category was not analyzed as it was considered equally unlikely for any of the rail shipping options, and the consequences would not be substantially different.

3.7.2 LOS

The possibility of particle releases from casks might be expected if impacts cause enough damage to force a seal to fail. However, strain to the exterior of the cask caused by a significant impact would more likely result in some LOS due to shifting of one of the interior layers of material (such as depleted uranium or lead) that provide external radiation shielding. Gamma shielding, lead in the case of the cask used in this analysis, is used to reduce external radiation doses to levels acceptable for transport. The presence and effectiveness of the shielding is subject to required testing during fabrication of the packaging. The shielding material usually performs no function other than shielding, and its presence is sufficient to satisfy this function. The shielding is usually enclosed by the inner and outer shells and, as a solid, is not subject to removal during normal conditions of transport. Under many accident conditions, the shielding remains in place and still performs the intended function. It is also possible, however, in an accident scenario to have impact forces or temperature conditions sufficient to cause lead slump, damage to the cask contents, or other conditions resulting in elevated radiation emission rates. The degradation of the lead shield reduces the effectiveness of the cask to perform its intended function. With spent-fuel casks, LOS is expected to be localized to a small fraction of the total surface area of the cask. In this case, although the contents of the cask are not directly exposed, at some locations on the cask surface, the level of radiation might exceed the normal transport level of 10 mrem per hour. Significant LOS can result from very high-speed impacts into soft surfaces and lower speed impacts into rigid surfaces. This LOS can result in a Category III accident, with dose rates ranging from the regulatory test allowable level of 1,000 mrem per hour at 3.3 ft (1 m) (10 CFR 71.51), to 4,300 mrem per hour or above. The exact degree of LOS and resulting exposure would depend upon the impact velocity, angle, and hardness of the impacted surface.

Sections 3.7.3 and 3.7.4 evaluate the potential consequences of hypothetical LOS incidents. Section 3.7.3 establishes the assumptions used for dose modeling, and Section 3.7.4 presents the findings. The analysis assumes that the only damage to the cask is to the shielding material (i.e., no seal leak or cask breach causing material release).

3.7.3 LOS Incident Consequence Calculations

The RADTRAN stop model was used to assess LOS incident consequences for the general population as well as emergency responders. The following sections discuss the input values used for the LOS modeling.

3.7.3.1 Cask Dose Rate

To evaluate LOS incidents, cask packages were constructed with the appropriate source strength to estimate the two dose rates that were analyzed for the subject cask, a single PWR fuel assembly in a steel-lead-steel rail cask with damaged lead shielding. The two dose rates analyzed were a 1 rem/hr (1,000 mrem/hr) at 3.3 feet (1 m) dose rate (equivalent to the maximum regulatory (10 CFR 71.51) emission limit permissible for a cask to pass accident scenario acceptance testing) and a 4.3 rem/hr (4,300 mrem/hr) at 3.3 ft (1 m) rate for a more severe hypothetical LOS incident.

For real LOS accidents, cask orientation combined with shielding by the undamaged portions of the cask shell and also by nearby buildings would mean that radiation exposures would be limited by the view factor to the spent fuel through the damaged portions of the cask shell where shielding is compromised. Because the exact geometry of an accident cannot be predicted in advance, however, a point-source model and a uniformly distributed surrounding exposed population were used to calculate population dose. Accordingly, the estimates of the LOS accident dose risks should be somewhat conservative.

3.7.3.2 Population Density

General Population. Three LOS accident locations (urban, suburban, and rural) were evaluated. General population densities for these three locations were assumed to equal the mean of the respective population density distributions for the six routes, i.e., 5,477 persons/sq mi, 1,067 persons/sq mi, and 28 persons/sq mi (2,115 persons/sq km, 412 persons/sq km, and 11 persons/sq km), respectively (see Table 34). Population is modeled as being uniformly distributed around the source.

Table 35 shows the predicted populations within the evacuated areas. Population densities were adjusted for the anticipated level of cordoning that would happen around the accident site. Note that these numbers include emergency responders working within the general population areas.

Table 34. Average General Population Density for All Routes

	Average Population Density persons/sq mi (persons/sq km)		
Route	**Urban**	**Suburban**	**Rural**
1	6,237 (2,408)	1,164 (449)	26 (10)
2	5,641 (2,178)	976 (377)	38 (15)
3	5,169 (1,996)	1,006 (389)	26 (10)
4	4,964 (1,917)	919 (355)	30 (12)
5	6,109 (2,359)	1,028 (397)	28 (11)
6	4,744 (1,832)	1,307 (505)	17 (7)
Average	**5,477 (2,115)**	**1,067 (412)**	**28 (11)**

Source: Census 2000.

Table 35. General Population Densities for LOS Scenarios

Location		Annular Radii Min.–Max. ft (m)	Population Density in persons/mi² (persons/km²)		
			Urban	Suburban	Rural
Urban, Rural, & Suburban	Before Evacuation	49–2,625 (15-800)	5,477 (2,115)	1,067 (412)	28 (11)
	After Evacuation	49-328 (15-100)	0*	0*	0*
		328-2,625 (100-800)	6,492 (2,507)	1,264 (488)	34 (13)

* Assumes 49-328 ft (15-100 m) area cordoned off–no general population access.

Emergency Responders. In addition to the general population, this analysis considers the rail worker and emergency response populations. All railroads that handle shipments would have specific emergency response procedures to safely expedite recovery of shipments that are involved in a rail line accident. Continually manned railroad operation centers maintain the capability to contact personnel from a variety of resources that should provide appropriate equipment and manpower at the accident scene. A wide array of personnel would likely respond to such an incident: police and fire personnel, railroad personnel, wrecking contractors, railroad emergency response contractors, regulators, and shipper representatives. Rerailing the SNF train would likely require, at a minimum, lift capability and track repair personnel who would be required to work in close proximity to the cask. Table 36 shows the mix of personnel assumed for this analysis.

Each incident is unique. Many unknowns exist, such as actual response times, capability and readiness, lift capability/availability/location, fire or involvement of other hazardous materials, accessibility to accident location, and site terrain. Each of these factors could change the mix of personnel and equipment required, as well as the duration of the event.

3.7.3.3 Distance from Source

The dose that could be received by a person decreases rapidly with distance from the cask and the highest doses are received at the points closest to the accident. Similarly dose decreases with lateral distance from the maximum dose point (centerline) at any distance. The following describes the distances from the source used in the calculation for total dose for the LOS incidents.

General Population. The areas occupied by the general population were annular areas with a 49-ft (15 m) inner radius to 0.5-mile (0.8-km) outer radius. Table 35 shows the selected radii and population densities for the urban, suburban, and rural scenarios.

Emergency Responders. For rail worker and emergency response personnel distances to the source will vary for each accident situation. Table 36 shows the distances used for this analysis.

Table 36. LOS Emergency Response Personnel–Distance

Population	Number of Persons	Distance from Source ft (m)	
		Dedicated	Regular/Key
Lift	9[*]	9.8 (3)	9.8 (3)
Track Repair	16	50 (15.2)	50 (15.2)
Fire/Police	2	300 (91.3)	2,140 (652.3)
	2	98 (29.9)	98 (29.9)
	30	328.1 (100)	328 (100)
Regulators	6	32.8 (10)	32.8 (10)
	12	328.1 (100)	328 (100)
Crew	2	300 (91.2)	98 (652.3)
Escorts	4	98 (29.3)	98 (29.3)

[*] 4 tractor operators, 4 groundsmen, 1 supervisor.

3.7.3.4 Exposure Duration/Evacuation

General Population. For the general population, the exposure duration begins at the time of the incident and ends when the train is underway again. For general population, dose estimates for 3- to 72-hour incident durations were analyzed to account for a range of incidents from a single car derailment to multiple car or locomotive derailments.

In urban, suburban, and most rural areas where people could be exposed, emergency response actions will limit the chain of events through establishment of an exclusion zone around the accident site, thus reducing the amount of exposure. Because of evacuation/crowd control measures by first responders, the areas in which the highest dose could be received have a relatively small area. Locations very close to the accident site are unlikely to be occupied by people for any length of time after an accident. In the absence of specific information for this variable, 0.42 hours in urban areas and 0.67 hours in rural and suburban areas were the values used [DOE, 1995].

Emergency Responders. Table 37 shows exposure durations for emergency responders. Fire and police are assumed to be within 65.6 ft (20 m) of the cask for a ½-hour period for personnel injury response and then within 328 ft (100 m) for the duration of the LOS event. It was assumed that lift personnel would require 2-7 hours to rerail the derailed cars. An engineering estimate was made that, based on car derailments, a certain amount of track (360 ft (109.7 m) for dedicated trains and 480 ft (146.3 m) for regular/key trains) would require repair, and this is accomplished at a rate of 120 ft (36.6 m) per hour. These repair times were used to estimate the duration of exposure for track personnel.

Table 37. LOS Emergency Response Personnel–Duration

Population	Number of Persons	**Duration** (hours)	
		Dedicated 6-car train 30-50 mph (48.2–80.4 km/hr) 2 cars derailed 360 ft (109.7 m) track damaged	**Regular/Key** 70-car train 30-50 mph (48.2–80.4 km/hr) 7 cars derailed 480 ft (146.3 m) track damaged
Lift	9*	2**	7***
Track Repair	16	3[3]	4[3]
Fire/Police	2	0.5	0.5
	2	0.5	0.5
	30	10	16
Regulators	6	1	1
	12	10	16
Crew	2	0.5	0.5
Escorts	4	0.5	0.5
* 4 tractor operators, 4 groundsmen, 1 supervisor ** assumes 1 hour per derailed car *** assumes 1 hour per 120 ft (36.6 m) of damaged track led car		**Total Duration** **10 Hours**	**Total Duration** **16 Hours**

3.7.3.5 Shielding Factor

General Population. The standard RADTRAN shielding factors (0.018, 0.87, and 1.0) for urban, suburban, and rural areas, respectively, were applied to the LOS scenarios. Table 38 shows these values.

Emergency Responders. No shielding for emergency responders was considered (shielding factor = 1).

Table 38. LOS General Population–Density, Duration, Distance, and Shielding

Incident Duration (hours)	**Incident Location**	**Before/After Evacuation**	**Duration of Exposure** (hours)	**Population Density** persons/mi^2 (persons/km^2)	**Annular Radii Min.–Max.** ft (m)	**Shielding Factor**
3	Urban	Before	0.42	816.61 (2,115)	49-2,625 (15-800)	0.018
		After	2.58	967.96 (2,507)	328-2,625 (100-800)	0.018
	Suburban	Before	0.67	159.07 (412)	49-2,625 (15-800)	0.87
		After	2.33	188.42 (488)	328-2,625 (100-800)	0.87
	Rural	Before	0.67	4.25 (11)	49-2,625 (15-800)	1
		After	2.33	5.02 (13)	328-2,625 (100-800)	1
10	Urban	Before	0.42	816.61 (2,115)	49-2,625 (15-800)	0.018
		After	9.58	967.96 (2,507)	328-2,625 (100-800)	0.018
	Suburban	Before	0.67	159.07 (412)	49-2,625 (15-800)	0.87
		After	9.33	188.42 (488)	328-2,625 (100-800)	0.87
	Rural	Before	0.67	4.25 (11)	49-2,625 (15-800)	1
		After	9.33	5.02 (13)	328-2,625 (100-800)	1
24	Urban	Before	0.42	816.61 (2,115)	49-2,625 (15-800)	0.018
		After	23.58	967.96 (2,507)	328-2,625 (100-800)	0.018
	Suburban	Before	0.67	159.07 (412)	49-2,625 (15-800)	0.87
		After	23.33	188.42 (488)	328-2,625 (100-800)	0.87
	Rural	Before	0.67	4.25 (11)	49-2,625 (15-800)	1
		After	23.33	5.02 (13)	328-2,625 (100-800)	1
48	Urban	Before	0.42	816.61 (2,115)	49-2,625 (15-800)	0.018
		After	47.58	967.96 (2,507)	328-2,625 (100-800)	0.018
	Suburban	Before	0.67	159.07 (412)	49-2,625 (15-800)	0.87
		After	47.33	188.42 (488)	328-2,625 (100-800)	0.87
	Rural	Before	0.67	4.25 (11)	49-2,625 (15-800)	1
		After	47.33	5.02 (13)	328-2,625 (100-800)	1
72	Urban	Before	0.42	816.61 (2,115)	49-2,625 (15-800)	0.018
		After	71.58	967.96 (2,507)	328-2,625 (100-800)	0.018
	Suburban	Before	0.67	159.07 (412)	49-2,625 (15-800)	0.87
		After	71.33	188.42 (488)	328-2,625 (100-800)	0.87
	Rural	Before	0.67	4.25 (11)	49-2,625 (15-800)	1
		After	71.33	5.02 (13)	328-2,625 (100-800)	1

3.7.4 LOS Incident Results

This section summarizes the results of the calculations for the radiological impacts for the two hypothetical LOS incidents during the transportation of SNF. The incidents were modeled using two cask dose rates–1,000 mrem/hr at 3.3 ft (1 m) and 4,300 mrem/hr at 3.3 ft (1 m). These scenarios correspond to the Category II and III accident severities.

3.7.4.1 General Population

Table 39 and Figure 41 show the general population dose for the Category II and Category III LOS incidents for three locations (urban, suburban, and rural) and for five exposure durations (3, 10, 24, 48, and 72 hours). Deleterious health effects ranging from minor to severe may arise from exposure of individuals and populations to ionizing radiation. These effects have been correlated to doses by the National Council on Radiological Protection and Measurement (NCRP), based on historical exposures and summarized in conversion factors that consider the probability of occurrence and a judgment of the severity of that effect [NCRP, 1993]. The NCRP LCF per person-rem conversion factor values used in this analysis for the estimated probabilities of a fatal cancer are 4.0×10^{-04} for workers and 5.0×10^{-04} for the public.

Table 39. Range of Dose/LCF for General Population LOS Events

Severity Category	Dose	Duration (hours)	Dose (person-rem)			LCFs		
			Urban	Suburban	Rural	Urban	Suburban	Rural
Category II	**1,000 mrem**	**3**	4.32×10^{-03}	4.26×10^{-02}	1.30×10^{-03}	2.16×10^{-06}	2.13×10^{-05}	6.52×10^{-07}
		10	1.36×10^{-02}	0.130	3.98×10^{-03}	6.80×10^{-06}	6.48×10^{-05}	1.99×10^{-06}
		24	3.22×10^{-02}	0.305	9.33×10^{-03}	1.61×10^{-05}	1.52×10^{-04}	4.67×10^{-06}
		48	6.40×10^{-02}	0.605	1.85×10^{-02}	3.20×10^{-05}	3.02×10^{-04}	9.26×10^{-06}
		72	9.59×10^{-02}	0.904	2.77×10^{-02}	4.79×10^{-05}	4.52×10^{-04}	1.39×10^{-05}
Category III	**4,300 mrem**	**3**	1.86×10^{-02}	0.183	5.61×10^{-03}	9.29×10^{-06}	9.16×10^{-05}	2.81×10^{-06}
		10	5.85×10^{-02}	0.559	1.71×10^{-02}	2.92×10^{-05}	2.80×10^{-04}	8.54×10^{-06}
		24	0.139	1.31	4.01×10^{-02}	6.94×10^{-05}	6.54×10^{-04}	2.00×10^{-05}
		48	0.272	2.60	7.96×10^{-02}	1.36×10^{-04}	1.30×10^{-03}	3.98×10^{-05}
		72	0.412	3.89	0.119	2.06×10^{-04}	1.94×10^{-03}	5.94×10^{-05}

Note: LCF rates for worker population: 0.0004 per person; for general population: 0.0005 per person (source: NCRP 1993).

LOS incident dose to the general population in suburban areas is higher than for urban populations despite the lesser population density because of the higher shielding factor for urban construction and faster evacuation rate for urban populations.

3.7.4.2 Emergency Response Personnel

The radiological impact on transportation workers and emergency responders for a SNF shipment is potentially much greater than for the general population.

Table 40 shows the range of potential radiological impact on transportation workers and emergency response providers as the duration of the event increases. Single person dose rates for distances between 3.3 ft (1 m) and 2,624.6 ft (800 m) are provided. As shown in Table 40 the dose received decreases sharply as distance increases and duration decreases. With no additional protection, a worker 196.8 ft (60 m) from a 1,000 mrem/hr source, over a 10-hour period, would receive a dose of 9.00×10^{-03} rem, which corresponds to 3.60×10^{-06} LCF.

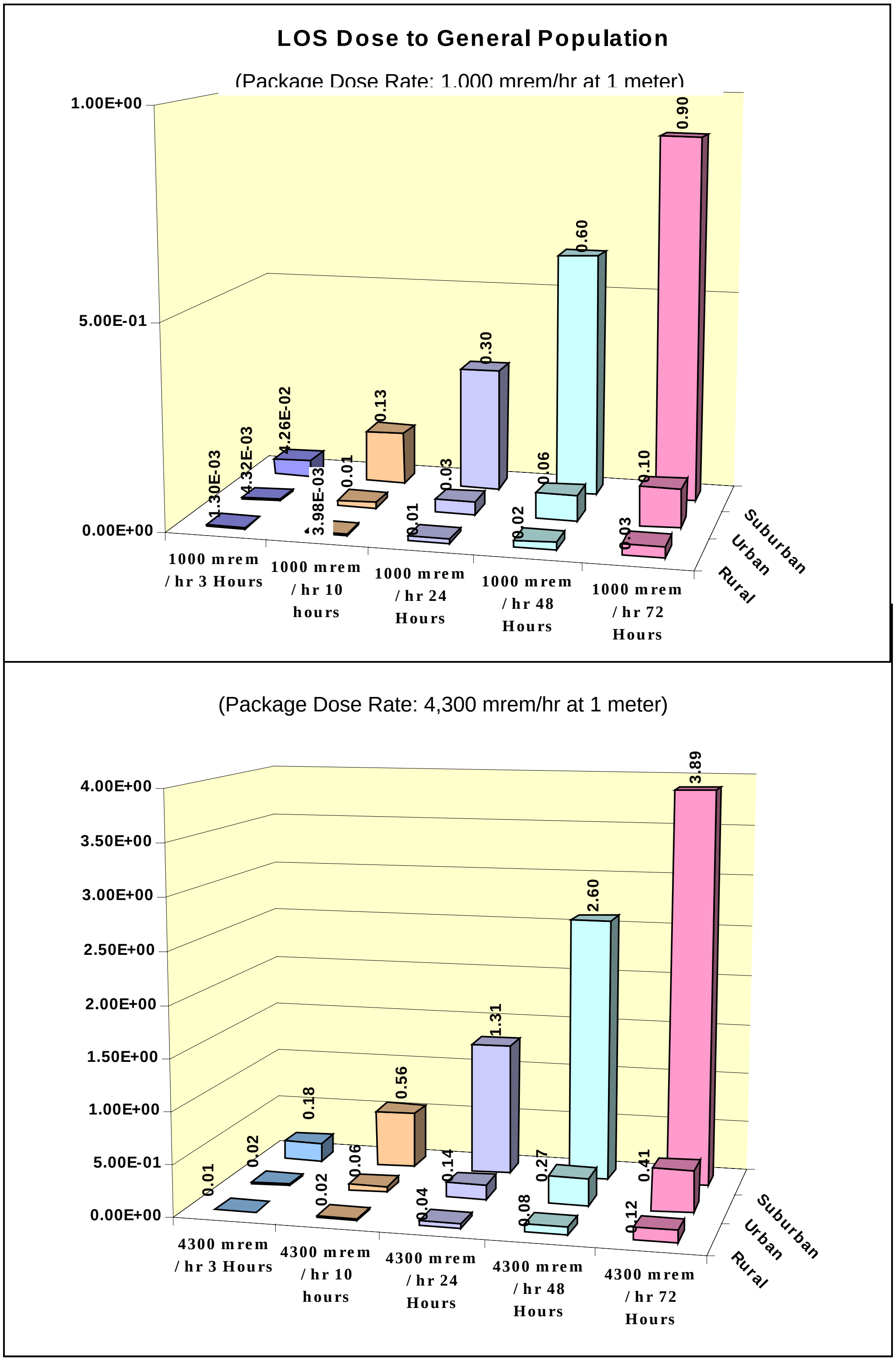

Figure 41. LOS Dose to General Population–Category II and III Events

Table 40. Range of Dose for Rail Worker/Emergency Responder–Single Person Dose (rem)–Category II LOS Event

Distance From Source ft (m)	Incident Duration (hours)				
	3	10	24	48	72
3.3 (1)	4.50	15.0	36.0	72.0	108.0
16.4 (5)	0.270	0.900	2.16	4.32	6.48
32.8 (10)	6.75×10^{-02}	0.225	0.540	1.08	1.62
65.6 (20)	1.69×10^{-02}	5.62×10^{-02}	0.135	0.270	0.405
98.4 (30)	7.50×10^{-03}	2.50×10^{-02}	6.00×10^{-02}	0.120	0.180
131.2 (40)	4.22×10^{-03}	1.41×10^{-02}	3.38×10^{-02}	6.75×10^{-02}	0.101
196.8 (60)	2.70×10^{-03}	9.00×10^{-03}	2.16×10^{-02}	4.32×10^{-02}	6.48×10^{-02}
328 (100)	6.75×10^{-04}	2.25×10^{-03}	5.40×10^{-03}	1.08×10^{-02}	1.62×10^{-02}
656.1 (200)	1.69×10^{-04}	5.62×10^{-04}	1.35×10^{-03}	2.70×10^{-03}	4.05×10^{-03}
984.2 (300)	7.50×10^{-05}	2.50×10^{-04}	6.00×10^{-04}	1.20×10^{-03}	1.80×10^{-03}
1,312.3 (400)	4.22×10^{-05}	1.41×10^{-04}	3.38×10^{-04}	6.75×10^{-04}	1.01×10^{-03}
1,968.5 (600)	1.88×10^{-05}	6.25×10^{-05}	1.50×10^{-04}	3.00×10^{-04}	4.50×10^{-04}
2,624.6 (800)	1.05×10^{-05}	3.52×10^{-05}	8.44×10^{-05}	1.69×10^{-04}	2.53×10^{-04}

Note: Assumes a shielding factor of 1 (no shielding).

Table 41 and Figure 42 show the consequences to emergency response personnel and the general public for the two hypothetical LOS events of severity Categories II and III.

Table 41. LOS Incident Consequences for Hypothetical Category II and III Events

	Total Dose (person-rem)			
	Category II		**Category III**	
Population	**Dedicated** 10-Hour Event	**Regular/Key** 16- Hour Event	**Dedicated** 10- Hour Event	**Regular/Key** 16- Hour Event
Lift	4.50E+00	1.58E+01	1.94E+01	6.77E+01
Track Repair	4.32E-02	5.76E-02	1.86E-01	2.48E-01
Fire/Police	7.04E-02	1.11E-01	3.02E-01	4.75E-01
Regulators	1.62E-01	1.78E-01	6.97E-01	7.67E-01
Crew	2.70E-04	5.29E-06	1.16E-03	2.27E-05
Escorts	5.25E-03	5.25E-03	2.26E-02	2.26E-02
General Population (Suburban)	1.30E-01	2.05E-01	5.59E-01	8.81E-01
Total	**4.9**	**16.4**	**21.2**	**70.1**

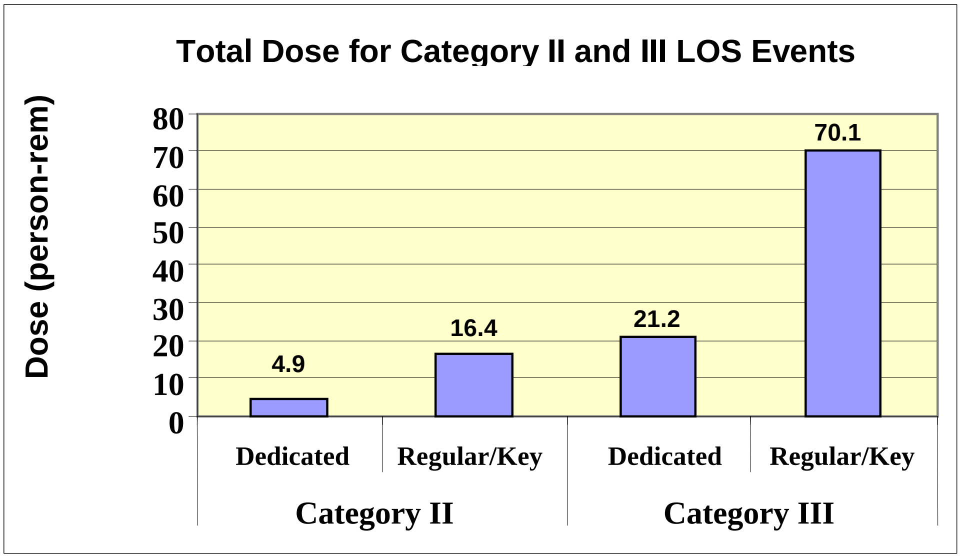

Figure 42. Total Dose for Category II and III LOS Events

Although it is difficult to predict the duration of an incident, since regular/key train service involves many more cars in the consist and the consist may contain other hazardous materials which could be involved in a fire, it is likely that an incident in regular/key train service will result in longer event durations than for the same incident in dedicated train service.

3.7.5 Comparison of Delay and LOS Incident Consequences

In addition to the LOS incidents evaluated above, elevated doses would also be experienced when SNF shipments with normal emission rate levels are delayed enroute or are involved in accidents with no LOS. This case was evaluated for situations where minor incidents or situations involving another train or piece of railroad equipment resulted in a significant delay for the cask-carrying train.

Figure 43 shows doses to crew, escorts, and the general population for a 10-hour delay event. The only distinction between train services is the crew dose, which is lower for regular/key trains due to the position of the crew relative to the cask.

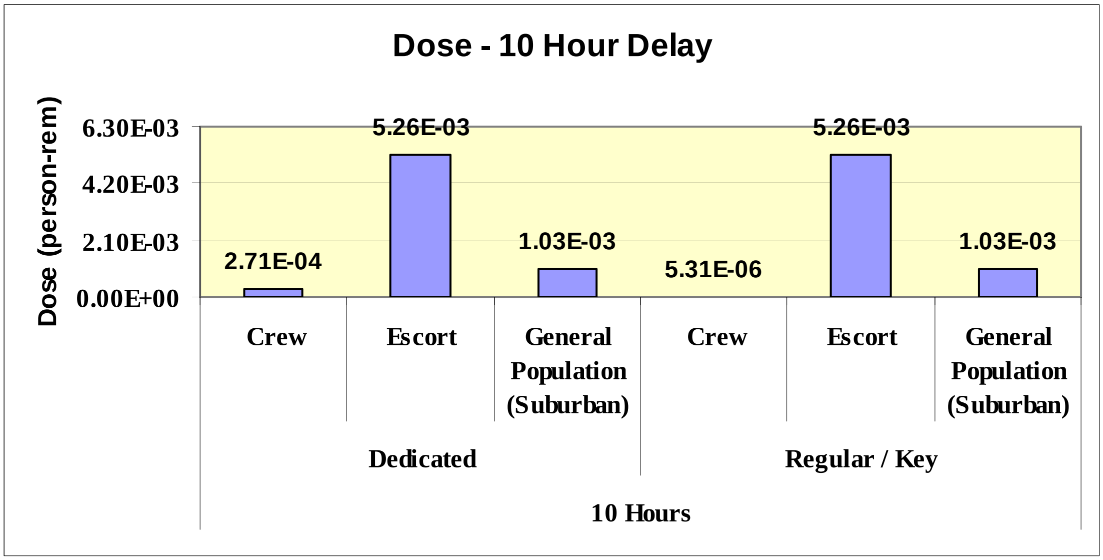

Figure 43. Dose–10-Hour Delay

Figure 44 shows the relative doses to the general population, rail crew, and escorts for a 10-hour delay event with an emission rate of 10 mrem/hr at 3.3 ft (1 m). Figure 44 also shows doses for Category II and III level LOS incidents with emission rates of 1,000 and 4,300 mrem/hr at 3.3 ft (1 m) for general population, rail workers, and emergency response personnel. This comparison assumes the level of response for the LOS incidents discussed in Tables 36, 37, and 38. The complement of workers and responders used is 9 lift personnel, 16 track repair, 34 fire/police, 18 regulators, 2 train crew, and 4 escorts. The data presented also include general population exposure.

Figure 44 illustrates the extent to which elevated emmision rates substantially increase the overall exposure. The Category II and III LOS doses are much higher than for the delay incident. All cases are considerably higher than the incident-free doses discussed in Chapter 2. Suburban incidents result in the most exposure because of the shielding factors. The relative safety of dedicated train service is based on reduced probability not consequence.

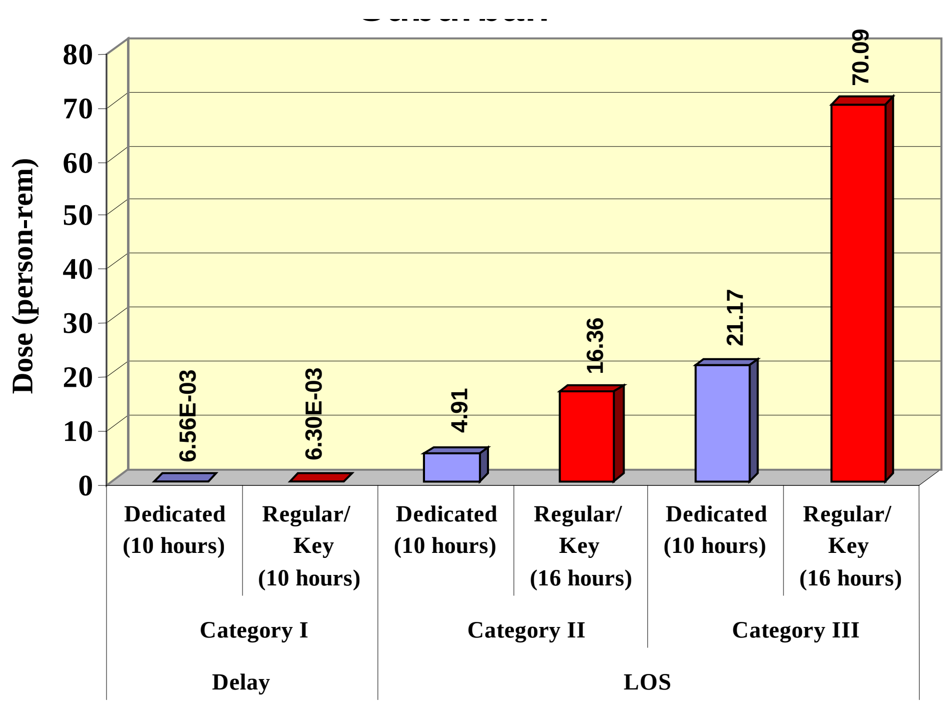

Figure 44. Total Dose for Category I, II, and III Events

The radiological consequences of three types of events summarized in Table 42 and Figure 44 are provided to show the difference in the radiation dose for accidents of varying severity.

The analyses of the severity of accidents for higher speeds and longer train lengths indicated that the duration of similar events at identical impacts were likely to differ. Emergency response and overall response time are likely to be longer when more rail cars are derailed or hazmat is present in a consist. Therefore, the consequences of these events has been scaled to reflect the typical response time for a dedicated (6-car) train versus a regular (70-car) train (see Table 42). Since exposure duration is critical in the calculation of overall consequences, the results for a shorter train in an equally severe event are lower.

Finally, the comparative risk of accident consequences for dedicated or regular/key train service is expressed as the expected number of LCFs resulting from accidents of Category I, II, and III severity. Table 42 shows the result of this comparison. The expected number of LCFs for regular/key and dedicated trains given an accident of Category I severity (10 mrem per hour) are nearly equal, 2.62×10^{-6} and 2.73×10^{-6}, respectively. For Category II (1,000 mrem per hour) and III (4,300 mrem per hour) accidents, however, the expected LCFs for dedicated trains are approximately 70 percent less than for regular/key trains, 1.98×10^{-3} versus 6.56×10^{-3} and 8.52×10^{-3} versus 2.81×10^{-2}, respectively.

Table 42. Summary of LCF Consequences–Delay/LOS Incidents

Event		Total Event Duration (hours)	Regular/Key Train: Total Dose–All Populations (person-rem)	Regular/Key Train: Predicted LCF	Dedicated Train: Total Dose–All Populations (person-rem)	Dedicated Train: Predicted LCF
Category I	Delay (No LOS) 10 mrem per hr	10	6.30×10^{-03}	2.62×10^{-06}	6.56×10^{-03}	2.73×10^{-06}
Category II	Regulatory Equivalent Impact–LOS 1,000 mrem per hr	10 Dedicated 16 Regular/Key	16.36	6.56×10^{-03}	4.91	1.98×10^{-03}
Category III	Hypothetical LOS 4,300 mrem per hr	10 Dedicated 16 Regular/Key	70.09	2.81×10^{-02}	21.17	8.52×10^{-03}
Category IV	Potential Release	Not Evaluated				

The delay event has no emergency response component.

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4. Conclusions

The report considers the risks to the general public and workers for incident-free transport and accident-related radiological exposure for regular, dedicated, and key trains.

4.1 Incident-Free Radiological Risk

The incident-free exposures calculated for regular, dedicated, and key train service are very low for the general public and other impacted populations along specific train routes. These exposures were calculated assuming that no accident of any type occurs during shipment, and the dose rate to which populations are exposed is the maximum allowable cask emission radiation (10 mrem per hour measured at 3.3 ft (1 m) from the package surface) that results during shipment. The maximum individual exposure is approximately equal to the exposure received in 2 seconds during a typical 4-hour jet flight.

The maximum expected dose to an individual in the general public for one incident-free shipment is about 4.32×10^{-04} mrem, which is four orders of magnitude below a typical exposure from a 4-hour airline flight of 3 mrem. The number of expected additional cancer fatalities from 10,000 incident-free shipments on the longest route is approximately 0.22 for regular/key trains compared to 0.18 for dedicated trains. The movement campaign to Yucca Mountain is expected to generate somewhere between 11,000 and 17,000 shipments of SNF and HLRW. The general public radiological exposure would result in less than one expected additional cancer fatality over the entire shipping campaign.

Individual crew doses for the duration of a single shipment are expected to range between 1.98×10^{-01} to 8.08×10^{-01} mrem for dedicated trains, and between 5.83×10^{-03} and 1.62×10^{-02} mrem for regular/key trains. Although the rail worker exposures and the LCFs are higher than those for the general population, the expected additional cancer rates are very low. For example, the average number of worker LCFs for Route 1 across all service types and speeds is 3.22×10^{-05} per shipment versus 1.43×10^{-05} for the general public. These numbers translate into one LCF for workers per approximately 31,073 shipments, versus one LCF per member of the public per 70,172 shipments.

Exposure time is the determining factor in the amount of radiation members of a population group receive. The exposure time was determined by train speed, whether run-through operations are allowed, and the number of stops required at yards or sidings. The speed restrictions on the dedicated and key trains increase in-transit exposure time when compared to regular trains. As seen by the results presented above, methods of shipment that minimize stop times and total transit times can minimize exposure.

4.2 Accident Analysis

An event tree analysis was used to estimate the difference in accident probability between regular, dedicated, and key trains, and the likelihood that a regular, dedicated, and key train would be involved in an extra-regulatory accident. As shown in Table 43 and Figure 45, the overall accident rate expected for all service types is about two accidents per million train miles or about one accident for every 160 trips on the longest route. Most train accidents are minor and of little consequence. Only a major accident involves enough energy to damage a cask. For the purposes of this report, accidents were broken down into four severity categories:

- *Category I* Delay event. Benign accident well below the regulatory compliance limit; dose rate assumed equivalent to the transport rate of 10 mrem/hr at 3.3 ft (1 m). Accidents in Category I result in an increased duration of exposure to certain individuals (such as crew and nearby population) due to the extended time required clearing the wreck.

- *Category II* Minor accident. An accident close to the regulatory compliance limit where some LOS or internal damage has occurred but no release. An increase in the surface dose rate occurs. The surface dose rate is assumed equal to 1 rem/hr (1,000 mrem/hr) at 3.3 ft (1 m). Accidents in Category II expose populations to higher doses of radiation for extended time periods.
- *Category III* Major accident. An accident that generates forces or temperatures that exceed the regulatory compliance limits. A greater LOS or internal damage occurs but no release of radioactive material. The surface dose rate is assumed to be equal to 4.3 rem/hr (4,300 mrem/hr) at 3.3 ft (1 m). Accidents in Category III expose populations to higher doses of radiation for extended time periods.
- *Category IV* Severe accident. An accident well in excess of the regulatory compliance limit. A significant LOS or cask damage with the release of some radioactive material occurs. This category was not analyzed.

The consequences of any of these four types of accidents are determined by the environment in which the accident occurred; the potential for a second event such as a fire following the initial impact, puncture, or fall; and the time required to respond to the accident.

4.2.1 Accident Probability

Train accidents are rare events, and operational and maintenance procedures can make them rarer.

The imposition of a speed restriction for dedicated and key trains was conservatively assumed not to reduce overall accident probability. The overall accident rate is affected by: (1) the environments in which the trains operate (yards, sidings, or mainline); (2) the duration of yard entries and whether classification activities are required; (3) whether other trains pass the cask-carrying train; and (4) how the train consist length and makeup affect its handling and derailment probability. Speed restrictions were assumed, however, to reduce the likelihood of accidents at high speeds (greater than 50 mph (80.4 km/hr)) and thus the severity of such accidents.

The estimated effect of imposing passing restrictions and shorter train consists is to reduce the overall mainline train accident rate from approximately 2.03×10^{-06} per train mile for regular and key trains to 1.96×10^{-06} per train mile for dedicated trains. Due to the reduction of time spent in yards by dedicated trains, it is assumed that there would be a larger reduction in expected accidents in yards will occur (from 1.50×10^{-05} to 3.76×10^{-06} per yard mile) compared to regular and key trains.

Table 43 illustrates that the train-to-train collision probability for regular trains overall is about 1.05×10^{-07} per train mile, and the adjusted probability (when raking collisions are reduced due to the no-pass rule) for dedicated trains is approximately 8.45×10^{-08} per train mile. The expected collision probability of key trains is equal to that of regular trains because no passing restrictions are assumed to apply to key train operations. The effect of operational restrictions and consist limitations for dedicated and key trains on Category III accident probability is illustrated in Figure and Table 43 for collisions and other types of accidents. In this figure, the relative risk contribution of each type of train service is expressed in accidents per million train miles. If regular train service is used, the probability that a train-to-train collision results in a Category III event is 4.05×10^{-10} per train mile or 0.4 accidents per billion train miles, based upon its allowable higher speeds. Since dedicated trains are assumed to operate at speeds below 50 mph (80.46 km/hr), the probability that a dedicated train will be involved in a Category III collision is 2.02×10^{-10} per train mile. The corresponding probability for key train Category III collisions is similar to dedicated trains but slightly higher, 2.03×10^{-10} per train mile, because the raking collisions are included.

Table 43. Comparison of Accident Rates for Regular, Dedicated, and Key Trains

Accident Type	Probability per Train Mile (Main and Yard)		
	Regular Train	Dedicated Train	Key Train
Mainline Accident Rate	2.03×10^{-06}	1.96×10^{-06}	2.03×10^{-06}
Train-Train Collision	1.05×10^{-07}	8.45×10^{-08}	1.05×10^{-07}
Train-Train Collision at Greater than NRC Cask Certification Equivalent Velocity (Category III)	4.05×10^{-10}	2.02×10^{-10}	2.03×10^{-10}
Derailment	1.36×10^{-06}	1.30×10^{-06}	1.36×10^{-06}
Derailment at Greater than NRC Cask Certification Equivalent Velocity (Category III)	9.52×10^{-08}	7.37×10^{-08}	7.70×10^{-08}
Highway-Rail Crossing	3.01×10^{-07}	3.01×10^{-07}	3.01×10^{-07}
Highway-Rail Crossing Impact at Greater than NRC Cask Certification Equivalent Velocity (Category III)	3.38×10^{-09}	2.74×10^{-09}	2.74×10^{-09}
Other	2.37×10^{-07}	2.37×10^{-07}	2.37×10^{-07}
Other Accidents at Greater than NRC Cask Certification Equivalent Velocity (Category III)	2.55×10^{-09}	2.07×10^{-09}	2.07×10^{-09}
Fire	3.14×10^{-08}	3.14×10^{-08}	3.14×10^{-08}
Engulfing Fire at Greater than NRC Cask Certification Compliance Duration and Intensity (Category III)	4.20×10^{-15}	4.66×10^{-16}	4.20×10^{-15}
Yard Accidents (per yard switching mile)	1.50×10^{-05}	3.76×10^{-06}	1.50×10^{-05}
Yard Accident at Greater than NRC Cask Certification Equivalent Velocity (Category III)	3.82×10^{-08}	9.54×10^{-09}	3.82×10^{-08}

The use of dedicated trains results in an overall reduction in the derailment rate (compared to regular trains) per train mile from 1.36×10^{-06} to 1.30×10^{-06} (see Table 43). Key trains are assumed to have the same derailment rate as regular trains since they are equally subject to train make-up- and handling-caused derailments.

The influence of restricting the speeds of dedicated trains is to reduce the probability that a high-speed derailment occurs resulting in a Category III accident from 9.52×10^{-08} to 7.37×10^{-08} per train mile. Key trains will have a similar, but slightly higher, probability of Category III derailments, 7.70×10^{-08} per train mile (see Figure 46), since key trains are more subject to train makeup and handling derailments than dedicated trains.

High-temperature fires are extremely rare events in railroading, but they do occur. Compared to regular trains, dedicated trains reduce the likelihood of high-temperature fires resulting from exposure to highly flammable hazardous material in the consist of the train, as well as reduce the likelihood of involvement in a fire during yard entries or classification activity in yards. Dedicated trains would reduce the likelihood that the cask might be involved in a severe, fully engulfing fire that results in a Category III event from 4.20×10^{-15} to 4.66×10^{-16} per train mile or from about once in 20 billion trips to about once in 200 billion trips on the longest route (see Figure 46). Since the specific definition of key train operations imposes no restrictions upon other allowable materials in the consist, such as flammable hazardous materials, and no explicit restrictions regarding the number or duration of yard entries (other than the normal operations of a regular train), the fire probability for a key train is assumed to be equal to that of a regular train.

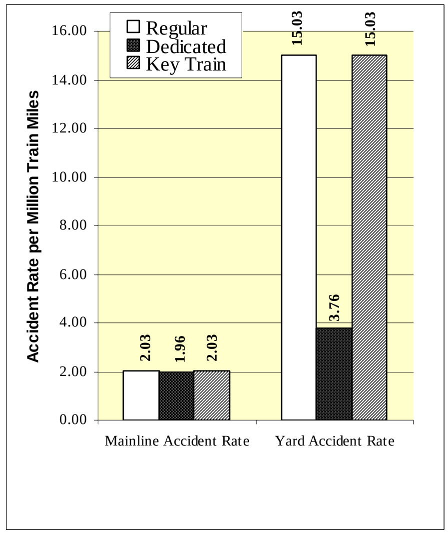

Figure 45. Comparative Risk per Million Train Miles of Regular, Dedicated, and Key Trains by Mainline and Yard Accident Rates

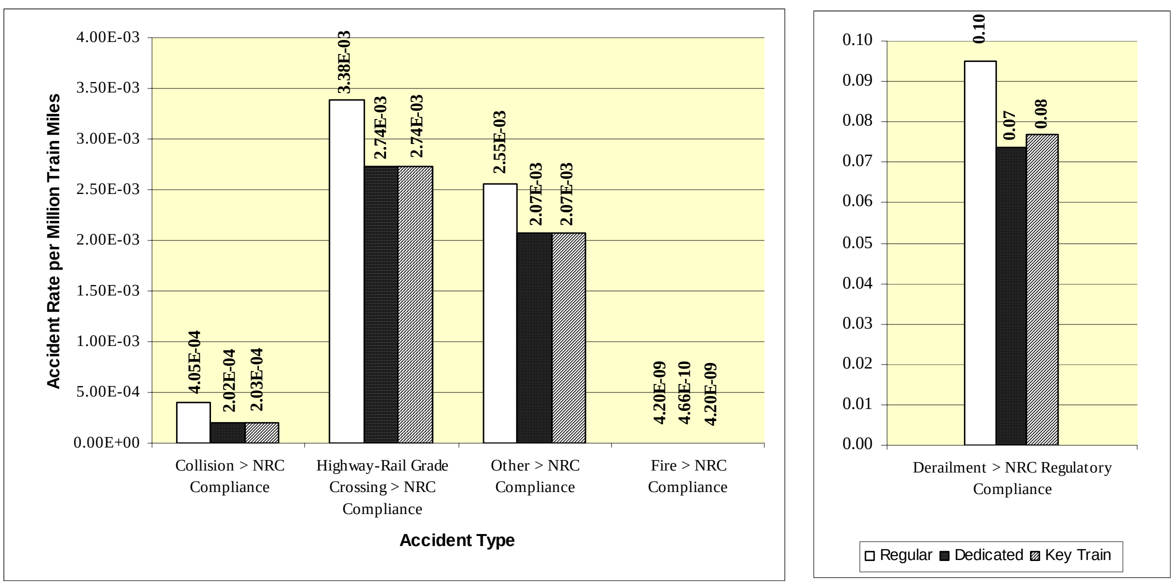

Figure 46. Comparative Risk per Million Train Miles of Regular, Dedicated, and Key Trains by Accident Type

In the case of highway crossing and other accidents (not collisions or derailments), the interventions associated with dedicated or key trains were not expected to make a difference in overall accident probability (see Table 43). The reduced speeds of dedicated and key trains, however, will reduce the probability of Category III highway grade crossing and other accidents.

4.2.2 Accident Consequences

Of the four accident categories, consequences were evaluated for the first three: incidents where a delay is caused but no elevated emission level results, and two levels of incidents where the radiation protection provided by the cask is compromised due to an accident. The report describes the likely doses to general population, workers, and emergency response personnel for a 10-hour delay incident with an emission rate of 10 mrem/hr at 3.3 ft (1 m) and for two incidents with emission rates of 1,000 and 4,300 mrem/hr at 3.3 ft (1 m) lasting between 3 and 72 hours. The probability of a Category IV accident was considered remote for any of the methods of transport considered, and the consequences would not vary with shipment choice so the case was not directly studied.

Elevated emission rates resulting from either scenario substantially increase the overall exposure. The Category II and III scenario exposures are much higher than for the delay incident. All cases are considerably higher than the incident-free exposures developed in this study. Individual doses for the 10-hour Category II accident could be 0.5 rem for dedicated trains and 1.8 rem for regular/key trains. The maximum allowable annual occupational, whole-body dose for an individual by Occupational Safety and Health Administration (OSHA) standards is 5 rem [20 CFR 1910.1096-OSHA/10 CFR 20.1201-NRC]. Since a single individual could receive a substantial portion of the annual allowable dose in the time necessary to respond to the Category III accident, it is possible that personnel time rotation, distancing, and radiation protection measures may need to be taken to limit any one individual's exposure to an acceptable level.

Using a very conservative assumption to calculate crew exposure, for each case the exposure for the dedicated train service is higher than for regular and key train service for an equal duration, due primarily to the relative location of the crew to the cask. (Although train crews do not participate in the accident response and would not stay with the train for the duration of the accident response, they may require rescue after an accident.)

Overall, the time required to resolve/remediate dedicated train incidents is expected to be substantially shorter than those required for regular or key train incidents, due to such complicating factors as length of the consist and other cargo that might be on the regular or key train. Suburban incidents result in the most exposure because of their relatively high populations and the moderate radiation shielding that wood-frame construction provides.

4.3 Summary

This study has examined the risk of radiological exposure resulting from transport of SNF and HLRW using three alternative rail shipment methods. Incident-free risk for shipment by all three methods would result in very low additional population exposures. Dedicated trains would produce lower exposures when compared to regular trains or key trains, with the exception of crew and escort doses. This is due to the assumed position of the car in the consist relative to the crews in each type of train service. These doses are very low and fall substantially below the typical dose an individual receives during a 4-hour airline flight.

The two most significant accident threats considered in the analysis are: (1) the potential for high-speed collisions and derailments that could result in a high-speed cask impact with a hard surface and (2) the potential for long duration high-temperature fires resulting from exposure to other hazmat on a train consist or in a yard. The risks associated with high-speed derailments are very small, and the likelihood of a long-duration, high-temperature fire are extremely small. Nevertheless, the speed restrictions associated with the use of dedicated and key trains is expected to reduce high-speed accident probability (compared to regular trains). Reduction of yard entries also substantially reduces the expected accident rate for dedicated trains, compared to regular or key trains.

Analysis of the location and pattern of accident occurrences indicated that it is best to evaluate each of the potential operational restrictions in light of route-specific factors that may contribute to increases (or decreases) of a particular type of risk. In this report's example, between Humboldt, CA, and Yucca Mountain, NV, the highest frequency of accidents occurred in mountainous territory and within yard limits. The use of a dedicated train could allow the railroad to avoid classification yard entries and impose restrictions, such as the no-passing rule in territory that may be operationally challenging.

Based upon analyses of the typical number of cars involved in derailments and the possibility that other hazmat may be included in the consists of regular or key trains, the duration of the incidents involving dedicated trains are likely to be much shorter than those of regular or key trains. The duration of the event determines the amount of radiological exposure to surrounding population and responders. When duration is included, the result shows that dedicated trains reduce the potential exposure when compared to regular or key trains. The expected number of LCFs for either case is very small. Given a Category II accident event (1,000 mrem per hr at 1 m), the expected number of LCFs for regular/key trains is 6.56×10^{-03} compared to 1.98×10^{-03} for dedicated trains.

The shipment of SNF and HLRW by any of the methods analyzed presents a very small risk to the general public and workers even when considering major accident scenarios (Category III). Operational restrictions can reduce the likelihood of even the rarest of events. Dedicated trains are not required to implement most of the operational restrictions described above; with the exception of elimination or reduction of classification yard entries, all other operational restrictions analyzed in this study could, potentially, be required of regular or key trains. The shipment of SNF and HLRW in trains with longer consists, however, poses other operational concerns for the railroads. On long routes where multiple stops in yards would be required, use of a dedicated train would expedite shipment and allow the carrier much more discretion in routing the train and choosing the operating speed.

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Appendix A.
AAR Circular OT-55-D - Recommended Practices for Transportation of Hazardous Materials

ASSOCIATION OF AMERICAN RAILROADS

P. G. Kinnecom
Executive Director - Tank Car Safety

August 30, 2001

CIRCULAR NO. OT-55-D

(CPC-1126)

SUBJECT: Recommended Railroad Operating Practices for Transportation of Hazardous Materials

TO MEMBERS AND PRIVATE CAR OWNERS:

Based on recommendations of the Inter-Industry Task Force on the Safe Transportation of Hazardous Materials by Rail, AAR published Circular No. OT-55 on January 4, 1990 to document recommended railroad operating practices for the transportation of hazardous materials. The circular included recommended road and yard operating practices, designation of key routes, proposed separations from hazmat storage areas, training of transportation employees, and implementation of TRANSCAER®, a national community outreach program to improve community awareness, emergency planning and incident response for the transportation of hazardous materials.

Circular No. OT-55 has been modified to revision D dated 8/23/2001 (copy attached). Circular No. OT-55-D incorporates the transportation of spent nuclear fuel and high level radioactive waste, and updates the list of PIH materials and environmentally sensitive chemicals that are subject to OT-55.

A copy of Circular No. OT-55-D, *Recommended Railroad Operating Practices for Transportation of Hazardous Materials*, is attached for your reference and use.

Sincerely,

P. G. Kinnecom

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ASSOCIATION
OF AMERICAN
RAILROADS

C. E. Dettmann
Executive Vice President
Safety and Operations

August 23, 2001

Circular No. OT-55-D
Recommended Railroad Operating Practices For Transportation of Hazardous Materials

Chief Operating Officers:

Based on recommendations of the AAR Hazardous Materials (BOE) Committee, the Safety and Operations Management Committee, on August 23, 2001, approved the following revised recommended operating practices for the transportation of hazardous materials. They are effective August 23, 2001.

Road Operating Practices

I. "Key Trains"

A. Definition: Any train with five tank car loads of Poison Inhalation Hazard (Hazard Zone A or B) or 20 car loads or intermodal portable tank loads of a combination of PIH (Hazard Zone A or B), flammable gas, Class 1.1 or 1.2 explosives, and environmentally sensitive chemicals, or one or more car loads of spent nuclear fuel (SNF) or high level radioactive waste (HLRW) shall be called a "Key Train". Attached as Appendix A is a list of PIH (Hazard zone A or B) and environmentally sensitive chemicals with 49 Hazmat Codes.

B. Restrictions:

1. Maximum speed -- "Key Train" - 50 MPH.
2. Unless siding or auxiliary track meets FRA Class 2 standards, a Key Train will hold main track at meeting or passing points, when practicable.
3. Only cars equipped with roller bearings will be allowed in a Key Train.
4. If a defect in a "Key Train" bearing is reported by a wayside detector, but a visual inspection fails to confirm evidence of a defect, the train will not exceed 30 MPH until it has passed over the next wayside detector or delivered to a terminal for a mechanical inspection. If the same car again sets off the next detector or is found to be defective, it must be set out from the train.

II. Designation of "Key Routes"

A. Definition: Any track with a combination of 10,000 car loads or intermodal portable tank loads of hazardous materials, or a combination of 4,000 car loadings of PIH (Hazard zone A or B), flammable gas, Class 1.1 or 1.2 explosives, environmentally sensitive chemicals, spent nuclear fuel (SNF) or high level radioactive waste (HLRW) over a period of one year.

B. Requirements:

1. Wayside defective bearing detectors shall be placed at a maximum of 40 miles apart on "Key Routes," or equivalent level of protection may be installed based on improvements in technology.
2. Main Track on "Key Routes" is inspected by rail defect detection and track geometry inspection cars or any equivalent level of inspection no less than two times each year; and sidings are similarly inspected no less than one time each year.
3. Any track used for meeting and passing "Key Trains" must be Class 2 or higher. If a meet or pass must occur on less than Class 2 track due to an emergency, one of the trains must be stopped before the other train passes.

III. **Yard Operating Practices**

A. Maximum reasonable efforts will be made to achieve coupling of loaded placarded tank cars at speeds not to exceed 4 MPH.

B. Loaded placarded tank cars of PIH (Hazard zone A or B) or flammable gas which are cut off in motion for coupling must be handled in not more than 2-car cuts; and cars cut off in motion to be coupled directly to a loaded placarded tank car of PIH (Hazard zone A or B) or flammable gas must also be handled on not more than 2-car cuts.

IV. **Storage**

Separation Distance for New Facilities

Loaded Tank Cars and Storage Tanks from Mainline Class II Track or Higher

Activity	PIH (Zone A or B), Class 3, Division 2.1, Division 2.2 and all other Hazard Classes	Combustible Liquids, Class 8, and Class 9
Loading and Unloading	100 FEET	50 FEET
Storage of Loaded Tank Cars	50 FEET	25 FEET
Storage in Tanks	100 FEET	50 FEET

Note 1 - With regard to existing facilities, maximum reasonable effort should be made to conform to this standard taking into consideration cost, physical and legal constraints.

Note 2 - The proposals apply to storage on railroad property and on chemical company property located close to railroad mainline.

V. **TRANSCAER®** (Transportation Community Awareness and Emergency Response Implementation of Transcaer®)

Railroads will assist in implementing TRANSCAER®, a system-wide community outreach program to improve community awareness, emergency planning and incident response for the transportation of hazardous materials. Objectives of TRANSCAER® are as follows:

- Demonstrate the continuing commitment of chemical manufacturers and transporters to the safe transportation of hazardous materials;

- Improve the relationship between manufacturers, carriers and local officials of communities through which hazardous materials are transported;
- Inform Local Emergency Planning Committees (LEPC's) about hazardous materials moving through their communities and the safeguards that are in place to protect against unintentional releases;
- Assist LEPC's in developing emergency plans to cope with hazardous materials transportation incidents;
- Assist community response organizations in preparations for responding to hazardous materials incidents.

TRANSCAER® activities are also addressed in the Distribution Code of the American Chemistry Council's Responsible Care® program. Many members have joined the Responsible Care® Partnership Program to help describe and improve their ongoing safety, health and environmental programs.

An important product of the TRANSCAER® program will be to overcome the widespread belief that every local firefighter and policeman must have the expert skills and equipment to respond personally to any hazardous materials emergency. Through the awareness training and contingency planning provided through TRANSCAER®, states and local communities will be able to pool their expertise and resources with those of industry to provide for a more coordinated and better managed emergency response system.

TRANSCAER® should be highly publicized to produce the maximum desirable enhancement of public awareness.

VI. **<u>Criteria for Shipper Notification</u>**

The railroads will initiate the shipper's emergency response system by calling CHEMTREC, or the appropriate contact telephone number as required by regulation on the shipping document, when an incident occurs involving any car (load or residue) containing a hazardous material regulated in transportation by the Department of Transportation.

An incident is defined as a rail car which is derailed and not upright, or which has sustained body or tank shell damage, or has sustained a release of any amount of product.

The shipper's emergency response system should also be initiated if the carrier believes there is reason to suspect any other potential for injury to people, property or the environment.

In the event of a major rail accident, a consist (to include shipper, consignee and commodity description for each hazardous material), waybill or equivalent document, should be provided to CHEMTREC or the appropriate shipper contact as identified by the emergency response telephone number displayed on the shipping document. This can be accomplished by facsimile or other appropriate and acceptable electronic means.

A major rail accident is defined as one resulting in fire, explosion, the potential for an explosion, fatalities, evacuation of the general public, or multiple releases of hazardous materials.

Anytime a consist or other document is provided to CHEMTREC or the appropriate contact a follow-up call by the carrier should be made to confirm the receipt of the information as well as to provide other additional information pertaining to the incident not contained in the facsimile or electronically transmitted document.

This practice does not preclude any carrier from notifying CHEMTREC or the appropriate shipper contact of a rail incident involving hazardous materials that does not meet the criteria outlined above.

VII. Time Sensitive Materials

Railroads and shippers will be responsible for monitoring the shipments (loads & residue) of products classified by the Department of Transportation as being time sensitive.

This monitoring process will, at a minimum, provide a means to ensure the movement of rail cars containing time sensitive materials in order to achieve delivery of the product within the time specified by the Department of Transportation.

As warranted, railroads will implement an internal escalation process and communicate with shippers, receivers and other rail carriers concerning any rail car containing a time sensitive product that has been delayed in transit to the extent that it may not reach destination within the time specified by the Department of Transportation. In such cases, an expedited movement of the rail car, or other action as deemed appropriate by the carrier and shipper will be taken.

Each AAR member will commit without reservation to comply with these recommendations/standards on its operations within the United States of America.

On behalf of the Safety and Operations Management Committee.

Very truly yours,

Original signed by:

C. E. Dettmann

Attachment

Supersedes Circular No. OT-55-C dated October 20, 2000.

Appendix A to
Circular OT-55-D

August 23, 2001

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Acetone cyanohydrin, stabilized	4921401
Acrolein, inhibited	4927007
Allyl alcohol	4921019
Allylamine	4921004
Allyl chloroformate	4930001/4923113
Arsenic trichloride	4923209
Boron tribromide	4932010
Bromine or Bromine solutions	4936110
Bromine trifluoride	4918507
Bromine pentafluoride	4918505
Bromoacetone	4921727
n-Butyl chloroformate	4921730
sec-Butyl chloroformate	4921207
n-Butyl isocyanate	4907415/4927027
tert-Butyl isocyanate	4907485/4927026
Chloroacetone, stabilized	4921558
Chloroacetonitrile	4921009
Chloroacetyl chloride	4931210/4923117
Chloropicrin	4921414
2-Chloroethanal	4921402
Chloropivaloyl chloride	4921746
Chlorosulfonic acid	4930204
Crotonaldehyde, stabilized	4909137/4921248
Cyclohexyl isocyanate	4921010
3, 5 Dichloro-2, 4, 6 trifluoropyridine	4921741
Diketene, inhibited	4912433/4921254
Dimethylhydrazine, symmetrical	4909352/4921251
Dimethylhydrazine, unsymmetrical	4921202
Dimethyl sulfate	4921405
Ethyl chloroformate	4921020
Ethyl chlorothioformate	4933327
Ethyldichloroarsine	4921404
Ethylene chlorohydrin	4921420
Ethylene dibromide	4921497
Ethyleneimine, inhibited	4927006
Ethyl isocyanate	4907434
Ethyl phosphonothioic dichloride, anhydrous	4921745
Ethyl phosphonous dichloride, anhydrous	4921742
Ethyl phosphorodichloridate	4921744
Hexachlorocyclopentadiene	4821722/4921722
Hydrocyanic acid solution in alcohol	4921239
Hydrocyanic acid aqueous solution or hydrogen cyanide, aqueous solutions	4921028
Hydrogen cyanide, stabilized	4927014
Iron pentacarbonyl	4927004
Isobutyl chloroformate	4921211
Isobutyl isocyanate	4907409
Isopropyl chloroformate	4907628/4921252

Isopropyl isocyanate	4909306
Methacrylonitrile, inhibited	4910370
Methanesulfonyl chloride	4921239
Methyl isothiocyanate	4907453
Methoxymethyl isocyanate	4909307
Methyl bromide and ethylene dibromide,mixture	4921438
Methyl chloroformate	4927008
Methylchloromethyl ether	4927012
Methyldichloroarsine	4921275
Methylhydrazine	4927011
Methyl iodide	4921304
Methyl isocyanate	4927009/4921487
Methyl orthosilicate	4907452/4921255
Methyl phosphonic dichloride	4921695
Methyl phosphonous dichloride	4921008
Methyl vinyl ketone, Stabilized	4927022
Nickel carbonyl	4927010
Nitric acid, red fuming	4931201
Pentaborane	4916138
Perchloromethylmercaptan	4921473
Phenylcarbylamine chloride	4921587
Phenyl isocyanate	4921216
Phenyl mercaptan	4921413
Phosphorus oxychloride	4932352
Phosphorus trichloride	4921016/4832359/ 4932359
Poisonous liquids, corrosive, n.o.s. (antimony pentachloride, arsenic trichloride)	4821269/4921269
Poisonous liquids, corrosive, n.o.s. (sulfur chloride)	4921276
Poisonous liquids, corrosive, n.o.s. (vanadium oxytrichloride and titanium tetrachloride)	4921262
Poisonous liquids, corrosive, n.o.s. (sulfur dichloride)	4921223
n-Propyl chloroformate	4921756
n-Propyl isocyanate	4907458/4927025
Sulfur Chloride	4930260
Sulfuric acid, fuming	4830030/4930030
Sulfur trioxide, inhibited	4930050/4936565
Sulfur trioxide, uninhibited	4930051
Tetranitromethane	4918180
Thiophosgene	4923298
Titanium tetrachloride	4932385
Toxic liquid, inorganic, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927020
[inhalation hazard, Packing Group I Zone B]	4921234
Toxic liquid, corrosive, inorganic, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927021
[inhalation hazard, Packing Group I Zone B]	4921237

Toxic liquid, corrosive, inorganic, n.o.s.	
(antimony pentachloride, arsenic trichloride)	4821261/4921261
Toxic liquid, corrosive, inorganic, n.o.s.	
(sulfur dichloride)	4921264
Toxic liquid, corrosive, inorganic, n.o.s.	
(sulfur chloride)	4921278
Toxic liquids, corrosive, organic, n.o.s.	
[Inhalation Hazard, Packing Group I, Zone A]	4927005
[Inhalation Hazard, Packing Group I, Zone B]	4921270
Toxic liquids, corrosive, organic, n.o.s.	
(bis(tri-chloromethyl sulfide and dimethyl formamide)	4921263
Toxic liquids, flammable, organic, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927001
[inhalation hazard, Packing Group I Zone B]	4921271
Toxic liquids, flammable, organic, n.o.s.	
(chloropicrin)	4921015
Toxic liquids, flammable, organic, n.o.s.	
(chloropicrin, dichloropropene)	4921064
Toxic liquids, flammable, organic, n.o.s.	
(methylchlorosilane, dimethylchlorosilane)	4921021
Toxic liquids, organic, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927002
[inhalation hazard, Packing Group I Zone B]	4921272
Toxic liquids, oxidizing, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927003
[inhalation hazard, Packing Group I Zone B]	4921273
Toxic liquids, water-reactive, n.o.s.	
[inhalation hazard, Packing Group I Zone A]	4927030
[inhalation hazard, Packing Group I Zone B]	4921256
Trichloroacetyl chloride	4935231
Trimethyl acetylchloride	4921063
Trimethyloxysilane	4921213
Trimethylacetyl chloride	4931745

Poisonous Inhalation Hazard Gases - Hazard Zones A & B

Arsine	4920135
Boron trifluoride	4920522
Bromine chloride	4920715
Carbonyl fluoride	4920559
Chlorine	4920523
Chlorine pentafluoride	4920189
Chlorine trifluoride	4920352
Chloropicrin and methyl bromide mixtures	4920547/4920516
Chloropicrin and methyl chloride mixtures	4920392
Compressed or liquefed gas, toxic, flammable, n.o.s	
[inhalation hazard Zone A]	4920165
[inhalation hazard Zone B]	4920396
Compressed or liquified gas, toxic, n.o.s.	
[inhalation hazard] Zone A]	4920181
[inhalation hazard] Zone B]	4920570
Compressed gas, toxic, corrosive, n.o.s.	
[inhalation hazard] Zone A]	4920102
[inhalation hazard] Zone B]	4920331
Compressed gas, toxic, flammable, corrosive, n.o.s.	
[inhalation hazard] Zone A]	4920102
[inhalation hazard] Zone B]	4920303
Compresses gas, toxic, oxydizing, corrosive, n.o.s.	
[inhalation hazard] Zone A]	4920103
[inhalation hazard] Zone B]	4920306
Compresses gas, toxic, oxydizing, n.o.s.	
[inhalation hazard] Zone A]	4920104
[inhalation hazard] Zone B]	4920337
Cyanogen chloride, inhibited	4920178
Cyanogen, liquified	4920395
Diborane	4920107
Dichlorosilane	4920398
Dinitrogen tetroxide, liquefied	4920174
Fluorine, compressed	4920180
Germane	4920354
Hexafluoroacetone	4920528
Hydrogen selenide, anhydrous	4920122
Hydrogen sulfide, liquefied	4920513
Insecticide gas, toxic, flammable, n.o.s	
[inhalation hazard Zone A]	4920116
[inhalation hazard Zone B]	4920302
Liquified gas, toxic, n.o.s.	
[inhalation hazard] Zone A]	4920195
[inhalation hazard] Zone B]	4920571
Liquefied gas, toxic, flammable, n.o.s	
[inhalation hazard Zone A]	4920164
[inhalation hazard Zone B]	4920382
Liquefied gas, toxic, corrosive, n.o.s	
[inhalation hazard Zone A]	4920105
[inhalation hazard Zone B]	4920311
Liquefied gas, toxic, flammable, corrosive, n.o.s	
[inhalation hazard Zone A]	4920108

[inhalation hazard Zone B]	4920314
Liquefied gas, toxic, oxidizing, corrosive, n.o.s	
[inhalation hazard Zone A]	4920110
[inhalation hazard Zone B]	4920312
Liquefied gas, toxic, oxidizing, n.o.s	
[inhalation hazard Zone A]	4920111
[inhalation hazard Zone B]	4920317
Methylchlorosilane	4920394
Nitric oxide	4920112
Nitric oxide and dinitrogen tetroxide mixtures	4920113
Nitrogen dioxide	4920174
Nitrogen trioxide	4920175
Oxygen difluoride	4920173
Perchloryl fluoride	4920356
Phosgene	4920184
Phosphine	4920160
Phosphorus pentafluoride	4920183
Silicon Tetrafluoride	4920357
Selenium hexafluoride	4920106
Stibine	4920167
Sulfur tetrafluoride	4920187
Tellurium hexafluoride	4920188
Trifluoroaceetylchloride	4920347
Tungsten hexafluoride	4920371

Environmentally Sensitive Chemicals

Allyl Chloride	4907412
Carbon Tetrachloride	4821831/4860106/ 4921830/4921831/ 4960115
Chlorobenzene	4909153
Chloroform	4925224/4925225 4921767/4921769
o-Dichlorobenzene	4915132/4925203
Dichloropropane (Propylene dichloride)	4909265
Dichloropropane/Dichloropropene mixture	4910234
Dichloropropene	4909255
Ethyl Chloride	4905712/4908129/ 4908162
Ethylene Dibromide (already listed as PIH)	
Ethylene Dibromide and Methyl Bromide Mixtures (already listed as PIH)	
Ethylene Dichloride	4909166/4912081/ 4908129/4910437/ 4913242/4913295/ 4921030
Epichlorohydrin	4921005
Methyl Chloroform (1,1,1 Trichloroethane)	4825182/4925182/ 4910463/4010475/ 4915969/4925310/ 4960205
Methylene Chloride (Dichloromethane)	4925131/4905764
Methylene chloride/chloroform mixture	4960150
Perchloroethylene (Tetrachlorothylene)	4825202/4910134 4840355/4925202
Perchloroethylene/Trichloroethylene mixture	4940373
Trichloroethylene	4925181

Appendix B.
Dedicated Train Workshop Notes - Stakeholder Positions

The Brown Palace
Denver, Colorado
September 28 & 29, 1992

PLEASE NOTE:

This is intended to capture salient verbal comments made during the two days of the workshop. Comments have been loosely organized by subject and so do not follow in chronological order. The name of the commenter is given in (parentheses) preceding or sometimes following the statement. Statements that are available in written form are only briefly summarized to the chairman for consideration in the study is not included herein.

DOE/OCRWM. (Mike Conroy) OCRWM shipments must move in compliance with DOT and NRC regulations (unlike the Naval Reactor shipments). The NRC-certified packages assure safe transport. DOE does not believe dedicated trains are necessary for safety, a position said to be corroborated by the findings in various court cases. DOE also points out that the Congressional Office of Technology Assessment found (in its 1986 report on hazmat transport) that the casks provide a high level of public protection and that mandated use of dedicated trains was found by the Interstate Commerce Commission (ICC) to be wasteful. Furthermore, DOE maintains that dedicated trains are not needed to meet NRC safeguard requirements. However, OCRWM will use dedicated trains where they are operationally advantageous and cost effective. Plans are to use them for MRS-to-repository shipments where DOE would have control over both origin and destination sites. DOE has been studying use of dedicated trains from the reactors as well, but they may not be possible or cost effective from all of the facilities.

Conrail. [written statement submitted] (Allan Fisher) Conrail believes dedicated trains are necessary because the railroad can:

- Plan route to avoid urban areas and use safest route
- Avoid yards
- Control schedule
- Provide better surveillance and security
- Limit accident forces on cask by limiting speed
- Better control speed and braking, buff and draft forces
- Control other trains being met or passed
- Provide for emergency response more quickly
- Reduce the chance that the cask will be involved in a fire

Union Pacific. [written statement submitted] (Leo Tierney) “It is UP’s strong position that dedicated trains are essential for the movement of these radioactive materials in order to satisfy all the operational and safety considerations surrounding these shipments.” The 35 mph restriction on DOD SNF shipments has a negative impact on the safety of train operations. It is not feasible to use slow, local trains to provide the service. UP must put cask cars on manifest or secondary trains which must be slowed to 35 mph. This disrupts operations and increases risk (in addition to increasing cost and having service impacts). As shown in the TMI campaign, dedicated trains have the following safety advantages: less handling and switching, less likelihood of equipment failure including derailment, safer train handling, easier to meet surveillance requirements, and eliminates potential exposure to hazmat in accident.

Southern Pacific. [written statement submitted] (John Smith and Ken Moore) SP believes that dedicated trains are required for the DOD SNF shipments “for maximum security and risk reduction.” Like UP, SP “does not hold itself out to offer 35 mph service.” That speed restriction makes for a slow transit in regular service with much time sitting, often in exposed locations. This makes the cask car an easier target for terrorists and obstructionists. Security is further impaired by the anonymity (e.g., secrecy and lack of placarding) with which these moves take place. SP is also concerned about the risk to the cask of placing it in the same train with flammables, explosives and other hazmat. Furthermore, the DOD requirement that the heavy cask car be placed at the end of the train creates track/train dynamics that increase the likelihood of derailment, especially for long regular trains, as evidenced in ongoing analyses.

Utilities/ Edison Electric Institute. (John Vincent) Uncertain of the safety improvement of dedicated trains.

States.

(Don Howell- ID) A state’s attitude is a function of whether it is a generating state (of SNF), a repository state, or a transit state.

(Max Power- WA) Outreach is important. Advance planning needs to be done, in part to assure better preparedness. (State) control over the shipping activity is important and there should be no surprises (for state officials). They need to know the what, when, where about each shipment. Placarding is important.

(Bob Halstead- NV) Low risk is not the same as no risk. Risks are higher with regular freight service. Minimize the number of shipments through the use of dedicated trains and use the AAR guidelines for their operations, in general.

“Most people” assume that if there were an MRS, DOE would use dedicated trains (3 casks each) from the reactor sites as well as between MRS and repository.

To maintain the nuclear power option, shippers should be willing to take (safety) measures. Utilities behave more this way than DOE. Dedicated trains would address some of the public concerns.

National Conference of State Legislature (NCSL). (Senator Hickey, Chairman of the Task Force on High-Level Radioactive Waste/Hazardous Materials Transportation) NCSL supports the use of dedicated trains. In its position statement, NCSL recommends that DOE “utilize to the maximum extent unit or dedicated trains for spent fuel shipments to enhance safety and to increase public acceptability.” States need to have a direct relationship with railroads regarding RAM transportation, much like that they have with motor carriers now. Concerns over emergency response are substantiated by the recent Springfield, Massachusetts incident as documented in NTSB report. Also, there are concerns over the safety of mixed trains (compared to dedicated trains) due to (1) lower reliability of braking systems, given the mix of “foreign” cars, (2) potential for terrorist acts, and (3) the use of 2-man crews. The effect of crew reductions have yet to show up in train safety data due to the short time since this practice became developed.

Additional Recommended Safety Measures

The qualitative assessment performed by workshop participants also identified four safety measures that have notable potential for enhancing safety.

1. *Maintain a fixed train set.* This ensures that the train equipment is, at all times, of appropriate quality and type. Also, the reliability of the braking system is improved since no "foreign" cars are used and (de) coupling is eliminated. Dedicated trains are a decided advantage because the consist would normally be fixed, with only the locomotive(s) switched between railroads. A fixed train set or consist, other than the cask car block, is not practical with regular service.

2. *Ensure the use of appropriate, safe equipment.* In recent years, about 15% of all accidents have been due to equipment failures.[1] Therefore, it is important that all equipment in the train be reliable. In particular, buffer cars should be good quality, heavy, low-profile cars; in the past, railroads have often supplied poor, non-revenue cars as buffers. Operating a fixed cask car block helps. Employing a fixed train set plus frequent inspections ensure that the entire (dedicated) train is made of appropriate, reliable equipment.

3. *Enhance crew competency.* About 1/3 of all accidents are caused by "human factors."[2] Such accidents might be reduced by cutting duty hours and increasing the size of the crew (unfortunately, the latter would also increase total crew exposure). It has also been suggested that crews for cask trains could be specially trained and hand-picked. However, labor contracts and work rules limit what can be done, even with a dedicated train.

4. *Increase awareness of shipments and safety measures taken.* Public officials contend that the more that the public is aware of shipping campaigns, safety measures taken, and the timing of the shipments themselves, the safer the operation becomes. Demand for counterproductive (i.e., hazardous) measures such as the use of chase cars, is reduced. Unnecessary evacuations may be avoided along with other improper emergency response actions. Occurrence of demonstrations and related actions may be diminished.[3] Advantages for dedicated trains are the enhanced visibility and precision of their movements and the greater number of safety measures that are being taken.

Other Findings

Most of the 25 safety measures were found by the Denver September 1992 study team to offer little or no potential for safety enhancement by virtue of using dedicated trains. Either they were judged to be relatively ineffective and/or they could be implemented nearly as well with regular train service.

Interestingly, a net decrease in safety was found for implementing two of the 25 measures. In one case, counterproductive aspects were thought to outweigh the benefits and, in the other, regular trains were found to have the advantage:

1. *Passing Restrictions.* Requiring one of two passing trains to stand (stop) was thought to be potentially counterproductive. Benefits of the passing restriction included a reduction in the

[1] Of the 2785 accidents reported to FRA in 1993, 13% were due to mechanical and electrical failures of locomotives and cars (Ref. 32, FRA).

[2] In 1993, 31% of all reported accidents were attributed to "train operation – human factors" Ref. 32, FRA).

[3] Some shippers contend that awareness may only breed unreasonable demands for more "safety" measures and obstructionist activities, and may degrade security.

likelihood and severity of raking accidents as well as elimination of the chance of involvement with derailments of the train on the adjacent track during passing. However, these benefits are probably outweighed by the hazards associated with the considerable disruption of rail traffic, especially the braking of following trains.[4]

2. *Cask Car Placement.* Constraining the location of the cask car in the consist was found to be a potentially effective means of reducing the chance that the cask would be damaged in an accident. Radiological dosage to onboard personnel can be lessened as well. The advantage, however, lies with regular trains. Short dedicated trains offer little opportunity to use placement of the cask car in the consist as a means of cutting risk.

Results of the Qualitative Analysis

In summary, the qualitative analysis of 23 safety measures associated with dedicated trains showed that some appear to have the potential to significantly improve safety, but most do not. Run-through operation benefits. Both incident-free and accident-induced radiological risk for such operations should be relatively low. However, the former can be estimated more accurately because it is directly related to transit time, an easily measured variable. Transit time should be 20-40% of that for regular trains; radiological exposure should be similarly lower.[5] In addition to this certain enhancement of safety, the accident-related risk should be less, though it is difficult to determine this quantitatively with any confidence; accident rates and release probabilities for dedicated trains are largely a matter of conjecture. Nonetheless, there are important factors that suggest a much lower accident rate. Run-through operations do not enter classification yards, the site of nearly half of all accidents (albeit low-speed ones). The short, fixed consist is safer to operate: derailments due to equipment failures and track-train dynamics would be far fewer, train controls would be simpler and safer, and the braking system more reliable. However, should an accident occur, the short train may or may not have an advantage. Lower kinetic energy would mean lower accident forces (and release probabilities) and the absence of flammable and explosives in the dedicated consist reduces that hazard. However, the train's short length would increase the chance that the cask would be impacted in front or rear collisions.

The qualitative analysis also indicated that operational restrictions may not be warranted.

Accident Rates – Insight from "Key Train" Operations

Accident rate data (accidents per million train-miles) is not available for dedicated trains because information on accidents and train-miles is not kept by type of train. However, some indication of what that accident rate might be can be gleaned from recent experience with "key trains," for which some data was obtained for this study. In 1990, the AAR published a circular entitled, *Recommended Railroad Operating Practices for Transportation of Hazardous Materials.* That publication defines "key trains" as those trains that would receive special treatment because of the particularly hazardous nature of their cargo. Among other restrictions, AAR recommends that key trains be limited to 50 mph (80.4 km/hr), that no cars with friction bearings be allowed in the consist, and that they remain on the main track at meets and passes.

[4] Detailed simulations of railroad operations incorporating hazard probabilities would be necessary to verify this subjective conclusion.

[5] There are, of course, other factors. Dose levels for the train crew would be higher for the shorter train, for example. On the other hand, workers in yards would not be exposed in run-through operations.

Data for key trains operated by Union Pacific were analyzed to see if trains that are made up and operated in ways intended to improve safety actually experience lower accident rates. Over the past three years, UP has operated from two to five daily trains that were permanently designated as "key trains."[6] In addition to the restriction AAR recommends, Union Pacific generally limits the length of designated key trains to 100 cars or 6,000 feet. Information on key trains was obtained from Union Pacific: accidents reported to the FRA, number of trains run annually, and train-miles operated. For 1990-1992, UP operated 4,368 key trains a total of 2.4 million train-miles.

For the two years for which comparable data on UP's other train operations are available (1990-1991), the train accident rate for designated key trains averaged 2.2 per million train-mile vs. 7.1 for the Union Pacific as a whole. A statistical analysis of these data found that, despite the relatively small size of the database, there was nearly a 99% probability that key trains actually did have a lower accident rate during that period.[7]

Examination of the eight accidents reported for designated key trains (1990-1992) indicates that half of them would not have happened to a dedicated train and that one quarter would have been less likely. Three accidents occurred during activities in which dedicated trains do not engage, namely, yard operations and setting out and picking up cars along the mainline. A fourth inapplicable accident was caused by exceeding a 30 mph restriction for a bridge crane car that was part of the key train consist. Two of the accidents, though applicable to dedicated trains, would be less likely due to shorter train length. One of these, a serious release of hazardous materials, was caused by a journal failure on one of 72 cars in the train. The shorter dedicated train would experience proportionally fewer journal failures per million train-miles. In another accident, a broken switch point caused the last car of a 126-car train to derail. Assuming this was a random event that could affect any car in a train, a short dedicated train would be less likely to experience such a derailment accident because it has fewer cars. Two accidents, one at a grade crossing and another during delivery of cars on a poor industrial track, were judged to be as likely to occur to a dedicated train as to a key train.

Setting aside the four accidents that would not be applicable to dedicated trains and scaling the probabilities for the two accidents that are a function of consist size yields a rate of slightly less than 1 accident per million train-miles. This compares with a rate of 3.3 for UP's key trains (1990-1992), an overall average for UP of 6.7 (1986-1991), and a national average of 4.9 accidents per million miles over the years 1986-1991. While this suggest that dedicated trains would have a substantially lower accident rate than regular trains, it would not be appropriate to use these results in a quantitative analysis. First, substantial differences remain between key trains and dedicated trains even after adjusting the accident history. Second, the sample size is small – there were only eight accidents in the key train data set.

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[6] The railroad also operates other key trains when circumstances warrant. However, only data on the permanently designated key trains could be made available.

[7] The size of the data set for key trains is small in light of the low frequency of train accidents. Consequently, large year-to-year fluctuation can be expected, as happened from 1991 to 1992 (from 2 to 4 accidents despite a significant decline in train-miles). More observations from other key train operations and/or over a longer period are needed to generalize these findings with appropriate levels of confidence.

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Appendix C.
Reported Incidents Involving Spent Nuclear Fuel Shipments 1949 to 2002

This appendix includes a summary of incidents involving spent nuclear fuel (SNF) shipments by rail and truck from 1949 through September 30, 2002. In reviewing this history, it is important to consider the changes in hazardous material transportation regulations and packaging requirements in particular. The incidents listed below cover a wide period of time during which packaging requirements were continuously refined. In the early 1950s, the Interstate Commerce Commission (ICC) first established radioactive material regulations limiting the radiation levels that emanate from packages to protect radiation-sensitive cargo. In l96l, the International Atomic Energy Agency (IAEA) adopted radioactive material transportation regulations (standards) based largely on those of the ICC. In 1973, revisions to IAEA standards introduced the concepts for Type B packages, to determine the extent to which each country must approve a package design when an international shipment is involved. In 1983, the U.S. Department of Transportation (DOT) and the Nuclear Regulatory Commission (NRC) adopted regulations, which essentially brought them into conformance with the 1973 edition of the IAEA requirements.

There have been 72 reported incidents involving SNF shipments by rail and truck from 1949 to September 30, 2002:

- From 1949 to 1970, 14 incidents were reported in a series of U.S. Atomic Energy Commission reports. They included six transportation-related accidents, three truck and three rail, none resulting in a release of radiation. The incidents also included eight non-transportation incidents (e.g., leakage of cask, contamination during loading/offloading) that resulted in small amounts of observed contamination.
- From 1971 to September 30, 2002, 58 incidents have been reported in the Radioactive Material Incident Report database operated by Sandia National Laboratories. They included seven transportation-related accidents, four truck and three rail, none resulting in a release of radiation. The incidents also included 51 non-transportation incidents, 49 of which resulted in small amounts of observed contamination.

The 72 incidents can be characterized as follows:

- 59 non-transportation incidents (e.g., leakage of cask, contamination during loading/offloading):
  - 4 incidents of accidental radioactive contamination beyond the vehicle
  - 4 incidents of accidental radioactive contamination confined to the vehicle
  - 49 incidents of accidental surface contamination
  - 2 other incidents without additional descriptive material
- 13 transportation-related incidents:
  - 7 truck incidents resulting in no release or contamination
  - 6 train incidents resulting in no release or contamination

Eight incidents of radioactive material contamination, which were discovered during shipping (between 1960-1984), involved leaks of water, liquid, or (reported as) coolant/moderator from casks. Description of the events and equipment are insufficient to evaluate the failure mechanisms or sources of contamination. The abbreviated information provided, however, seems to indicate contributing factors may include the absence of regulations for the design and use of transport casks, inadequate procedures, or not following the procedures.

Table C-1 describes each of the 72 incidents in more detail.

Table C-1. Reported Incidents Involving SNF Shipments 1949 to September 30, 2002 (72 incidents by type)

Date	Mode	Incident Description
Radioactive material contamination beyond the vehicle (4 of 72 incidents):		
6/2/60	Rail	Leak from cask, small areas at three rail yards contaminated, no runoff or aerial dispersion.
8/21/62	Truck	Cask leakage, trailer, and small portion of road contaminated.
11/11/64	Truck	Cask leakage, trailer, packages, and terminal contaminated.
1/27/84	Truck	Slow drip from bottom front end of empty cask while stored in transportation terminal.
Radioactive material contamination confined to vehicle (4 of 72 incidents):		
11/20/60	Truck	Small leak from cask onto trailer floor, result of shifting cask; contamination confined to vehicle.
9/22/61	Truck	Leak from cask onto trailer floor, result of shifting; contamination confined to vehicle.
12/10/63	Rail	Cask leakage, cask contaminated, contamination confined to trailer.
7/4/76	Truck	Pinhole leak, reported as coolant/moderator on outside jacket of cask. Shipment continued without risk to public.
Transportation accident with no release or contamination (13 of 72 incidents):		
12/1/56	Truck	Slid off icy road and overturned, two casks, one fell off trailer; no damage, no release.
1/29/57	Rail	Uncoupling, damage from debris; no release.
4/15/60	Truck	Trailer unhitched from tractor at 5 mph; no release.
11/15/60	Truck	Truck jackknifed; struck station wagon; no release.
12/7/60	Rail	Engine backed into cask car on siding; no release.
7/14/61	Rail	Minor derailment at 10-12 mph; no release.
12/8/71	Truck	Truck left road and cask thrown off; no release.
3/29/74	Rail	Derailed tank car struck cask car in yard, empty cask; no release.
2/9/78	Truck	Trailer buckled from weight; no release.
8/13/78	Truck	Empty cask broke through trailer bed; no release.
12/9/83	Truck	Tractor separated from intermediate set of axles, remained connected to trailer; no release.
3/24/87	Rail	Train struck automobile at rail crossing; no release.
1/9/88	Rail	One set of rail car wheels derailed when switching tracks, empty cask; no release.
Surface contamination (49 of 72 incidents):		
1/24/74	Truck	Surface contamination on shipping pallet.
2/26/74	Truck	Surface contamination on pallet and truck, empty cask.
4/29/74	Truck	Surface contamination on pallet.
12/11/74	Truck	Surface contamination on pallet.
12/23/74	Truck	Surface contamination on pallet.
1/13/75	Truck	Surface contamination on cask.
2/27/77	Truck	Surface contamination on lifting yoke, empty cask.
4/13/77	Truck	Surface contamination on trailer, empty cask.
5/3/77	Truck	Surface contamination on empty cask.
5/12/77	Truck	Surface contamination on empty cask.
5/16/77	Truck	Surface contamination caused by small crack in impact limiter.
7/26/77	Truck	Surface contamination on empty cask.
8/3/77	Truck	Surface contamination.
8/23/77	Truck	Surface contamination on cask.
2/16/78	Truck	Surface contamination caused by open drain valve, empty cask.
2/27/78	Truck	Surface contamination on empty cask.

5/16/78	Truck	Surface contamination on empty cask.
7/24/78	Truck	Surface contamination on empty cask.
7/29/78	Truck	Surface contamination on cask.
8/1/78	Truck	Surface contamination on cask.
8/7/78	Truck	Surface contamination on cask.
11/27/78	Rail	Surface contamination on empty cask, yoke, and rail car caused by defective valve or closure.
3/28/79	Truck	Surface contamination on empty cask and trailer.
4/2/79	Truck	Surface contamination on cask.
4/2/79	Truck	Surface contamination on empty cask.
4/3/79	Truck	Surface contamination on tire chains, hold-down chains, and tighteners caused by loading or unloading cask from trailer.
4/4/79	Truck	Surface contamination on empty cask.
4/5/79	Truck	Surface contamination on trailer, empty cask.
7/23/80	Truck	Surface contamination on empty cask.
8/25/80	Truck	Surface contamination on cask.
2/2/81	Truck	Surface contamination on empty cask and trailer.
5/30/81	Truck	Surface contamination on cask and trailer.
5/31/81	Truck	Surface contamination on empty cask.
6/2/81	Truck	Surface contamination on cask. Third consecutive instance of surface contamination. NRC suspends further shipments.
8/25/83	Truck	Surface contamination on empty cask.
9/30/83	Truck	Surface contamination on empty cask.
10/21/83	Truck	Surface contamination on empty cask.
1/7/84	Truck	Surface contamination on empty cask.
1/25/84	Truck	Surface contamination on empty cask.
2/24/84	Truck	Surface contamination on cask.
1/11/85	Truck	Surface contamination on trailer; empty cask.
2/3/85	Truck	Surface contamination on cask.
7/8/85	Truck	Surface contamination on empty cask.
2/28/86	Truck	Surface contamination on empty cask.
7/29/86	Truck	Surface contamination on cask.
7/29/86	Truck	Surface contamination on empty cask and trailer.
8/19/86	Truck	Surface contamination on cask.
10/15/91	Truck	Surface contamination on empty cask.
8/14/92	Truck	Surface contamination on cask.
Unknown (2 of 72 Incidents):		
1965-1967	One incident, details not available.	
1968-1970	One incident, details not available.	

Definitions for release and contamination as used in transport accident or event reports:

RELEASE An official definition for release from a cask is not found in NRC's 10 CFR 71.4, *Definitions*. An NRC definition of release as it pertains to transportation, however, can be inferred from 10 CFR 71 as follows:

> [10 CFR 71.4, *Definitions*] "Containment System means the components of a packaging intended to retain the radioactive material during transport."
>
> [10 CFR 71.5 1, *Additional requirements for Type B packages*] Paragraph (a)(1) prohibits loss or dispersal of radioactive contents for normal condition of transport. Paragraph (a)(2) restricts escape of krypton or other radioactive materials for hypothetical accident

conditions. Finally, the word “release” is used in paragraph (b) which states: “Compliance with the permitted activity release limits of paragraph (a) of this section must not depend upon filters or upon a mechanical cooling system.”

From the above 10 CFR 71 material the authors can develop a definition that is consistent with NRC’s rules and regulations. Release means loss, dispersal, or escape of radioactive material from the package’s containment system.

CONTAMINATION 10 CFR 71.87(l)(1) and (1)(2), routine determinations refers to non-fixed (removable) radioactive contamination on external surfaces. These paragraphs prescribe specific limits for transport of radioactive materials. A formal definition, however, is not provided.

Although the NRC’s regulations do not provide a definition for contamination in 10 CFR 71, a definition is provided in NUREG-0770 (U.S. Nuclear Regulatory Commission, Glossary of Terms Nuclear Power and radiation, NUREG-0770, Washington, DC 20555, June 1981). Contamination is defined as “the deposition of unwanted radioactive material on the surface of structures, areas objects, or personnel.”

Appendix D.
Route-Specific Analysis

An example using Geographic Information System (GIS) data for one route identified major features and risk exposure:

In most of the analyses in this appendix, data are aggregate. As in Chapter 2, this analysis focuses on presenting information at a route-specific level for several reasons. First, analyses of this sort generally focus on route-specific risk, and for comparability to similar studies (such as NUREG 6672) presentation of this type of information is valuable. Second, the true effect of operational restrictions can be most easily illustrated by looking at route-specific risks. Finally, it enables the quantification of the accident probability impacts for the route in the same form with which non-accident risk is evaluated. Several inputs were used to conduct this route specific risk analysis:

- Identification of a rail route that conforms to the U.S. Department of Energy preferred routing (using their rail route selection criteria specified in INTERLINE).
- Identification of risk factors for that route including:
    - Yards
    - Accident locations
    - Bridges
    - Surface hardness
    - Local topography

To address route-specific risk in the accident analysis, one route was selected for further detailed analysis. The Humboldt, CA, to Yucca Mountain, NV, route was used to illustrate how risk may be concentrated in specific environments, as well as what the effect of train speed and operational restrictions may be on the likelihood of accident involvement.

Available data are incomplete and insufficient to fully characterize release probability (using surface hardness or topography) for the Humboldt route. Figure D-1 and Figure D-2 illustrate the percent of the total route area that could be characterized with available data from the U.S. Geological Survey (USGS) on surface hardness in the vicinity of the track and surface contour. The location of railroad bridges, yards, and the proximity of accidents to these environments, however, illustrates that risk is not evenly distributed throughout this route, therefore leading to the hypothesis that a uniform accident rate per route mile may be inappropriate for evaluating shipment routes.

An examination of the Humboldt route allowed the researchers to characterize the position of several track features (including switches, signals, yards, bridges, and stations) to characterize the slope and environment adjacent to the track for about 10 percent of the route and describe the surface hardness in that area. Using the milepost location reported in the accident reports in Railroad Accident/Incident Reporting System (RAIRS), 232 accidents were assigned on the route. These represent (232/11,485) 0.2 percent of the mainline accidents during the time period.

The California route represents approximately 1,000 rail route miles from Humboldt, CA, to Yucca Mountain, NV (although complete rail access to Yucca is not available at this time) [DOE, 2000]. Traffic density on this route varies from approximately 40 to 149 million gross tons per year. The route includes about 700 of the State's 3,300 public grade crossings.

Of the 232 accidents that were assigned to the route based upon the RAIRS accident record, 131 occurred within 262 miles of one another (see Figure D-1). This mileage amount reflects approximately 26 percent of the total rail route miles, but the accidents represent 65 percent of the total assigned to locations on this route.

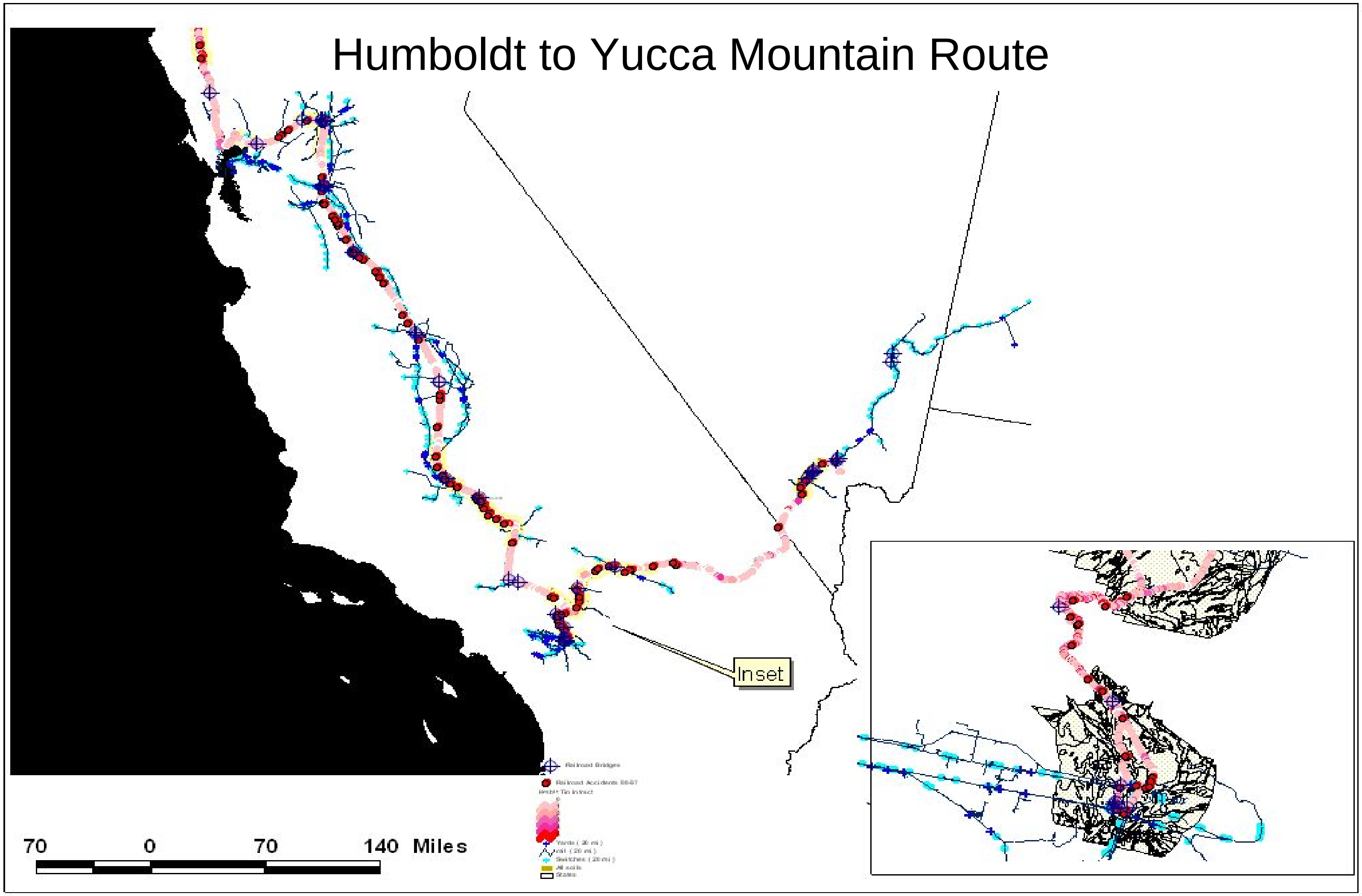

Figure D-1. Humboldt to Yucca Mountain Route–All Features

Humboldt Route Detail Soil and Contour Data Included

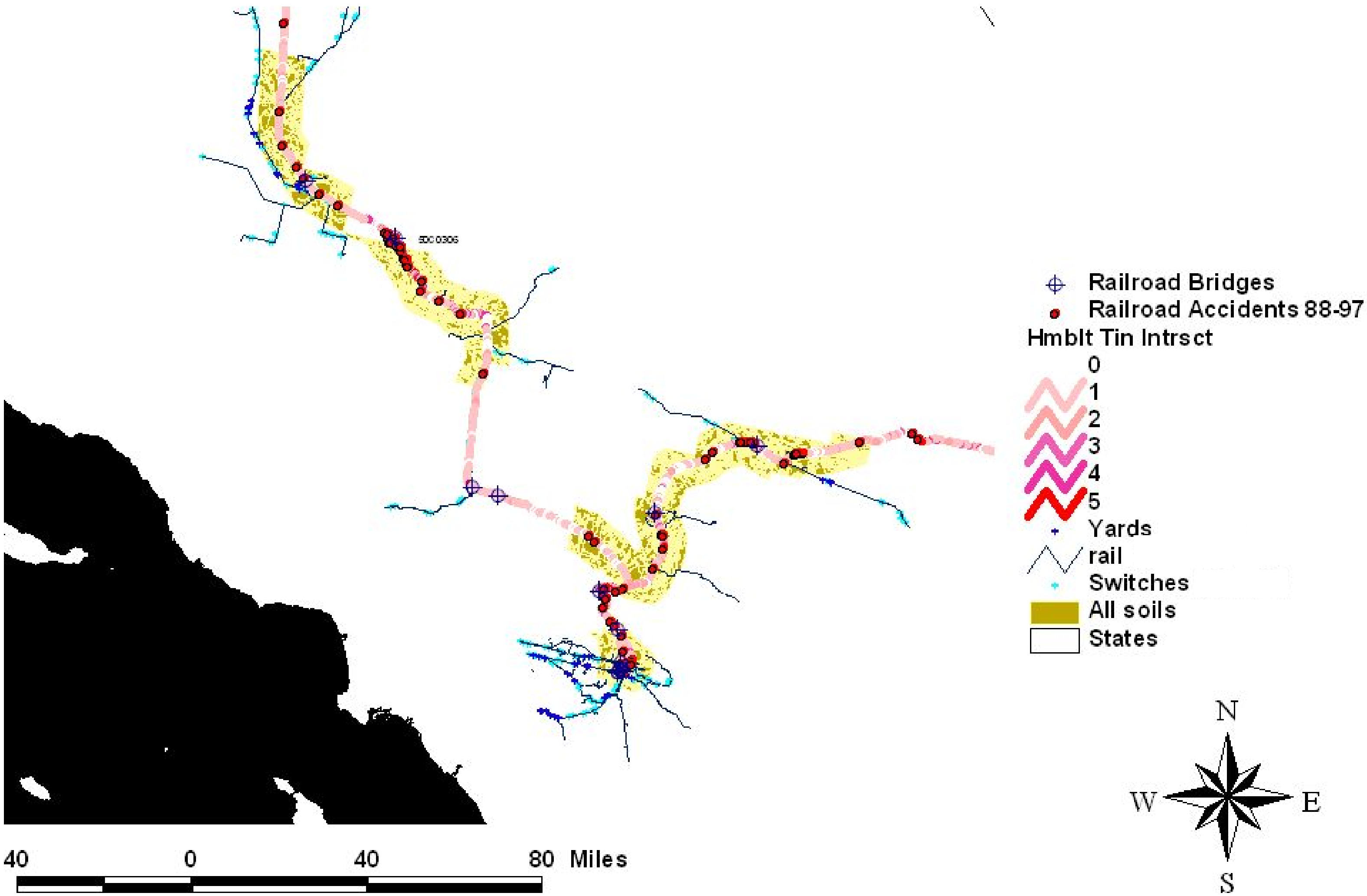

Figure D-2. Humboldt Route Detail–Soil Hardness and Contour Data Coverage

Characterization for Surface Hardness

An examination of the environmental characteristics of the Humboldt route included an estimate of the slope of the ground in the immediate vicinity of the track and the surface hardness of that environment based upon soil usage data.

Slope data was assigned to a significant portion of the route (see Figure D-2). Slope categories were defined based upon the percent of grade change in the area and assigned to a value 1-5 with 1 being the least slope. Figure D-2 illustrates that a significant portion of the accidents that occurred in the southern portion of the Humboldt route occurred in the vicinity of the highest category of slope. In addition, many of these accidents occurred in close proximity to bridges and yards.

Railroad Bridges

Table D-1 shows the California/Humboldt route bridge numbers and clearances.

Table D-1. California Railroad Bridges

	Total Route Miles	Number of Railroad Bridges	Clearance Average	Clearance Maximum	Bridges per Route Miles
State of California	6393	729	16.4 feet (5 meters)	98.4 feet (30 meters)	11.5
Humboldt Route	801	346	9.8 feet (3 meters)	18.0 feet (5.5 meters)	43

Bridge Derailments

Probability of Cask Car Involvement Given Bridge Derailment

During the analysis period, 245 bridge-related accidents were identified. Using this gross-level data, the national probability that a derailment occurs on a bridge is 245/24,380 or 0.01. (One of those accidents occurred on the Humboldt route.)

A complete characterization of bridge heights and clearances was obtained for Route 4 in the study. Figure D-3 shows the distribution of bridge heights for the River Bend, LA to Yucca Mountain, NV route. Only 84 of the 1,332 railroad bridges listed by the Union Pacific Railroad for this route exceed a 30-ft (9.1-m) height, yielding a probability of encountering a bridge high enough to result in an equivalent drop to the U.S. Nuclear Regulatory Commission (NRC) compliance level of 84/1332 or 0.063. Multiplied by the probability per mile of encountering a bridge, 0.01, the probability of encountering a bridge over 30 ft (9.1 m) is equal to 0.00063.

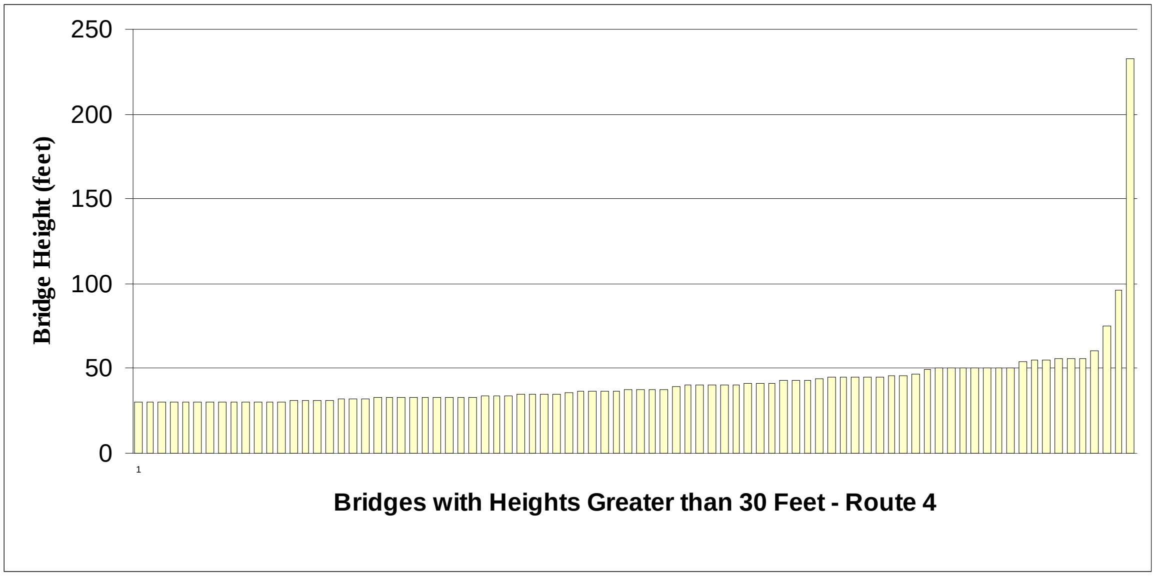

Figure D-3. Bridge Maximum Height–Route 4

Derailments at bridges that may result in the cask car (or other cars in the consist) derailing and falling from a significant height is of concern, particularly since drops of greater than 30 ft (9.1 m) may exceed the impact velocity threshold defined by the NRC's compliance tests. Few of these bridges, however, span environments that can be described as unyielding surfaces.

For the purposes of this study, the issue of bridge heights and their potential hazard is limited to whether or not the dedicated train is more or less likely to be at risk crossing bridges than would be a regular train. To address this issue, the question of whether the position of the car in the consist (either in the front, the rear, or some other position) affected the likelihood of derailment was examined. It was thought that since, in the dedicated train, the cask car will be very near the front of the consist, and, in a regular or key train, it might be entrained toward the end of the train, the dedicated train risk might differ from a regular or key train. Figure D-4 illustrates the results. Based upon an analysis of the position of the first derailing car in bridge accidents, it was found that no one car position is more likely to be involved in the derailment at a bridge than any other. This figure plots the frequency of derailments in which the first car in the train was the first derailing car in a bridge derailment, second car, third car, and so on. The graph illustrates that the first derailing car is most often the locomotive, followed, in frequency, by the 9th car. However, the 3rd through 8th cars have nearly the same probability of being the first involved car. Since the probability that the cask will derail at the 5th car position as the first derailing car therefore sustaining the greatest impact after a fall, is equal for the 5th car position and the 29th car position, and only slightly different thereafter, no additional analyses of this factor in distinguishing regular and dedicated train risk was undertaken.

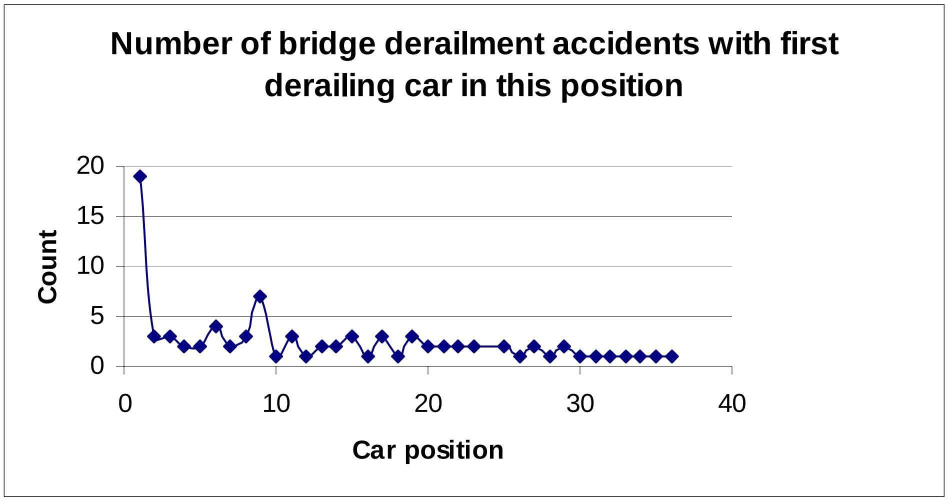

Figure D-4. Bridge Derailment Distribution

Conclusions from analysis of the Humboldt route are:

1. Most derailment risk is centered near yards (even on the mainline) and in the vicinity of features, such as switches or bridges.
2. Application of speed limits and operational restrictions would reduce the probability that high-speed derailments with high potential damage to the cask would occur.
3. Due to the proximity of yards to population centers along the route, reduction of yard visits would also reduce the probability that low consequence accidents (such as delays resulting from a low-speed derailment) could affect the surrounding population.

Appendix E.
Rail Transport of High-Level Radioactive Material

Shipping Patterns and Amounts: Past, Present, and Future

Compared with other hazardous materials, the shipping patterns for radioactive material (RAM) are relatively simple because a limited number of origins and destinations exist. Commercial shipments of spent fuel principally originate at the nuclear power reactors operated by utilities; some shipments are also from university and other research reactors. To date, most of these shipments were made because Spent Nuclear Fuel (SNF) storage pools at the reactor sites were at or near capacity. For the near term, reracking to increase pool capacity and the use of dry storage techniques will reduce the need for SNF transport from power plants. U.S. Department of Energy (DOE) shipments of naval spent fuel originate at the five U.S. Navy shipyards equipped to service the reactors of nuclear-powered ships: Bremerton, WA; Charleston, SC; Newport News, VA; Pascagoula, MS; and Portsmouth, NH. Future shipments of defense high-level waste would originate from current storage locations such as the Hanford Reservation, WA; Savannah River Site, SC; and the Idaho National Engineering Laboratory (INEL), ID. In the past, destinations have been other reactor sites (inter-plant transfers of SNF) and current high-level radioactive waste (HLRW) sites (e.g., DOE shipments of Department of Defense (DOD), SNF to INEL). Most future shipments will be destined for either: (1) private interim storage, such as PFS in Utah; (2) interim storage facilities for HLRW at Federal sites; or (3) the recently endorsed national repository at Yucca Mountain, NV.

For the years 1979-1991, approximately 1,200 commercial SNF shipments totaling 1,091 tons of uranium (990 metric tons of uranium (MTU)) existed. Most all of these were relocations of spent fuel to facilities that could provide interim storage. Only about 10 percent of the shipments were by rail, but these accounted for nearly two-thirds of the tonnage [NRC, 1992]. To date, there have also been about 500 shipments of naval SNF, mostly to INEL. All of these were via rail; more than half were moved in regular trains and the rest in dedicated trains.[1]

By the year 2046, the DOE estimates that waste inventories will be between 63,000 and 105,000 metric tons of heavy metal (MTHM) for commercial SNF; 2,333 to 2,500 MTHM for DOE SNF; and 8,315 to 222,280 canisters of HLRW [DOE, 2002]. This material will be transported to the national repository either directly from 72 commercial and 5 DOE sites across the United States or indirectly via interim storage and consolidation facilities. The number of rail shipments for SNF and HLRW over a 24-year campaign could range from 300 to 18,300 depending on the mode emphasis of the shipping campaign. This traffic would at most average two shipments per day, depending primarily upon the presence and location of an interim facility (or facilities).[2]

Casks, Trains, and Shipping Campaigns

The Nuclear Regulatory Commission must certify that a cask design meets those regulations before such casks can be used to transport spent fuel.[3] Rail casks commonly used in past and current commercial shipments weigh about 75 tons (68 metric tons); DOE's civilian waste program plans to use 100-ton (91-metric ton) casks. Those used most commonly to transport defense spent fuel and related material also weigh about 100 tons (91 metric ton). New, heavier casks are now replacing the existing fleet [ICC,

[1] According to the written statement submitted by Larry Blalock, Director of the Transportation Management Division (DOE), to the Dedicated Train workshop held September 28-29, 1992.

[2] Rail shipments to the proposed private fuel storage (PFS) facility in Utah will alter these numbers considerably since SNF would move there first and be moved again to the Yucca Mountain Repository when it opens.

[3] Applies to casks used by commercial shippers and those to be used by DOE in the civilian radioactive waste program. Casks used by DOE to ship DOD spent fuel need not be certified by NRC if DOE issues its own certificate. However, it has been DOE's practice to request NRC review of the cask designs for the Naval Reactors Program. In fact, NRC has issued certificates of compliance for all three types of casks including one for the M-140 cask (dated October 2, 1992).

1992a]. DOT regulations require that the casks be clearly marked with placards that identify the nature of their cargo. Casks and cask cars carrying DOE or DOD shipments which are "for the purpose of national security" and which are escorted by agency personnel are not subject to placarding requirements.[4]

Commercial rail casks are usually placed on conventional flatcars weighing about 30 tons (27 metric ton). The casks used in defense SNF shipments ride on specially designed rail cars. A 6-axle depressed center flatcar weighing about 60 tons (54 metric ton) is used with the older casks; an 8-axle, 70-ton car carries the heavier casks [ICC, 1992a].

In commercial and defense shipping campaigns, cask cars are accompanied by buffer cars which serve to separate them fore and aft from other cargoes and people on board. A single cask car is typically accompanied by two buffer cars and a personnel car, housing escorts and sometimes emergency response experts.[5] This unit of cars, referred to herein as a "cask car block," can either be hauled from origin to destination by a combination of local and manifest (i.e., regular) trains or a dedicated train.[6]

Rail shipping campaigns to date have used regular and dedicated train service. Over 700 shipments of naval reactor SNF and related material have been made since the late 1950s. Of these, about 300 used regular trains. In the past, dedicated trains were sometimes used at the initiative of certain carriers. All defense shipments now use regular train service. DOD/DOE has advised the railroads that the shipments are not time-restrictive and may be moved in local or non-priority regular train service. As a result, the railroads have moved the shipments at their convenience in recent years [ICC, 1992a].[7] Currently, about 50 shipments are made annually. Earlier commercial shipments also used regular train service, including 15 shipments (1969-1971) by Pacific Gas & Electric from Humboldt Bay, CA, to West Valley, NY. More recent commercial shipping campaigns have used dedicated trains, including 30 shipments (1984-1989) from Cooper, NE, to the General Electric facility in Morris, IL, and 29 shipments (1984-1987) from Monticello, MN, to the same destination. There have also been shipments from Robinson, SC, to a destination in North Carolina and intra-state movements within North Carolina. Shipments of debris from the failed reactor at Three Mile Island, PA, to INEL, ID, also used dedicated trains (1986-1990). Commercial shipping campaigns in recent years have also taken additional measures, including speed limits, onboard health physicists, operating a rail inspection car ahead of the cask train, escort vehicles, and other means of enhancing safety and security.

[4] 49 CFR 173.7(b). The escorts must travel in a separate vehicle and must have in their possession a document certifying that the shipment is for the purpose of national security.

[5] Under DOE Order 1540.4, governing "Physical Protection of Unclassified Reactor Fuel in Transit," an escort must accompany each shipment to maintain visual surveillance of the shipment when the train is stopped, but those duties may be assigned to a railroad employee. Classified DOD shipments are always accompanied by special escort personnel.

[6] In a regular train, buffer cars could be unplacarded; low profile cars from the consist were placed adjacent to the cask car to serve as buffers (i.e., not part of a dedicated block of cars). However, the use of other consist cars as buffers has been rendered unlikely by a highly publicized incident in which an inappropriate buffer car (placarded as containing flammable material) was substituted on a Three Mile Island train at an intermediate yard. All remaining Three Mile Island shipments used dedicated buffer cars that accompanied the cask car(s) from origin to destination as part of the cask car block.

[7] This ICC decision further notes that "for example, the Norfolk Southern will not move the shipments...in its 'corporate' or scheduled, time-sensitive trains. Moving at the convenience of Norfolk Southern, the radioactive shipments will move during weekends, when there is less time-sensitive traffic on its lines, in local service, or on an available 'extra train.'...Burlington Northern generally uses local trains for the movement of radioactive materials...Until recently, the Union Pacific accepted...shipments only at specified times on particular days in what it called 'operating window service,'...UP's way of limiting the service...to non-priority trains." UP's current policy is to move all DOD casks/cask cars (loaded and empty) in dedicated trains. The only exception is the use of a regularly scheduled, speed-restricted train that departs westbound from Kansas City on Sundays. This decision was reportedly prompted by findings of a recent study of longitudinal forces in trains hauling heavy cask cars (per letter from L. Tierney, Director of Chemical Transportation Safety, Union Pacific Railroad to G. Watros, US DOT/VNTSC, dated March 22, 1993).

Appendix F.
Current and Planned High-Speed Rail Corridors and Nuclear Power Plants

Table F-1 shows current and planned high-speed rail corridors and the nuclear power plant locations on or near the rail route.

Table F-1. Current and Planned High-Speed Rail Corridors and Nuclear Power Plant Locations Near Route

High-Speed Rail Corridor Endpoint Cities	Nuclear Power Plants On and Near Route
Vancouver–Eugene	Trojan
Bay Area–Sacramento–Los Angeles (via valley)	Humboldt, Rancho Saco, G.E. Vallacentos
Bay Area–Los Angeles (via coast)	Diablo Canyon
Tulsa–Dallas, Little Rock–Dallas–San Antonio	Arkansas, Comanche Peak, Sequoyah Fuel Co.
Minneapolis–Chicago	Monticello, Prairie Island Station, LaCrosse, Zion
St. Louis–Chicago	Dresden, Braidwood
Detroit–Chicago	Palisades, Cook
Chicago–Toledo–Cleveland	Fermi, Davis Besse, Perry
New York City–Buffalo	Ginna, Nine Mile Point, Indian Point
Pittsburgh–Philadelphia	Parks Township, Cabot, Three Mile Island, Limerick
Philadelphia–Washington, D.C.	Salem, Hope Creek, Shieldal, Peach Bottom
Washington, D.C.–Richmond	Surrey, North Anna
Raleigh–Atlanta, Jessup, Savannah	Harris, McGuire, Catawba, Robinson, Brunswick, Summer, Oconee, Vogtle, Hatch
New Orleans–Houston	Waterford

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Appendix G.
Energy Absorption Analysis

Introduction

The information contained in this appendix outlines the procedure developed to study the absorption of energy if a rail Spent Nuclear Fuel (SNF) cask is involved in a collision with a heavy freight locomotive. Three relevant collision scenarios were analyzed: a head-on collision, a transverse collision at a rail crossing, and a raking collision. Considerable uncertainty is associated with any collision, and the subsequent damage that a SNF cask may experience is extremely event- and consist-dependent.

The purpose of developing a simplified approach to estimate energy absorption is to make a direct comparison of rail SNF cask responses in the rail environment for primary and secondary collision conditions. Primary collisions are defined as the initial contact of the rail SNF cask with a heavy piece of freight equipment; these analyses use a heavy freight locomotive as the object either being struck or striking the rail SNF cask. Rail SNF casks have historically been much stiffer than locomotives. When a collision occurs, momentum is exchanged, and the locomotive plastically deforms first and absorbs some of the initially available kinetic energy of the collision, reducing the speed of the cask.

The speed at which the cask moves upon separation with the locomotive is defined as the cask residual speed. This speed is used to compare against the U.S. Nuclear Regulatory Commission (NRC) 30-ft (9.1-m) impact into a rigid surface, which equates to 30-mph (48.2-km/hr) impact into a rigid surface. The secondary collision that may ensue with the surrounding rail environment is assumed to be rigid; therefore a direct comparison with the NRC 30-ft (9.1-m) impact into a rigid surface is an appropriate metric.

Development of Equations of Motion

The first step in the analysis is to define the system to be solved. This is a one-dimensional, lumped-parameter model of a single, bare cask striking a generic freight locomotive in a variety of orientations. To define independent force deflection behaviors for the crush of the locomotive and the rail SNF cask a dummy mass, the locomotive coupler is used to separate the response of the two objects involved in the collision. Figure G-1 shows a schematic of the system modeled. The stiffness of the cask is greater than that of the locomotive and so appears as a heavier spring in the schematic. The equations of motion for this system were written and solved numerically, using a standard Runge-Kutta differential equation solver in a MathCAD worksheet.

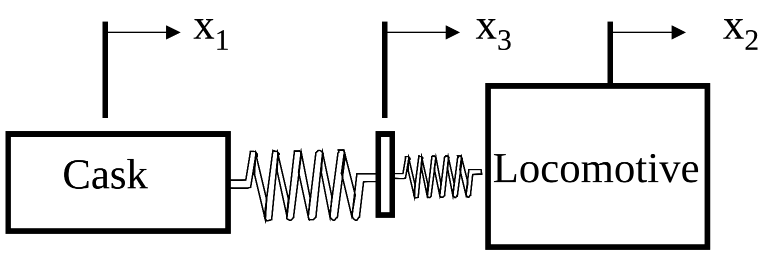

Figure G-1. Schematic of Collision Dynamic Model

The equations of motion for this system are:

$$m_1\ddot{x}_1 + (x_1 - x_3)k_{cask} = 0 \qquad \text{Equation G1.}$$
$$m_3\ddot{x}_3 + (x_3 - x_2)k_{loco} - (x_1 - x_3)k_{cask} = 0 \qquad \text{Equation G2.}$$
$$m_2\ddot{x}_3 - (x_3 - x_2)k_{loco} = 0 \qquad \text{Equation G3.}$$

These equations were re-written as first order equations and solved simultaneously.

Force-Deflection Characteristics

The stiffness of the cask and locomotive were developed from the force deflection characteristics provided. Three force deflection diagrams were used to represent cask behavior for impacts into a rigid planar surface: end-wise, side-wise, and corner over the rail SNF cask center of gravity. The force deflection information was obtained for a generic steel-lead-steel rail Sandia National Laboratory (SNF) cask studied by SNL in NUREG 6672, which Figure G-2 presents.

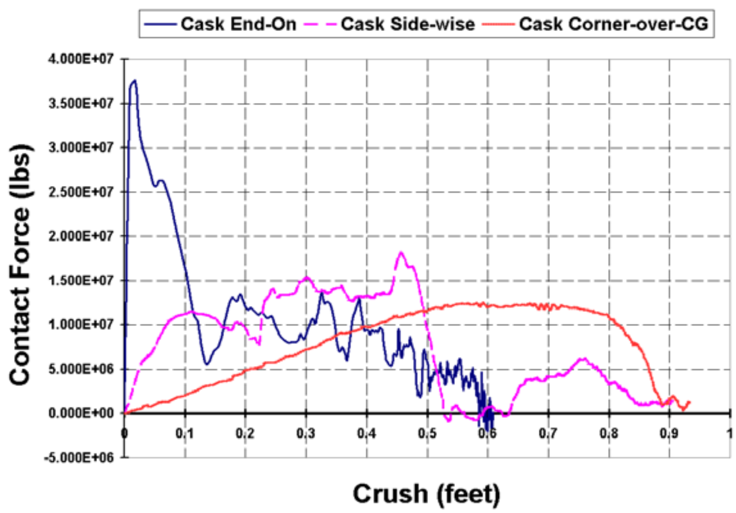

Figure G-2. Force Deflection of Steel-Lead-Steel Generic Rail SNF Cask for Three Impact Orientations at 30 mph into a Rigid Surface

Two force deflection diagrams are used to represent a generic heavy freight locomotive for alternative loading paths: along the neutral axis of the underframe and for a climbing condition. The two locomotive force deflection characteristics were used to ascertain the sensitivity of the final, predicted residual speeds to the shape of the locomotive force deflection characteristics. This force deflection information for the locomotives was obtained from research conducted on locomotive crashworthiness, as shown in Figure G-3.

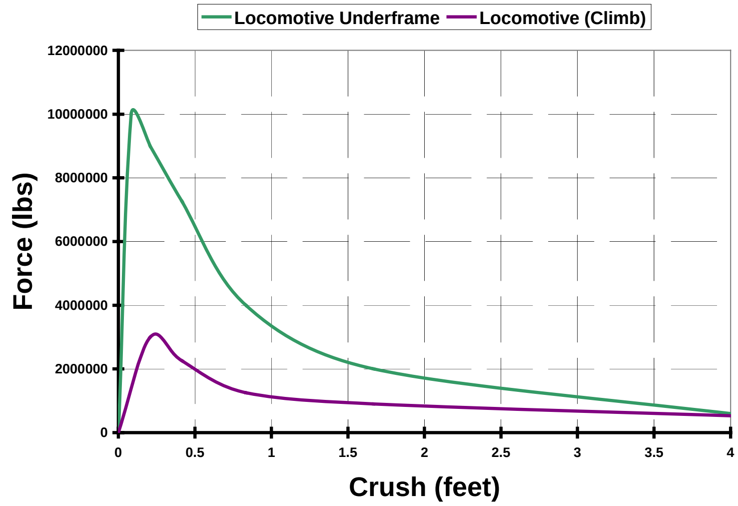

Figure G-3. Force Deflection of Heavy Freight Locomotive

These force deflection characteristics, for the locomotive and rail SNF cask, were inputs into the lumped-parameter, collision dynamic model. Using these characteristics and defining collision scenarios of concern at a variety of closing speeds, an estimate of the energy absorbed in the given collision scenario was obtained, as well as the predicted residual velocity. The residual velocity was then used as input in the event trees.

Collision Scenarios

Three collision scenarios were developed. The first scenario is a head-on collision between the rail SNF cask and the locomotive. The second scenario is a transverse impact between the locomotive and the cask at a rail-rail crossing. The third scenario is a raking collision where the rail SNF cask has swung off the transport car and is fouling the right-of-way of an oncoming freight consist. Each scenario has a different rail SNF cask force deflection diagram. Both locomotive force deflection characteristics were also used to ascertain the sensitivity of the solution to the shape and magnitudes of the forces involved. Three examples are presented with representative results, one for each collision scenario.

Head-On Collision Scenario

The head-on collision scenario assumes that a bare cask (without the impact limiters) breaks free of its transport car and consist, at the maximum rated speed of the consist (~ 50 mph (80.4 km/hr)) and impacts a heavy freight locomotive traveling in the opposite direction. The cask is traveling in its longitudinal direction so the end-wise force deflection characteristic is used. A number of speeds are used for the locomotive. This example uses a locomotive speed of 70 mph (112.6 km/hr). The loading at the locomotive underframe neutral-axis force-deflection characteristic was used. This characteristic will provide the greatest deformations on the rail SNF cask. The weight of the locomotive is assumed to be 440,000 lbs (199,581 kg). The cask weight is assumed to be 250,000 lbs (113,398 kg). To obtain the solution presented, 10,000 time-steps were used in the numerical integration scheme.

Figure G-4 presents the relative displacements of the two masses as a function of time. The solid-line curve represents the crush of the locomotive while the dashed-line curve represents the crush of the rail SNF cask. The locomotive is completely crushed while the cask sustains little deformation. This result means that the rail SNF cask cannot be damaged by a typical heavy freight locomotive when impacted in this orientation.

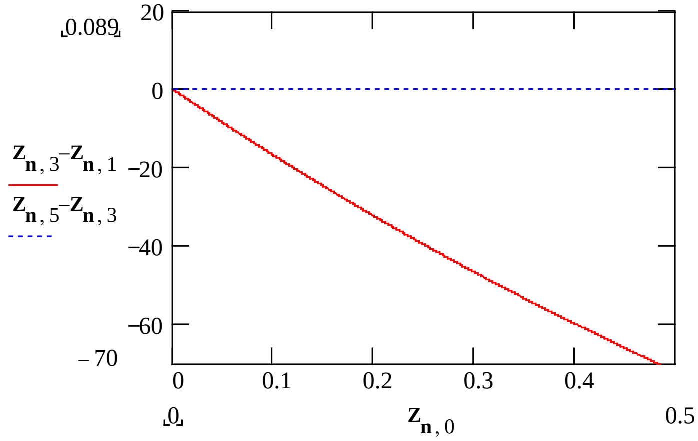

Figure G-4. Head-On Collision Scenario: Crush of Locomotive and Rail SNF Cask

Figure G-5 presents a plot of the velocities of the locomotive and the rail SNF cask. The solid-line curve represents the velocity of the locomotive while the dashed curve represents the velocity of the rail SNF cask. It is apparent that the force-deflection characteristic of the locomotive is exhausted due to the sharp change in the slope of the velocity. The time it takes to exhaust the force-deflection curve for the locomotive is ~ 0.4 seconds. The final cask speed is 28 mph (45.1 km/hr), and the final locomotive speed is 57 mph (91.7 km/hr). They are traveling in the opposite directions from one another after the event.

This result translates into a secondary impact speed (the residual speed of the cask) with the rail environment of 28 mph (45.1 km/hr). If the secondary impact is assumed to be with a rigid, planar surface, then this residual speed can be compared against the metric obtained from the 30-ft (9.1-m) drop onto an unyielding surface. A drop height from 30 ft (9.1 m) equates to an initial impact speed of 30 mph (48.2 km/hr). Since the residual speed calculated here is less than 30 mph (48.2 km/hr), this accident scenario would not damage the cask sufficiently to result in emissions that exceed the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m). The 70-mph (112.6-km/hr) speed was chosen as a good approximation of typical top track speed on Category 6 tracks.

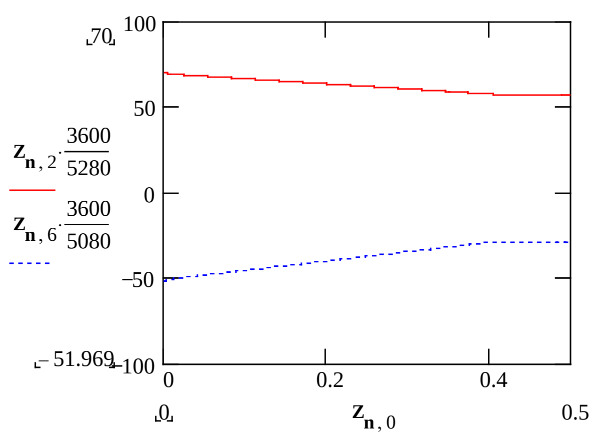

Figure G-5. Head-On Collision Scenario: Velocities of Locomotive and Rail SNF Cask

Rail-Rail Collision Scenario

The rail-rail crossing-collision scenario assumes that a bare rail SNF cask without its impact limiters is sitting at a crossing when it is hit on its side by a locomotive freight consist. Because the cask is hit on its side, the side-wise force-deflection characteristic was used. A number of speeds were used for the locomotive. This example will use a locomotive speed of 50 mph (80.4 km/hr). The loading at the locomotive underframe neutral-axis force-deflection characteristic was used. This characteristic provides the greatest deformations on the rail SNF cask. The weight of the locomotive is assumed to be 440,000 lbs (199,581 kg). The cask weight is assumed to be 250,000 lbs (113,398 kg). To obtain the solution presented, 10,000 time-steps were used in the numerical integration scheme.

Figure G-6 presents the relative displacements, crush, of the two masses as a function of time. The solid-line curve represents the crush of the locomotive while the dashed-line curve represents the crush of the rail SNF cask. The locomotive is crushed 19 feet, while the cask sustains very little deformation. This result means that the rail SNF cask cannot be damaged by a typical heavy freight locomotive when impacted in this orientation.

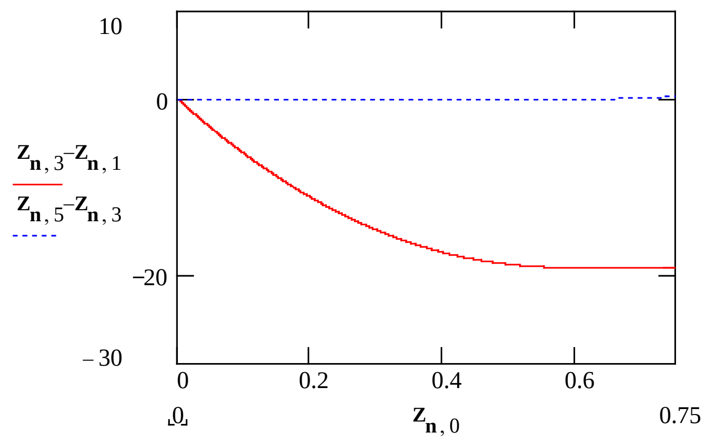

Figure G-6. Rail-Rail Crossing Collision Scenario: Crush of Locomotive and Rail SNF Cask

Figure G-7 presents a plot of the velocities of the locomotive and the rail SNF cask. The solid-line curve represents the velocity of the locomotive while the dashed curve represents the velocity of the rail SNF cask. The locomotive slows down from 50 mph (80.4 km/hr) to 31 mph (49.9 km/hr) as the cask is sped up from 0 mph (0 km/hr) to 33 mph (53 km/hr) in ~ 0.6 seconds. The cask is ejected from the locomotive at a slightly higher speed, but both are traveling in the same direction after the collision.

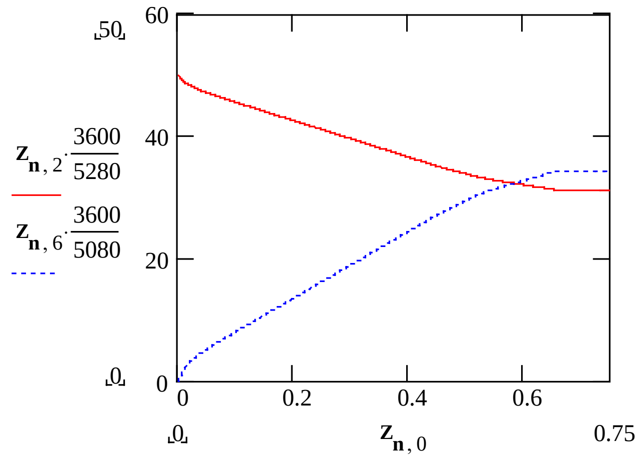

Figure G-7. Rail-Rail Crossing Collision Scenario: Velocities of Locomotive and Rail SNF Cask

This result translates into a secondary impact speed (the residual speed of the cask) with the rail environment of 33 mph (53 km/hr). If the secondary impact is assumed to be with a rigid planar surface, then this residual speed can be compared against the metric obtained from the 30-ft (9.1-m) drop onto an unyielding surface. A drop height from 30 ft (9.1 m) equals an initial impact speed of 30 mph (48.2 km/hr). Since the residual speed calculated here is greater than 30 mph (48.2 km/hr) this accident scenario could result in damage to the cask that exceeds allowable regulatory emission limits of 1,000 mrem/hr at 3.3 ft (1 m).

Raking Collision Scenario

The raking collision scenario assumes that a bare rail SNF cask without its impact limiters has swung off its transport car and is fouling the right-of-way of an oncoming train. Because the cask was impacted on its corner, the corner of the cask over its center of gravity force-deflection characteristic was used. A number of speeds are used for the locomotive. This example will use a locomotive speed of 70 mph (122.6 km/hr). The loading at the locomotive underframe neutral-axis force-deflection characteristic was used. This characteristic will provide the greatest deformations to the rail SNF cask. The weight of the locomotive was assumed to be 440,000 lbs (199,581 kg). The cask weight was assumed to be 250,000 lbs (113,398 kg). To obtain the solution presented, 10,000 time-steps were used in the numerical integration scheme.

Figure G-8 presents the relative displacements and crush of the two masses as a function of time. The solid-line curve represents the crush of the locomotive, and the dashed-line curve represents the crush of the rail SNF cask. The locomotive is fully crushed while the cask sustains very small deformations. Based on results presented in NUREG/CR 6672, this amount of cask deformation is not sufficient to cause a breach in the cask or a leak from one of the seals. There is the possibility of some loss of shielding, which would result in a small increase in emissions, but still within the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m).

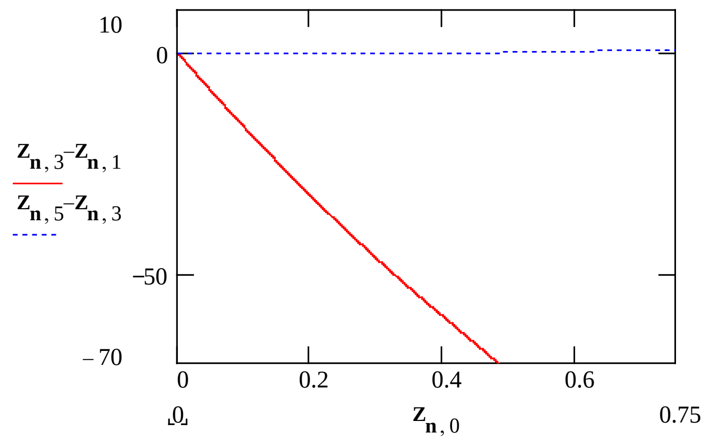

Figure G-8. Raking Collision Scenario: Crush of Locomotive and Rail SNF Cask

Figure G-9 presents a plot of the velocities of the locomotive and the rail SNF cask. The solid-line curve represents the velocity of the locomotive while the dashed-line curve represents the velocity of the rail SNF cask. It was apparent when the force-deflection characteristic of the locomotive was exhausted due to the sharp change in the slope of the velocity. The time it took to exhaust the force-deflection curve for the locomotive was ~ 0.4 seconds. The final cask speed was 28 mph (45 km/hr), and the final locomotive speed was 57 mph (91.7 km/hr). They were traveling in the opposite directions from one another after the event.

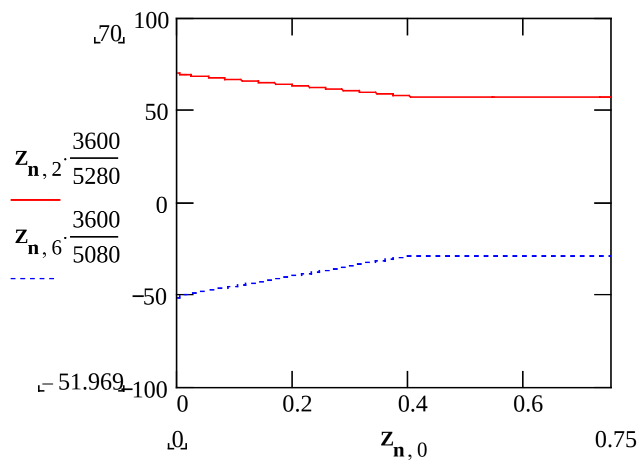

Figure G-9. Raking Collision Scenario:
Velocities of Locomotive and Rail SNF Cask

This result translates into a secondary impact speed (the residual speed of the cask) with the rail environment of 28 mph (45 km/hr). If the secondary impact was assumed to be with a rigid, planar surface, then this residual speed could be compared against the metric obtained from the 30-ft (9.1-m) drop onto an unyielding surface. A drop height from 30 ft (9.1 m) equals an initial impact speed of 30 mph (48.2 km/hr). Since the residual speed calculated here was less than 30 mph (48.2 km/hr), this accident scenario would not damage the cask sufficiently to result in emissions that exceed the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m). The 70 mph (112.6 km/hr) speed was chosen as a good approximation of typical top track speed on Category 6 tracks.

Conclusions

The results from three sample calculations were presented. For the head-on and raking collision scenarios, the calculated residual speeds for the highest estimated locomotive consist traveling speed do not result in an extra-regulatory loading condition. This means that both scenarios would not damage the cask sufficiently to result in emissions that exceed the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m). The head-on rail SNF cask force deflection characteristic is sufficiently stiff that no deformation is expected on the cask itself, and all the energy is consumed in plastic deformations of the locomotive and through the exchange of momentum. The raking collision scenario does show deformations on the rail SNF cask. These deformations, however, are not sufficiently severe so that a breach or seal failure is expected and resulting emissions would not exceed the allowable regulatory limit of 1,000 mrem/hr at 3.3 ft (1 m). The rail-rail crossing collision scenario does result in a residual speed in excess of the regulatory requirement and could pose a threat to the safety of the cask contents. The rail-rail crossing collision scenario, therefore, could result in damage to the cask that exceeds allowable regulatory emission limits of 1,000 mrem/hr at 3.3 ft (1 m).

Acronyms and Abbreviations

AAR	Association of American Railroads
ADL	Arthur D. Little, Inc.
AEC	U.S. Atomic Energy Commission
ALARA	as low as reasonably achievable
BNSF	Burlington Northern Santa Fe Railroad
BOE	Bureau of Explosives
BTS	Bureau of Transportation Statistics
CFR	Code of Federal Regulations
CG	center of gravity
CSF	commercial spent fuel
COFC	container on flatcar
DEIS	draft environmental impact statement
DI	ductile iron
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ECP	Electronically Controlled Pneumatic
EDE	effective dose equivalents
EIS	environmental impact statement
ERDA	Energy Research and Development Administration
FEIS	Final environmental impact statement
FRA	Federal Railroad Administration
ft	foot/feet
GRL	gross rail load
HAC	Hypothetical Accident Conditions
HAZMAT	hazardous materials
HLRW	high-level radioactive waste
HMTUSA	Hazardous Materials Transportation Uniform Safety Act
ICC	Interstate Commerce Commission
ICRP	International Commission on Radiation Protection
in	inch(es)
INEL	Idaho National Engineering Laboratory
km	kilometer(s)
km/hr	kilometers per hour
lbs	pounds
LCF	latent cancer fatalities
LNT	linear, no-threshold
LOS	loss of shielding
LPG	liquefied petroleum gas
LWR	light water reactor
m	meter(s)
mi	miles
MPC	multi-purpose canister
MPH	miles per hour
MRS	monitored retrievable storage
MTU	metric tons of uranium
MTHM	metric tons of heavy metal

NCRP	National Council on Radiation Protection
NFPA	National Fire Protection Association
NHTS	National Household Travel Survey
NRC	Nuclear Regulatory Commission
NTSB	National Transportation Safety Board
NUREG	Nuclear Regulations
OCRWM	Office of Civilian Radioactive Waste Management
O-D	origin-destination
ORNL	Oak Ridge National Lab
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
PFS	private fuel storage
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIH	poison inhalation hazard
PPS	Package Performance Study
PWR	pressurized water reactor
RAIRS	Railroad Accident/Incident Reporting System
RAM	radioactive material
RIA	regulatory impact assessment
RITA	Research and Innovative Technologies Administration
ROW	right-of-way
RSC	Regional Services Contractor
RSPA	Research and Special Programs Administration
SCOP	Safety Compliance Oversight Plan
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SS	stainless steel
STB	Surface Transportation Board
TI	Transportation Index
TOES	train operation energy simulation
TOFC	trailer on flatcar
UP	Union Pacific Railroad
USGS	United States Geological Survey

Glossary

Absorbed Dose. The energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray.

Accident. An unplanned sequence of events that results in undesirable consequences.

Activity Mean Aerodynamic Diameter. The diameter of a unit-density sphere with the same terminal settling velocity in air as that of an aerosol particle the radioactivity of which is the median for the entire aerosol.

Air Modes. Carriage of packages by cargo aircraft or passenger aircraft.

Atmospheric Dispersion. Movement of a contaminant as a result of the cumulative effect of the wind patterns and random motions of the air.

Atom. The smallest particle of an element that cannot be divided or broken up by chemical means. An atom consists of a nucleus, which contains protons and neutrons, and electrons that orbit the nucleus.

Attenuation. The process by which a beam of radiation is reduced in intensity when passing through some material.

Background Radiation. Radiation from cosmic sources; naturally occurring radioactive materials such as granite; and global fallout from nuclear testing.

Beta Radiation. Charged particles emitted from atomic nuclei during radioactive decay. A negatively charged beta particle is identical to an electron.

Buffer Cars. Railcars in front of or in back of those carrying spent nuclear fuel and high-level radioactive waste to provide additional distance to possibly occupied railcars or to railcars carrying hazardous materials other than radioactive materials. Federal regulations require the separation of a railcar carrying spent nuclear fuel and high-level radioactive waste from a locomotive, occupied caboose, carload of undeveloped film, or railcar carrying another class of hazardous material by at least one buffer car. These could be U.S. Department of Energy railcars or, in the case of general freight service, commercial railcars.

Canister. An unshielded metal container used as: (1) a pour mold in which molten vitrified high-level radioactive waste can solidify and cool; (2) the container in which U.S. Department of Energy and electric utilities place intact spent nuclear fuel, loose rods, or nonfuel components for shipping or storage; or (3) in general, a container used to provide radionuclide confinement. Canisters are used in combination with specialized overpacks that provide structural support, shielding, or confinement for storage, transportation, and emplacement. Overpacks used for transportation are usually referred to as transportation casks; those used for emplacement in a repository are referred to as waste packages.

Carrier. A company engaged in the transportation of passengers or property by land or water as a common, contract, or private carrier, or by civil aircraft.

Cask. A heavily shielded container that meets applicable regulatory requirements used to ship spent nuclear fuel or high-level radioactive waste.

Characteristic Package Dimension. Usually the largest package dimension from among the package's length, width, diameter, etc.

Collective Dose. The sum of the individual doses received in a given period of time by a specified population from exposure to a specified source of radiation.

Commercial Spent Nuclear Fuel. Commercial nuclear fuel rods that have been removed from reactor use. See spent nuclear fuel and U.S. Department of Energy spent nuclear fuel.

Corridor. As used in this transportation analysis, a strip of land, approximately 400-meters (0.25-mile) wide, that encompasses one of several possible routes through which rail transport spent nuclear fuel, high-level radioactive waste, and other material will pass to and from the proposed Yucca Mountain Repository.

Cosmic Radiation. A variety of high-energy particles, including protons, that bombard the Earth from outer space. They are more intense at higher altitudes than at sea level where the Earth's atmosphere is most dense and provides the greatest protection.

Dedicated Freight Rail Service. A train that handles only one commodity (in this case, spent nuclear fuel or high-level radioactive waste); this separate train with its own crew would limit switching between trains for the railcars carrying these materials.

Deformation. A change in the shape and size of a body.

Dose Equivalent. (1) The number (corrected for background) zero and above that is recorded as representing an individual's dose from external radiation sources or internally deposited radioactive materials; (2) the product of the absorbed dose in rads and a quality factor; (3) the product of the absorbed dose, the quality factor, and any other modifying factor. The dose equivalent quantity is used for comparing the biological effectiveness of different kinds of radiation (based on the quality of radiation and its spatial distribution in the body) on a common scale; it is expressed in rem.

Dose or Radiation Dose. A quantity of radiation or energy absorbed living tissues.

Dose Rate. The radiation dose delivered per unit of time, generally measured in millirem per hour.

Dose Risk. The product of a radiation dose and the probability of its occurrence.

Dual-purpose Canister. A metal vessel suitable for storing (in a storage facility) and shipping (in a shipping cask) commercial spent nuclear fuel assemblies.

Effective Dose Equivalent. The sum of the products of the dose equivalent to the organ or tissue and the weighting factors applicable to each of the organs or tissues that are irradiated.

Electron. An elementary particle with a unit negative charge. See beta radiation.

Element. One of the 103 known chemical substances that cannot be broken down further without changing its chemical properties. Examples are hydrogen, nitrogen, gold, lead, and uranium.

Escort Cars. Railcars in which escort personnel travel on trains carrying spent nuclear fuel or high-level radioactive waste.

Evacuation. The urgent removal of people from an area to avoid or reduce high-level, short-term exposure, usually from an airborne plume or from deposited activity.

Exclusive Use (also referred to as sole use or full load). Sole use by a single consignor of a conveyance for which all initial, intermediate, and final loading and unloading are carried out in accordance with the direction of the consignor or consignee. The consignor and the carrier must ensure that any loading or unloading is performed by personnel having radiological training and resources appropriate for safe handling of the consignment. The consignor must issue specific instructions in writing, for maintenance of exclusive use shipment controls, and include them with the shipping paper information provided to the carrier by the consignor (49 CFR 173.403).

Exposure. A measure of the ionization produced in air by X or gamma radiation; units of exposure in the air are the Roentgen or coulomb per kilogram (SI units).

Exposure (to Radiation). The incidence of radiation on living or inanimate material by accident or intent. Background exposure is the exposure to natural ionizing radiation. Occupational exposure is the exposure to ionizing radiation that occurs during a person's working hours. Population exposure is the exposure to a number of persons who inhabit an area.

Fissile Material. Plutonium-238, plutonium-239, plutonium-241, uranium-233, uranium-235, or any combination of these radionuclides. The definition does not apply to unirradiated natural uranium and depleted uranium, and natural uranium or depleted uranium that has been irradiated in a thermal reactor. Certain additional exceptions are provided in § 173.453 (173.403).

Fissile Material, Controlled Shipment. Any shipment that contains one or more packages that have been assigned, in accordance with § 173.457, nuclear criticality control transport indices greater than 10 (173.403).

Gamma Ray. The most penetrating type of radiant nuclear energy. It does not contain particles and can be stopped by dense materials, such as concrete or lead. See ionizing radiation.

General Freight Rail Service. Railroad line service that uses trains that move railcars, each of which might contain a different commodity. Railcars carrying spent nuclear fuel or high-level radioactive waste could be switched (in rail yards or on sidings) successively from one general freight train to another as they traveled from the commercial and U.S. Department of Energy locations to Nevada.

Geologic Repository. A system for disposing of radioactive waste in excavated geologic media, including surface and subsurface areas of operation, and the adjacent part of the geologic setting that provides isolation of the radioactive waste in the controlled area.

Half-Life. The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form.

Heavy Metal. All uranium, plutonium, and thorium used or generated in a manmade nuclear reactor.

High-Level Radioactive Waste. (1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (2) other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation. [DOE, 2002a]

Impact Limiters. Devices attached to rail shipping casks that would help absorb impact energy (reduce the acceleration of a package) in the event of a collision. Made of energy absorbing material (e.g., wood, foam, aluminum honeycomb).

Incident-Free Transportation. Routine transportation in which cargo travels from origin to destination without being involved in an accident.

Ion. An atom that has too many or too few electrons, causing it to be chemically active.

Ionizing Radiation. Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions. This includes alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, ultraviolet light, and other particles capable of producing ions.

Irradiation. Exposure to radiation.

Latent Cancer Fatality. A death resulting from cancer that has been caused by exposure to ionizing radiation. For exposures that result in cancers, the generally accepted assumption is that there is a latent period between the time an exposure occurs and the time a cancer becomes active.

Maximally Exposed Individual. A hypothetical individual whose location and habits result in the highest total radiological or chemical exposure (and thus dose) from a particular source for all exposure routes (for example, inhalation, ingestion, direct exposure). The concept of the maximally exposed individual is used to evaluate potential short-term impacts to individuals around the repository and from transportation. The concept of the maximally exposed individual is used to evaluate potential short-term impacts to individuals from transportation.

Metric Tons of Heavy Metal. Quantities of spent nuclear fuel without the inclusion of other materials, such as cladding (the tubes containing the fuel) and structural materials. A metric ton is 1,000 kilograms (1.1 tons or 2,200 pounds). Uranium and other metals in spent nuclear fuel (such as thorium and plutonium) are called heavy metals because they are extremely dense; that is, they have high weights per unit volume.

Millirem. One one-thousandth (0.001) of a rem.

Mitigation. Actions and decisions that (1) avoid impacts altogether by not taking a certain action or parts of an action; (2) minimize impacts by limiting the degree or magnitude of an action; (3) rectify the impact by repairing, rehabilitating, or restoring the affected environment; (4) reduce or eliminate the impact over time by preservation and maintenance operations during the life of the action; or (5) compensate for an impact by replacing or providing substitute resources or environments.

Naval Spent Nuclear Fuel. Spent nuclear fuel discharged from reactors in surface ships, submarines, and training reactors operated by the U.S. Navy.

Nuclear Waste. Unusable by-products of nuclear power generation, nuclear weapons production, and research, including spent nuclear fuel and high-level radioactive waste.

Occupational Dose. The dose received by an individual in a restricted area or in the course of employment in which the individual’s assigned duties involve exposure to radiation and to radioactive material from licensed and unlicensed sources of radiation, whether in the possession of the licensee or other person.

Package. Packaging and its radioactive contents.

Packaging. The assembly of components necessary to ensure compliance with packaging requirements. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The vehicle, tie-down system, and auxiliary equipment may be designated as part of the packaging.

Person-Rem. A unit used to measure the radiation exposure to an entire group and to compare the effects of different amounts of radiation on groups of people; it is the product of the average dose equivalent (in rem) to a given organ or tissue multiplied by the number of persons in the population of interest.

Photon. A quantum (or packet) of energy emitted in the form of radiation. Gamma rays and X-rays are examples of photons.

Point Source. Ideally, a source with infinitesimal dimensions. Practically, a source of radiation the dimensions of which are small compared with the viewing distance.

Population Dose. A summation of the radiation doses received by individuals in an exposed population; equivalent to collective dose and expressed in person-rem.

Pressurized Water Reactor. A nuclear power reactor in which heat is transferred from the core to a heat exchanger by high-temperature water kept under high pressure.

Private Fuel Storage. Privately owned temporary site for the storage of spent nuclear fuel.

Probability. The relative frequency at which an event can occur in a defined period. Statistical probability is about what actually happens in the real world and can be verified by observation or sampling. Knowing the exact probability of an event is usually limited by the inability to know, or compile the complete set of, all possible outcomes over time or space. Probability is measured on a scale of 0 (event will not occur) to 1 (event will occur).

Public Dose. The population dose received by members of the public from exposure to radiation and to radioactive material. It does not include occupational dose.

Qualitative. With regard to a variable, parameter, or data, an expression or description of an aspect in terms of non-numeric qualities or attributes. See quantitative.

Quantitative. Numeric expression of a variable. See qualitative.

Rad. The unit of measure of absorbed radiation dose in terms of energy. One rad is equal to an absorbed dose of 100 ergs per gram or 0.01 J per kg (0.01 gray). (In the metric system of measurements, an erg is a unit of energy. One foot-pound is equal to 13,560,000 ergs.)

Radiation. The emitted particles or photons from the nuclei of radioactive atoms. Some elements are naturally radioactive; others are induced to become radioactive by irradiation in a reactor. Naturally occurring radiation is indistinguishable from induced radiation.

Radiation (Ionizing Radiation). Alpha particles, beta particles, gamma rays, X-rays, neutrons, and other particles capable of producing ions.

Radiation Level. The radiation dose-equivalent rate expressed in millisievert(s) per hour or mSv/h (millirem(s) per hour or mrem/h) (49 CFR Part 173.403).

Radioactive. Emitting/Exhibiting radioactivity.

Radioactive Decay. The process in which one radionuclide spontaneously transforms into one or more different radionuclides, which are called decay products.

Radioactivity. The property possessed by some elements (for example, uranium) of spontaneously emitting alpha, beta, or gamma rays by the disintegration of atomic nuclei.

Radioisotope. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

Radionuclide. A general term referring to all known unstable or radioactive isotopes of a chemical.

Rail Classification Yard. A railroad switching yard where railcars arriving in inbound freight trains are classified and reassembled according to their routing to make up outbound freight trains.

Rail Route. Route from point of origin to the repository.

Receptor. A hypothetical person who is exposed to environmental contaminants (in this case radionuclides) in such a way—by a combination of factors including location, lifestyle, dietary habits, etc.—that this individual is representative of the exposure of the general population. U.S. Department of Energy used this hypothetical individual to evaluate long-term repository performance. The receptor represents the "Reasonably Maximally Exposed Individual (RMEI)," defined in 40 CFR Part 197.

Rem. A unit of dose equivalent.

Repository. See geologic repository.

Risk. The product of the probability that an undesirable event will occur, multiplied by the consequences of the undesirable event.

Shielding. Any material that provides radiation protection.

Shipment. The movement of a properly prepared (loaded, unloaded, or empty) cask from one site to another and associated activities to ensure compliance with applicable regulations.

Shipping Cask. A heavily shielded massive container that meets regulatory requirements for shipping spent nuclear fuel or high-level radioactive waste. See cask.

Single-purpose (Storage or Transportation) Cask. A heavily shielded massive container for the dry storage of spent nuclear fuel; it is usable for either storage or transportation but not for emplacement in a repository. See cask.

Spent Nuclear Fuel. Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing. [DOE, 2002a].

Storage. The collection and containment of waste or spent nuclear fuel in a way that does not constitute disposal of the waste or spent nuclear fuel for the purposes of awaiting treatment or disposal capacity.

Total Population. The sum of all people associated with direct and indirect exposure.

Transport Index. The dimensionless number (rounded up to the next tenth) placed on the label of a package to designate the degree of control to be exercised by the carrier during transportation. The transport index is determined as follows: (1) for non-fissile material packages, the number determined by multiplying the maximum radiation level in milliSievert(s) per hour at 3.3 ft (1 m) from the external surface of the package by 100 (equivalent to the maximum radiation level in millirem per hour at 3.3 ft (1 m)); or (2) or fissile material packages, the number determined by multiplying the maximum radiation level in milliSievert per hour at 3.3 ft (1 m) from any external surface of the package by 100 (equivalent to the maximum radiation level in millirem per hour at 3.3 feet (1 m)) or, for criticality control purposes, the number obtained by dividing 50 by the allowable number of packages which may be transported together, whichever number is larger (10 CFR Part 71.4/49 CFR 173.403).

Transuranic Waste. Waste materials (excluding high-level radioactive waste and certain other waste types) contaminated with alpha-emitting radionuclides that are heavier than uranium with half-lives greater than 20 years and that occur in concentrations greater than 100 nanocuries per gram. Transuranic waste results primarily from treating and fabricating plutonium, as well as research activities at U.S. Department of Energy defense installations.

U.S. Department of Energy Spent Nuclear Fuel. Radioactive waste created by defense activities that consists of more than 250 different waste forms. The major contributor to this waste form is the N-Reactor fuel currently stored at the Hanford Site. This waste form also includes 65 metric tons of heavy metal of naval spent nuclear fuel.

Vitrification. A waste treatment process that uses glass (for example, borosilicate glass) to encapsulate or immobilize radioactive wastes.

X-Rays. Penetrating electromagnetic radiation having a wavelength much shorter than that of visible light. X-rays are identical to gamma rays but originate outside the nucleus, either when the inner orbital electrons of an excited atom return to their normal state or when a metal target is bombarded with high-speed electrons.

Yucca Mountain Site. The area on which U.S. Department of Energy has built or would build the majority of facilities or cause the majority of land disturbances related to the proposed repository.

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