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SPENT FUEL TRANSPORTATION RISK ASSESSMENT: ROUTINE TRANSPORTATION

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ABSTRACT

The RADTRAN model for calculating radiation doses is based on the well-understood behavior of ionizing radiation. Absorption of ionizing radiation depends on the energy and type of radiation and on the absorbing material. The casks that are used to transport spent nuclear fuel have walls that absorb most of the emitted ionizing radiation and thereby shield the public and the workers. For routine transportation, RADTRAN models the cask as a sphere and assumes that the longest dimension of the trailer or railcar carrying the cask is the same as that of the cask. The dose rate in Sv/hour at one meter from the cask is modeled as a virtual source at the center of a sphere whose diameter is the longest dimension of the actual spent fuel cask.

INTRODUCTION

People who live along the cask's route and the people in vehicles that share the route are exposed to external radiation from the cask. The dose to workers and the public from a cask during routine transportation depends on the time that the workers or public are exposed to the cask, the distance from the cask, and the cask's external radiation. When the vehicle carrying the cask is traveling along the route, the faster the vehicle travels, the less exposure to anyone along the vehicle's route. Therefore, an individual member of the public receives the largest dose from a moving vehicle when he or she is as close as possible to the vehicle, and the vehicle is traveling as slowly as possible. In the present analysis, these doses are in the range of four to seven nanosieverts. Collective doses along the route depend on the size of the exposed population. In this study, such doses were of the order of 0.1 person-millisieverts. The appropriate comparison between the collective dose from a shipment of spent fuel is not a comparison between the radiation dose form the shipment and zero dose, but between the background radiation dose in the presence and absence of a shipment; e.g., 8.810096 person-Sv if there is a shipment and 8.81000 person-Sv if there is no shipment.

The RADTRAN computer code (Taylor and Daniel, 1977) is used in this chapter to estimate risks from routine[1] transportation of SNF. Sandia National Laboratories initially developed RADTRAN for the NUREG–0170 risk assessment (NRC, 1977). During the past several decades, the calculation method and RADTRAN code have improved to stay current with computer technology and supporting input data have been collected and organized. The basic RADTRAN analysis approach has changed little since the original development of the code, and the risk assessment method used in the RADTRAN code is accepted worldwide; about 25 percent of the 500 RADTRAN users are international.[2]

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

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

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

RADIATION EMITTED DURING ROUTINE TRANSPORTATION

The external radiation doses from the casks in this study determined from values reported in the cask Safety Analysis Reposrts (SARs), are shown in Table 1 (Holtec, 2000; NAC, 2004; General Atomics, 1998).

Table 1 External Radiation Doses from the Casks in this Study

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

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

THE RADTRAN MODEL OF ROUTINE, INCIDENT-FREE TRANSPORTATION

For analysis of routine transportation, RADTRAN models the cask as a sphere with a radiation source at its center and assumes that the dimensions of the trailer or railcar carrying the cask are the same as the cask dimensions. The emission rate of the radiation source is based on the TI instead of a shielding calculation. The radiation source is modeled as a virtual source at the center of the sphere shown in Figure 1 that produces the same TI as the cask. The diameter of this spherical model, called the “critical dimension,” is the longest dimension of the actual spent fuel cask.

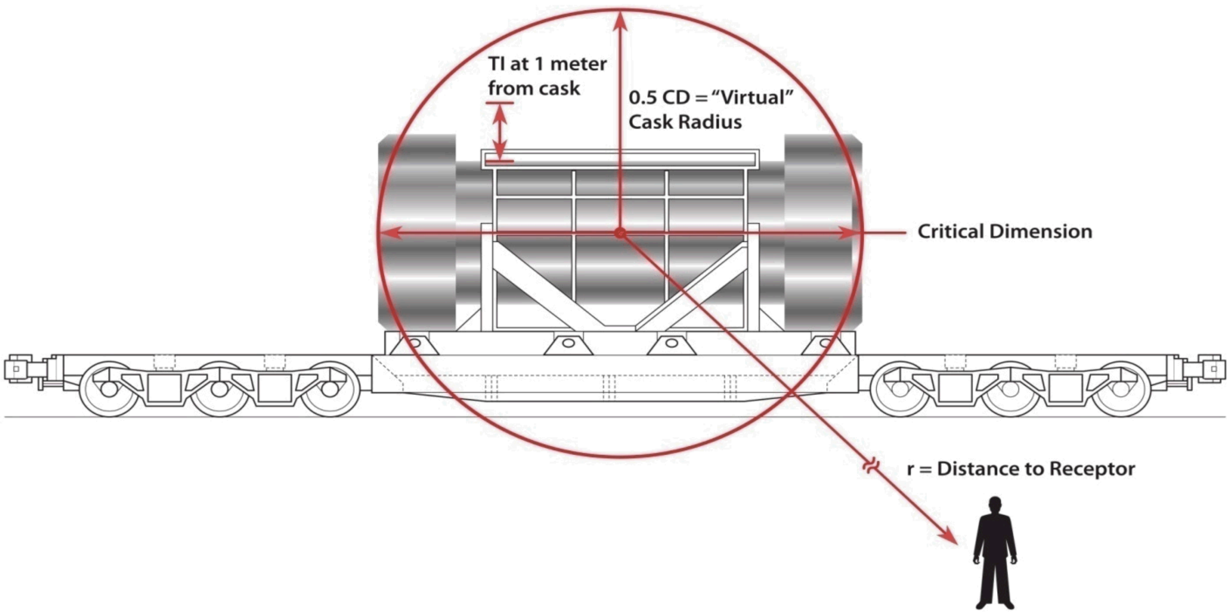

Figure 1 RADTRAN model of the vehicle in routine, incident-free transportation. The cask in this diagram is positioned horizontally and the critical dimension is the cask length.

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

Equation (1)

$$D(x) = \frac{2 \cdot Q_1 \cdot k_0 \cdot DR_v}{V} \cdot \int_x^{\infty} \left(\frac{e^{(-\mu \cdot r)} \cdot B(r)}{r \cdot \left(r^2 - x^2\right)^{0.5}} \right) dr$$

D(x) = Total integrated dose absorbed by an individual at distance x (rem)
Q_1 = Unit conversion factor
k_0 = Point source package shape factor (m^2)
DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)
V = Shipment speed (m/s)
m = Attenuation coefficient (m^{-1})
r = Perpendicular distance of individual from shipment path (m)
B(r) = Buildup factor expressed as a geometric progression

The product ($e^{=\mu r}$) (B(r)) =1 for gamma radiation for this calculation. An individual member of the public residing near the transport route receives the largest dose from a moving vehicle when he or she is as close as possible to the vehicle and the vehicle is traveling as slowly as possible.

For trucks and trains carrying spent fuel at a speed of 24 kilometers per hour (kph) (15 miles per hour (mph)) and a distance of 30 meters (approximately 100 feet) are assumed for maximum exposure. Table 2 shows the maximum dose to an individual member of the public under these conditions. The Rail-Lead cask delivers a higher dose than the Rail-Steel cask because it has a higher TI. The Truck-DU cask has a higher dose than the Rail-Lead cask (same TI) because it has a longer critical dimension. The transit speed used for both rail and truck transport in the calculation of the maximum individual dose is 24 kph (15 mph). These doses are about the same as 1 minute of average background: 6.9×10^{-9} Sv (6.9×10^{-4} mrem).

Table 2 Maximum Individual In-Transit Doses

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

When a vehicle carrying a spent fuel cask travels along a route, the people who live along that route and the people in vehicles that share the route are exposed to the external radiation from the cask. Doses to groups of people are collective doses; the units of a collective dose are person-Sv (person-rem). RADTRAN calculates collective doses along transportation routes by integrating over the width of a band along the route where the population resides (the r in Figure 2) and then integrating along the route. Collective doses to people on both sides of the route are included. The exposed population is in a band 770 meters (approximately 0.5 miles) on either side of the route: from 30 meters (100 feet) from the center of the route to 800 meters (0.5 miles). Figure 2 shows how these bands are defined with examples of distances within the bands.

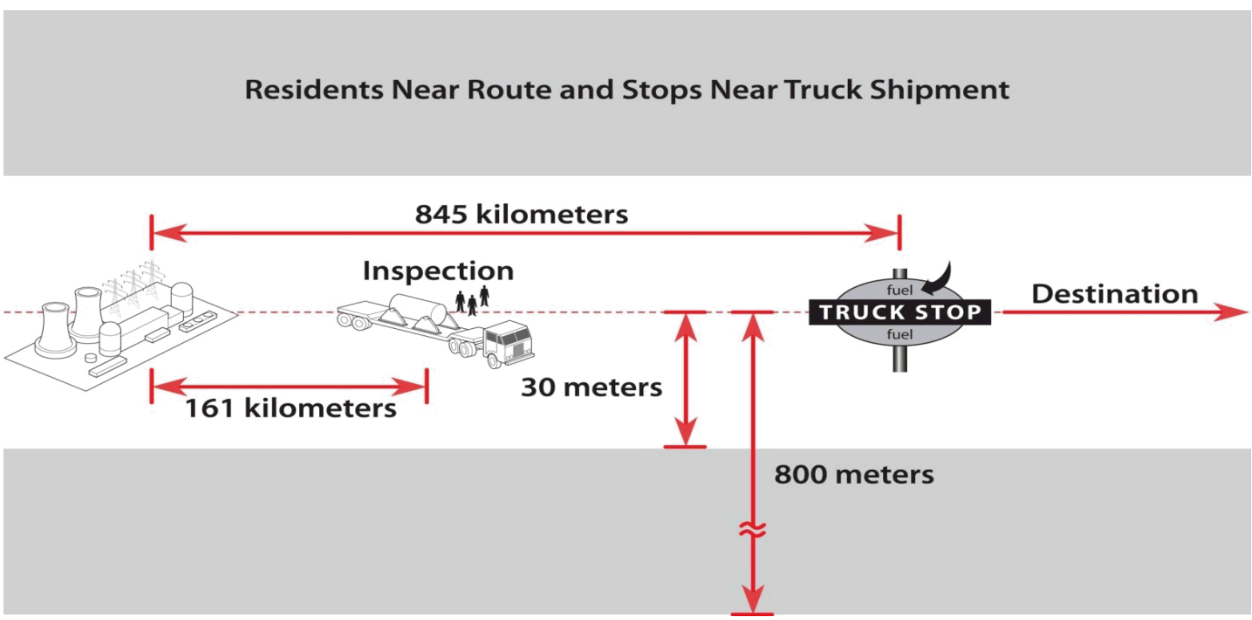

Figure 2 Diagram of a truck route as modeled in RADTRAN (not to scale).

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

Transportation Routes

Any route can be divided into as many sections as desired for dose calculation. For this study, routes are divided into rural, suburban, and urban segments according to the population/km^2 (population density). Table 3 summarizes the characteristics of each population type that is part of the RADTRAN dose calculation.

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

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

[a] Johnson and Michelhaugh, 2003; [b]Weiner et al., 2009 Appendix D; [c]DOT, 2004a; [d]DOT, 2004b, Appendix D; [e]DOT, 2009 (these are average railcars per hour); [f]DOT, 2008, Table 1-11; [g]Applies only to sidewalks on secondary roads in urban areas.

Equation (2) shows the impact of the route parameters on Equation (1), Equation (2)

$$D_{offlink} = Q \cdot \frac{4\,k_0\,DR_p.DIST_L.PD_L.SF_L}{V_L} \cdot \int_{x\min}^{x\max}\int_{r}^{\infty} \frac{\exp(-\mu r)B(r)}{r(r^2 - x^2)^{1/2}} dr dx$$

$DR_{p\ or\ v}$ = package or vehicle exernal dose rate

$DIST_L$ = length of route segment (link) in km

V_L = vehicle speed on the link

PD_L = persons/km^2 on the link

SF_L = residential shielding factor

x_{max} - x_{min} defines the bandwidth

Figure 3, an interstate truck route through Salt Lake City, UT is an example of the distribution of rural, urban, and suburban areas. The broad stripe is the half-mile band on either side of the highway. The red areas are urban populations, the yellow areas are suburban, and the green areas are rural. Instead of analyzing each separate, rural, urban, and suburban segment of this stretch of highway, the rural, suburban, and urban areas are each combined for RADTRAN dose calculations. The routing code WebTRAGIS (Johnson and Michelhaugh, 2003) provided these combinations for each State traversed by a particular route. WebTRAGIS (Transportation Routing Analysis Geographic Information System) software, developed by Oak Ridge National Laboratory (ORNL), determines routes from specified starting and ending points for highway, rail, or waterway transportation within the continental United States. Various criteria for the route(s) to be determined may be specified including Highway Route Controlled Quantity (HRCQ) criteria, which are used for the 16 routes presented within this document. WebTRAGIS also uses data from the ORNL database Landscan USA to determine populations along the route and bin these populations into rural, suburban, and urban subsets for each state within the route. For population determinations, the user may specify the buffer zone from which the population is calculated. The default buffer zone used in this document is 800 meters (on either side of the route).

The maps in Figures 4 through 7 show the 16 truck and 16 rail routes analyzed in this report. These illustrative routes were selected as representative of possible cross-country transport. No actual spent fuel transport has occurred or is planned from any of these points of origin to any of these destinations. The maps are adapted from the output of the routing code WebTRAGIS (Johnson and Michelhaugh, 2003).

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I-80 Corridor
Salt Lake City

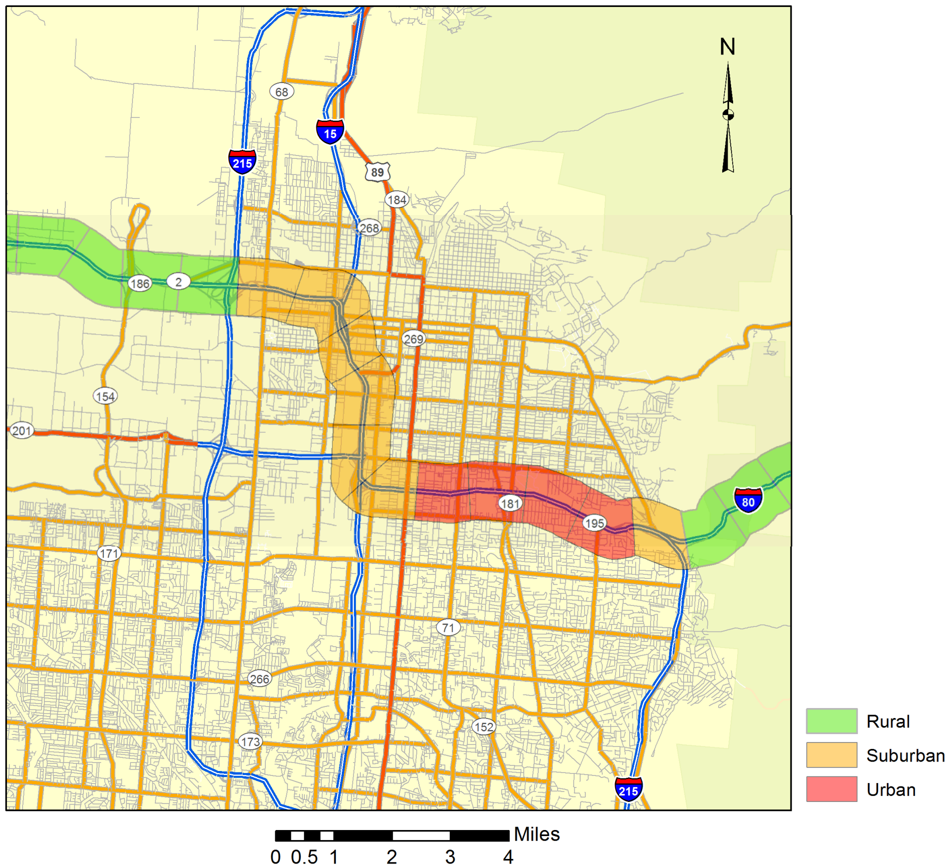

Figure 3 A segment of I-80 through Salt Lake City, UT

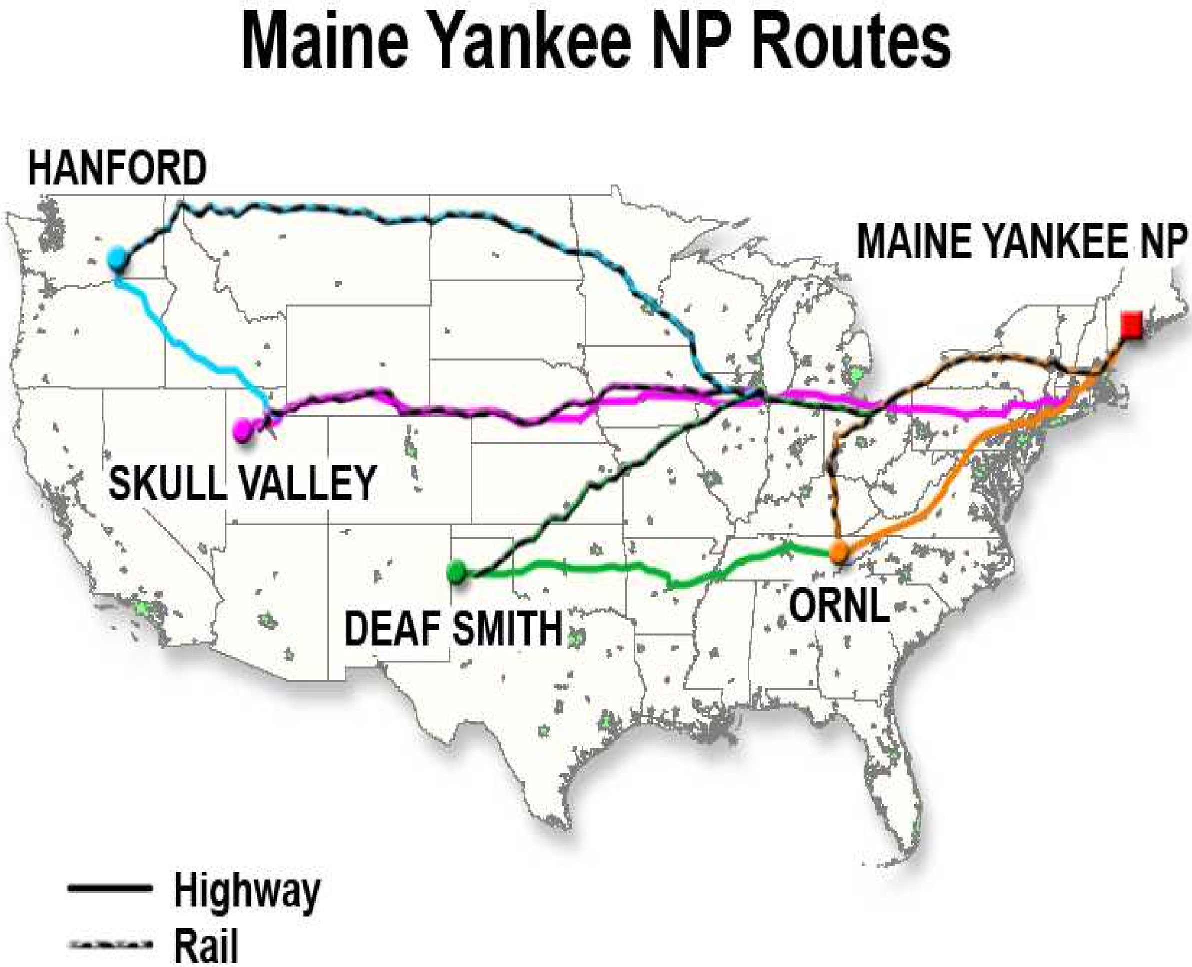

Figure 4   Highway and rail routes from Maine Yankee Nuclear Plant site

Kewaunee NP Routes

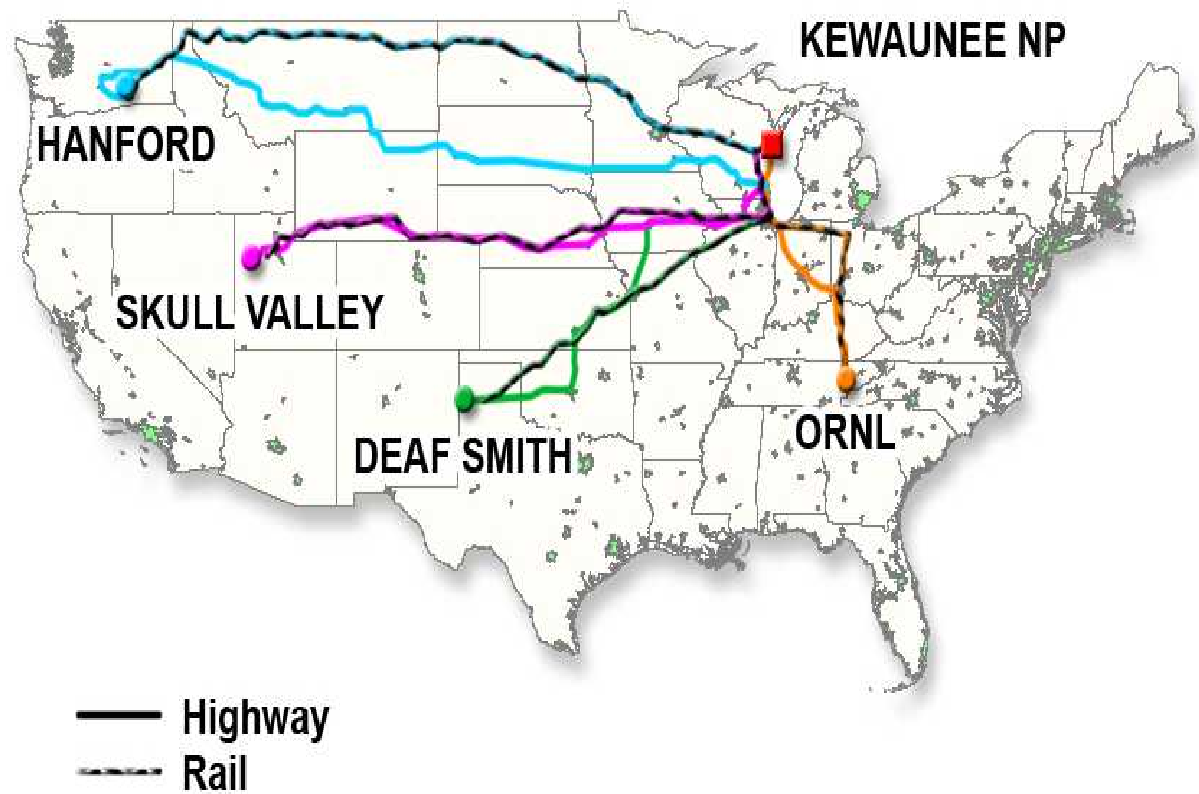

Figure 5 Highway and rail routes from Kewaunee Nuclear Plant

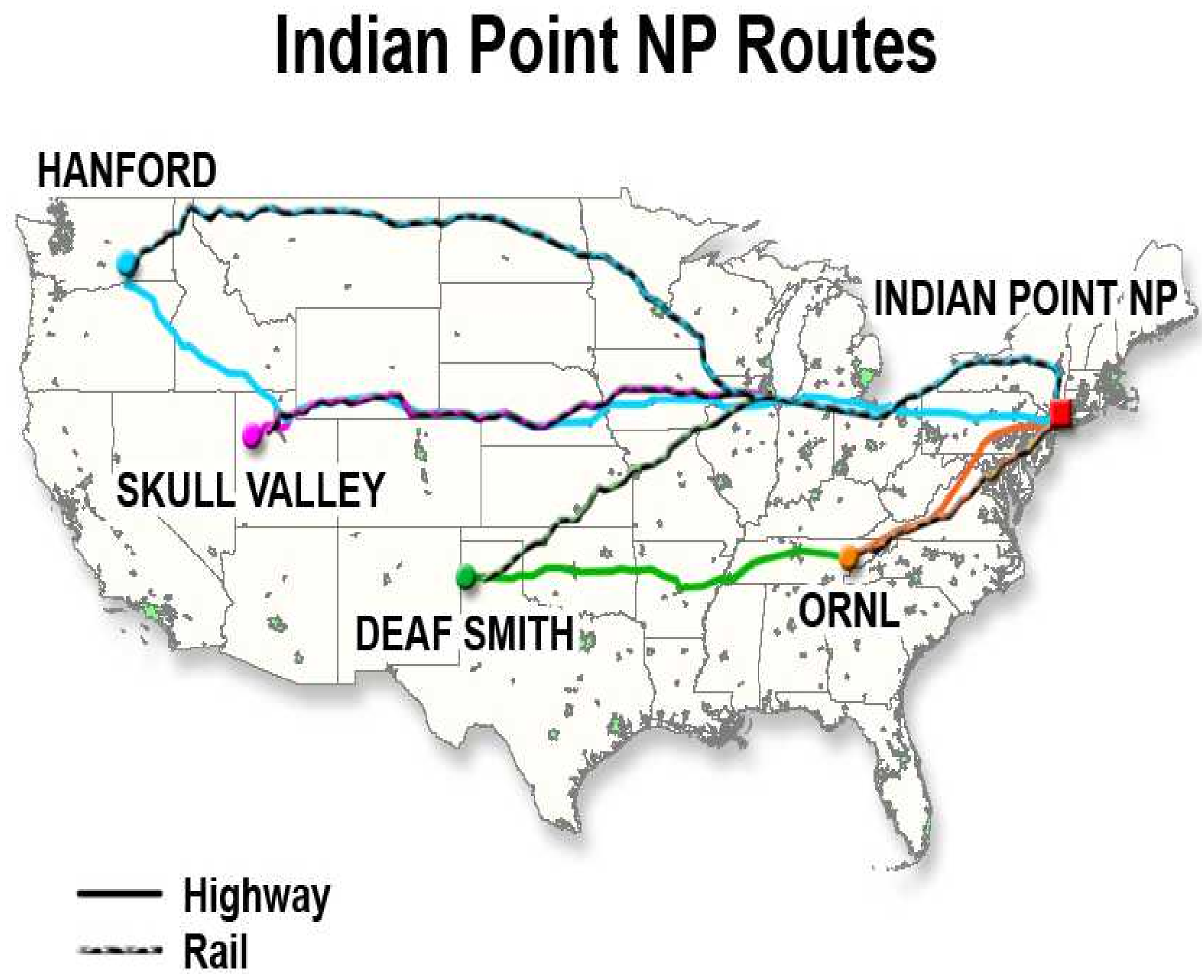

Figure 6 Highway and rail routes from Indian Point Nuclear Plant

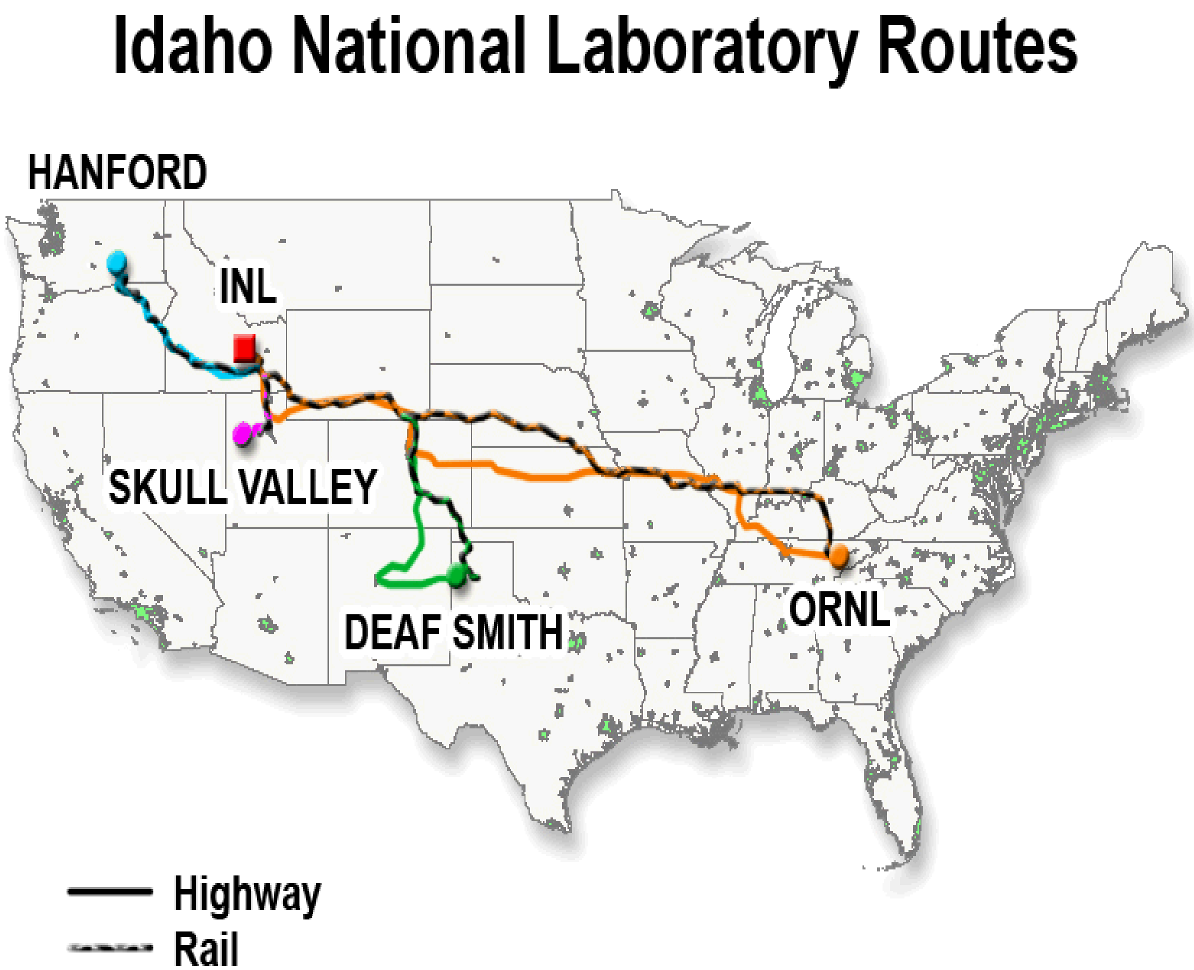

Figure 7 Highway and rail routes from Idaho National Laboratory

Collective doses, which depend on route length and on the populations along the route, were calculated for one shipment over each of 16 truck and 16 rail routes. Collective doses are reported as person-Sv. The sites where the shipments originated include two nuclear generating plants (Indian Point and Kewaunee), a storage site at a fully decommissioned nuclear plant (Maine Yankee), and INL. The routes modeled are shown in Table 2-5. Both truck and rail versions of each route are analyzed.

Table 4 Population and length of routes. Urban km. are Included in total km.

Origin	Destination	Population within 800 m (1/2 mile)		Total Kilometers		Urban Kilometers	
		Rail	Truck	Rail	Truck	Rail	Truck
Maine Yankee Site, ME	Hanford, WA	1,647,190	1,129,685	5,084	5,013	355	116
	Deaf Smith County,	1,321,024	1,427,973	3,36	3,596	211	165
	Skull Valley, UT	1,451,325	1,068,032	4,06	4,174	207	115
	Oak Ridge, TN	1,146,478	1,137,834	2,12	1,748	161	135
Kewaunee NP, WI	Hanford, WA	476,914	423,163	3,028	3,453	60	52
	Deaf Smith County,	677,072	494,920	1,88	2,146	110	60
	Skull Valley, UT	806,115	505,226	2,75	2,620	126	58
	Oak Ridge, TN	779,613	646,034	1,39	1,273	126	92
Indian Point NP, NY	Hanford, WA	961,026	869,763	4,781	4,515	229	97
	Deaf Smith County,	1,027,974	968,282	3,08	3,074	204	109
	Skull Valley, UT	1,517,758	808,107	3,97	3,672	229	97
	Oak Ridge, TN	1,146,245	561,723	1,26	1,254	207	60
Idaho National Lab, ID	Hanford, WA	164,399	132,662	1,062	959	20	15
	Deaf Smith County,	298,590	384,912	1,91	2,291	40	52
	Skull Valley, UT	169,707	132,939	455	466	26	19
	Oak Ridge, TN	593,680	569,240	3,30	3,287	75	63

These routes represent a variety of route lengths and populations. The routes include the eastern United States, western United States, and cross-country routes. They vary in length and include a variety of urban areas. Two of the three nuclear plants chosen as origin sites (Kewaunee, WI, and Maine Yankee, ME) and two of the destination sites (Hanford, WA, and Skull Valley, UT) are origins and destinations used in NUREG/CR-6672 (Sprung et al., 2000). Indian Point Nuclear Plant, NY, involves a different set of cross-country and east coast routes than Maine YankeeThe destination sites include two proposed repository sites (Deaf Smith County, TX, and Hanford, WA) (DOE, 1986), the site of the proposed private fuel storage facility (Skull Valley, UT), and ORNL. These routes were not intended to provide a "worst case" result, but were chosen to provide representative results over a broad range of conditions,

Population densities were updated from the 2000 census using the 2008 Statistical Abstract (U.S. Bureau of the Census 2008, Tables 13 and 21), which includes data up through 2006. The population data in Table 4 is directly from the WebTRAGIS outputs, and do not include the updates to 2006. All other tables in this NUREG use the updated 2006 populations. It was anticipated that 2010 census data would be available for this final report, but at the time of this writing it still was not possible to obtain updated population data in WebTRAGIS.

Table 5 show the collective radiation doses from rail transportation of slent nuclear fuel along the routes studied. Table 6 shows such doses for highway (truck) transportation.

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

FROM/TO	Rail-Lead				Rail-Steel			
	Rural	Suburban	Urban	Total	Rural	Suburban	Urban	Total
MAINE YANKEE								
ORNL	1.5x10^{-}	1.8x10^{-4}	9.0x10^{-6}	2.1x10^{-}	1.2x10^{-}	1.4x10^{-4}	6.8x10^{-6}	1.6x10^{-}
DEAF SMITH	1.9x10^{-}	2.2x10^{-4}	1.1x10^{-5}	2.5x10^{-}	1.4x10^{-}	1.7x10^{-4}	8.7x10^{-6}	1.9x10^{-}
HANFORD	2.4x10^{-}	2.6x10^{-4}	1.3x10^{-5}	2.9x10^{-}	1.8x10^{-}	2.0x10^{-4}	9.9x10^{-6}	2.3x10^{-}
SKULL	2.6x10^{-}	2.7x10^{-4}	1.0x10^{-5}	2.9x10^{-}	2.0x10^{-}	2.0x10^{-4}	7.6x10^{-6}	2.2x10^{-}
KEWAUNEE								
ORNL	1.0x10^{-}	1.1x10^{-4}	6.7x10^{-6}	1.3x10^{-}	7.9x10^{-}	8.3x10^{-5}	5.1x10^{-6}	9.6x10^{-}
DEAF SMITH	8.2x10^{-}	9.5x10^{-5}	5.8x10^{-6}	1.1x10^{-}	6.3x10^{-}	7.2x10^{-5}	4.4x10^{-6}	8.3x10^{-}
HANFORD	1.2x10^{-}	9.3x10^{-5}	3.0x10^{-6}	1.1x10^{-}	9.3x10^{-}	7.1x10^{-5}	2.3x10^{-6}	8.3x10^{-}
SKULL	1.4x10^{-}	1.2x10^{-4}	6.6x10^{-6}	1.4x10^{-}	1.1x10^{-}	9.0x10^{-5}	5.0x10^{-6}	1.1x10^{-}
INDIAN POINT								
ORNL	7.5x10^{-}	1.4x10^{-4}	1.4x10^{-5}	1.6x10^{-}	5.7x10^{-}	1.1x10^{-4}	1.1x10^{-5}	1.2x10^{-}
DEAF SMITH	1.7x10^{-}	1.8x10^{-4}	1.2x10^{-5}	2.0x10^{-}	1.3x10^{-}	1.3x10^{-4}	8.9x10^{-6}	1.5x10^{-}
HANFORD	2.2x10^{-}	2.1x10^{-4}	1.3x10^{-5}	2.5x10^{-}	1.7x10^{-}	1.6x10^{-4}	9.9x10^{-6}	1.9x10^{-}
SKULL	2.3x10^{-}	2.0x10^{-4}	1.3x10^{-5}	2.4x10^{-}	1.7x10^{-}	1.5x10^{-4}	1.0x10^{-5}	1.8x10^{-}
IDAHO NATIONAL LAB								
ORNL	1.8x10^{-}	1.1x10^{-4}	3.7x10^{-6}	1.3x10^{-}	1.4x10^{-}	8.6x10^{-5}	2.8x10^{-6}	1.0x10^{-}
DEAF SMITH	6.6x10^{-}	5.8x10^{-5}	2.2x10^{-6}	6.7x10^{-}	5.0x10^{-}	4.5x10^{-5}	1.7x10^{-6}	5.2x10^{-}
HANFORD	5.3x10^{-}	3.0x10^{-5}	1.1x10^{-6}	3.6x10^{-}	4.0x10^{-}	2.3x10^{-5}	8.2x10^{-7}	2.8x10^{-}
SKULL	3.0x10^{-}	2.5x10^{-5}	1.5x10^{-6}	3.0x10^{-}	2.3x10^{-}	1.9x10^{-5}	1.1x10^{-6}	2.2x10^{-}

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

FROM	TO	Truck-DU				
		Rural	Suburban	Urban	Urban Rush Hour[a]	Total
MAINE YANKEE	ORNL	$5.0x10^{-6}$	$8.9x10^{-5}$	$2.0x10^{-}$	$4.5x10^{-7}$	$9.6x10^{-5}$
	DEAF SMITH	$1.0x10^{-5}$	$1.2x10^{-4}$	$2.1x10^{-}$	$4.8x10^{-7}$	$1.4x10^{-4}$
	HANFORD	$1.4x10^{-5}$	$1.0x10^{-4}$	$1.5x10^{-}$	$3.2x10^{-7}$	$1.2x10^{-4}$
	SKULL VALLEY	$1.1x10^{-5}$	$9.5x10^{-5}$	$1.5x10^{-}$	$3.3x10^{-7}$	$1.1x10^{-4}$
KEWAUNEE	ORNL	$4.1x10^{-6}$	$4.6x10^{-5}$	$1.1x10^{-}$	$2.5x10^{-7}$	$5.2x10^{-5}$
	DEAF SMITH	$6.6x10^{-6}$	$3.9x10^{-5}$	$7.6x10^{-}$	$1.7x10^{-7}$	$4.7x10^{-5}$
	HANFORD	$9.1x10^{-6}$	$4.1x10^{-5}$	$7.0x10^{-}$	$1.5x10^{-7}$	$5.1x10^{-5}$
	SKULL VALLEY	$7.3x10^{-6}$	$3.1x10^{-5}$	$6.7x10^{-}$	$1.5x10^{-7}$	$3.9x10^{-5}$
INDIAN POINT	ORNL	$4.1x10^{-6}$	$6.4x10^{-5}$	$1.6x10^{-}$	$1.6x10^{-7}$	$6.9x10^{-5}$
	DEAF SMITH	$1.3x10^{-5}$	$1.3x10^{-4}$	$6.9x10^{-}$	$3.1x10^{-7}$	$1.4x10^{-4}$
	HANFORD	$1.3x10^{-5}$	$7.6x10^{-5}$	$2.6x10^{-}$	$2.6x10^{-7}$	$8.9x10^{-5}$
	SKULL VALLEY	$1.0x10^{-5}$	$6.6x10^{-5}$	$2.7x10^{-}$	$2.7x10^{-7}$	$7.7x10^{-5}$
IDAHO NATIONAL LAB	ORNL	$8.8x10^{-6}$	$5.3x10^{-5}$	$7.7x10^{-}$	$1.7x10^{-7}$	$6.3x10^{-5}$
	DEAF SMITH	$4.6x10^{-6}$	$3.0x10^{-5}$	$6.9x10^{-}$	$1.5x10^{-7}$	$3.7x10^{-5}$
	HANFORD	$5.5x10^{-6}$	$8.8x10^{-6}$	$1.1x10^{-}$	$4.2x10^{-8}$	$1.4x10^{-5}$
	SKULL VALLEY	$1.2x10^{-6}$	$1.0x10^{-5}$	$2.7x10^{-}$	$5.9x10^{-8}$	$1.2x10^{-5}$

[a] During rush hour RADTRAN halves the truck speed and doubles the vehicle density to take into account traffic jams and gridlock. The rush-hour collective dose is included in the total.

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

- Suburban residents sustain the largest dose for all routes and shipment modes. The urban dose is less than the suburban dose because urban residences are modeled as 83 percent shielded, while suburban residences are modeled as13 percent shielded.

- Urban residents sustain a larger dose from a single rail shipment than a truck shipment on the same State route even though urban population densities are similar and the external dose rates from the cask are nearly the same. As shown in Table 2-5, most (though not all) rail routes have more urban miles than the analogous truck route. Train tracks go from city center to city center whereas trucks carrying spent fuel must use interstates and bypasses. In several cases shown in Table 2-5, the rail route had twice as many urban miles as the corresponding truck route. Also, train speeds in urban areas are only one-fourth of truck speeds.

- Overall, collective doses are larger for a single shipment on rail routes than truck routes because rail routes are often longer, especially in the western United States, where there is rarely a choice of railroads and train speeds are lower than truck speeds, especially in urban areas. However, rail casks hold about six times as much spent fuel as the truck cask. Therefore, to move a given amount of spent fuel would take six truck shipments for each rail shipment, making the total dose from shipping by truck higher.

- The collective doses shown in Tables 5 and 6 are all very small. However, they are not the only doses people along the route receive. Background radiation is 0.0036 Sv (360 mrem) per year in the United States, or 4.1×10^{-7} Sv/hour (0.041 mrem/hr). The contribution of a single shipment to the population's collective dose is illustrated in the following example of the Maine Yankee to ORNL truck route:

  - From Table 6 the total collective dose to residents for this route is 9.6×10^{-5} person-Sv (9.6 person-mrem).

  - From Table 4, there are 1,137,834 people within 800 meters (1/2 mile) of the route.

  - Background is 4.1×10^{-7} Sv/hour (0.041 mrem/hr), which everyone is exposed to all the time, whether a shipment occurs or not.

  - A truck traveling at an average of 108 km per hour (67 mph) travels the 1,748 km (1086 miles) in 16 hours.

  - During those 16 hours, the 1,137,834 people will have received a collective background dose of 7.56 person-Sv, (756 person-rem) about 80,000 times the collective dose from the shipment.

  - To illustrate, the total collective dose during a shipment to these 1,137,834 people is not 9.6×10^{-5} person-Sv (9.6×10^{-3} person-rem), but 7.560096 person-Sv (756.0096 person-rem).

  - The NRC recommends that collective dose only be used for comparative purposes (NRC, 2008).

  - The appropriate comparison between the collective dose from this shipment of spent fuel is not a comparison between 9.6×10^{-5} person-Sv (9.6×10^{-3} person-rem) from the shipment and zero dose if there is no shipment, but between 7.560096 person-Sv (756.0096 person-rem) if there is a shipment and 7.560000 person-Sv (756.0000 person-rem) if there is no shipment.

Radiation Doses to Occupants of Vehicles Sharing the Route

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

The dose to occupants of other trains in this situation depends on train speed and the external dose rate from the spent fuel casks. Table 7 shows the collective dose to public passengers of trains sharing the route, assuming for calculation purposes that train occupants are represented by one person in each passing railcar in rural and suburban areas, and five people in urban areas. The rural and suburban collective doses probably are unrealistically high, since most freight rail going through rural and many suburban areas never encounters a passenger train. Data were not available to account for the occupancy of actual passenger trains, including commuter rail, that share rail routes with freight trains.

Table 7 Collective Doses (Person-Sv) per Shipment to Occupants of Trains Sharing Rail Routes (1 Sv=10^{5} mrem)

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

Unlike trains, trucks carrying spent fuel share the primary highway system with many cars, light trucks, and other vehicles. The occupants of any car or truck that passes the spent fuel cask in either direction will receive a small radiation dose. This dose is modeled in RADTRAN as shown in Figure 8. RADTRAN assumes there is always a vehicle in the adjacent lane.

The radiation dose to occupants of other vehicles depends on the exposure distance and time, the number of other vehicles on the road, and the number of people in the other vehicles. Occupants of the vehicles that share the route are closer to the cask than residents or others beside the route. Occupants of vehicles moving in the opposite direction from the cask are exposed to radiation from the cask for considerably less time because the vehicles involved are moving past each other. The exposure time for vehicles traveling in the same direction as the cask is assumed to be the time needed to travel the link at the average speed (Neuhauser et al., 2000). It is assumed that there is always a vehicle in the adjacent lane at the position of the cask and a vehicle in the same lane at the minimum distance from the cask.

The number of other vehicles that share truck routes is very large; the average number of vehicles per hour on U.S. interstate and primary highways in 2004 (Weiner et al., 2009, Appendix D) were:

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

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

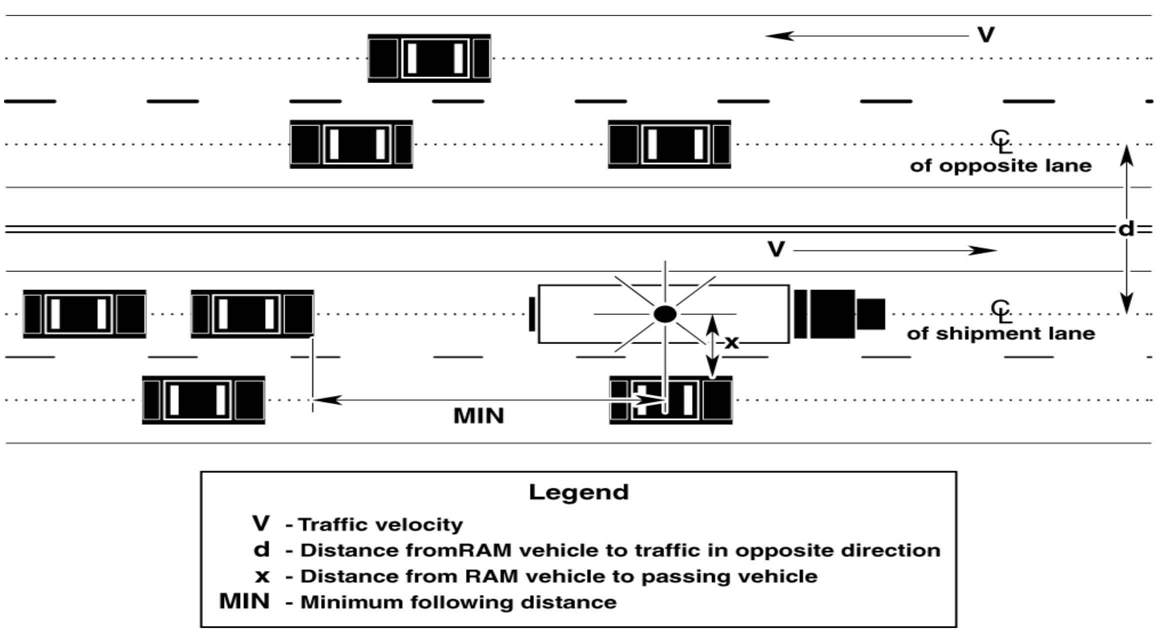

Figure 8 Diagram used in RADTRAN for calculating radiation doses to occupants of other vehicles (from Neuhauser et al., 2000)

The collective doses for truck traffic are shown in Table 8.

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

FROM	TO	Truck-DU				
		Rural	Suburban	Urban	Urban Rush Hour[a]	Total[b]
MAINE YANKEE	ORNL	$1.3\times10^{-}$	2.4×10^{-4}	$5.2\times10^{-}$	4.8×10^{-5}	4.6×10^{-4}
	DEAF SMITH	$2.8\times10^{-}$	3.3×10^{-4}	$6.9\times10^{-}$	6.4×10^{-5}	7.3×10^{-4}
	HANFORD	$4.5\times10^{-}$	3.0×10^{-4}	$4.3\times10^{-}$	4.0×10^{-5}	8.3×10^{-4}
	SKULL VALLEY	$3.7\times10^{-}$	2.5×10^{-4}	$4.4\times10^{-}$	4.5×10^{-5}	7.0×10^{-4}
KEWAUNEE	ORNL	$9.6\times10^{-}$	1.4×10^{-4}	$4.8\times10^{-}$	4.4×10^{-5}	3.3×10^{-4}
	DEAF SMITH	$1.8\times10^{-}$	8.9×10^{-5}	$2.2\times10^{-}$	2.0×10^{-5}	3.1×10^{-4}
	HANFORD	$3.4\times10^{-}$	1.4×10^{-4}	$3.3\times10^{-}$	3.0×10^{-5}	5.4×10^{-4}
	SKULL VALLEY	$2.4\times10^{-}$	8.6×10^{-5}	$2.5\times10^{-}$	2.3×10^{-5}	3.8×10^{-4}
INDIAN POINT	ORNL	$1.8\times10^{-}$	2.1×10^{-4}	$3.3\times10^{-}$	3.0×10^{-5}	4.6×10^{-4}
	DEAF SMITH	$2.8\times10^{-}$	3.1×10^{-4}	$5.6\times10^{-}$	5.2×10^{-5}	6.9×10^{-4}
	HANFORD	$4.2\times10^{-}$	2.2×10^{-4}	$4.8\times10^{-}$	4.4×10^{-5}	7.2×10^{-4}
	SKULL VALLEY	$3.6\times10^{-}$	2.2×10^{-4}	$4.5\times10^{-}$	4.1×10^{-5}	6.6×10^{-4}
IDAHO NATIONAL LAB	ORNL	$3.0\times10^{-}$	1.5×10^{-4}	$2.4\times10^{-}$	2.2×10^{-5}	5.0×10^{-4}
	DEAF SMITH	$2.2\times10^{-}$	7.3×10^{-5}	$2.7\times10^{-}$	2.5×10^{-5}	3.4×10^{-4}
	HANFORD	$1.0\times10^{-}$	8.5×10^{-5}	$9.5\times10^{-}$	8.7×10^{-6}	2.0×10^{-4}
	SKULL VALLEY	$3.7\times10^{-}$	3.2×10^{-5}	$8.5\times10^{-}$	7.8×10^{-6}	8.5×10^{-5}

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

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

Stops

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

People exposed at a rail stop include those listed below.

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

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

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

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

Inspection stations may be combined with truck weigh stations; therefore, inspectors of both the truck carrying the spent fuel and the trucks carrying other goods can be exposed in addition to crew from other trucks. “Stop-like” situations include inspections, vehicle escorts, and vehicle crew when the vehicle is in transit. Any of these situations can be modeled in RADTRAN.

Figure 9 is a diagram of the truck stop model. The inner circle defines the area occupied by people who share the stop with the spent fuel truck, who are between the truck and the building, and who are not shielded from the truck’s external radiation. People in buildings at the stop are assumed to be completely shielded.

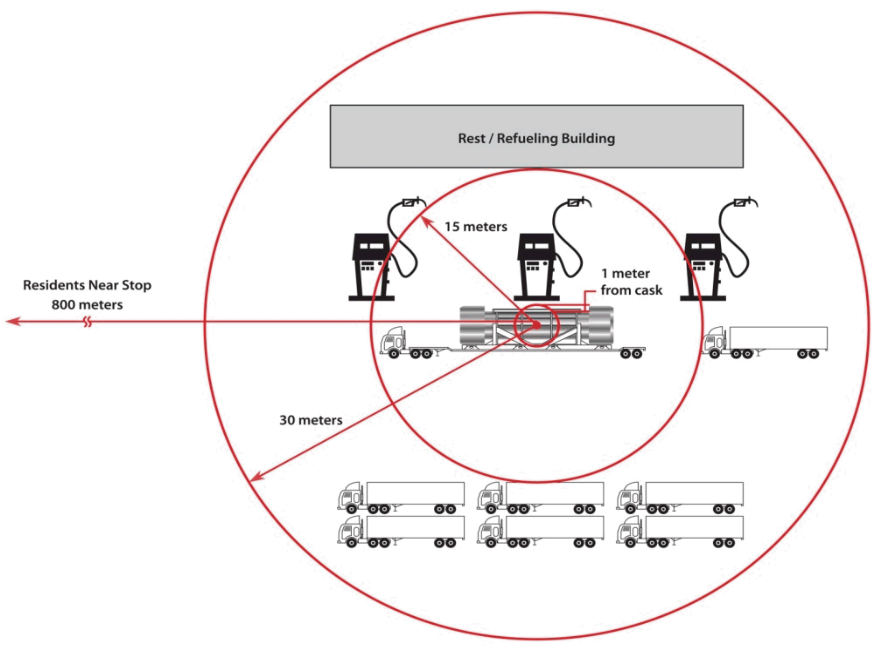

Figure 9 Diagram of truck stop model (not to scale).

Table 9 lists the input data used to calculate doses at truck and train stops.

Table 9 Input Data for Calculating Doses at Truck and Train Stops

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

[a] From Griego et al., 1996

The collective dose from the radioactive cargo to the railyard workers at 27-hour classification stops for the two rail casks studied is:

- 1.46×10^{-5} person-Sv (1.46 person-mrem) for the Rail-Lead
- 1.09×10^{-5} person-Sv (1.09 person-mrem) for the Rail-Steel

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

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

Table 10 shows the train stops doses to yard workers and residents near the stops for the Maine Yankee-to-Hanford rail route calculated using the input data from Table 9. The doses for all 16 rail routes were calculated in a similar fashion and are presented in Table 11. The difference in collective dose to residents near stops from route-to-route is primarily due to the different population densities at the classification stops, which may be either in rural or suburban areas.

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

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

Table 11 Collective Dose to Residents near Stops and Workers at Stops and Onboard the Train (Person-Sv) (1 Sv=10^5 mrem)

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

Table 12 shows the collective doses to residents near stops for the rural and suburban segments of the 16 truck routes studied calculated using the input data from Table 9. Urban stops were not modeled because truck stops serving semi-detached trailer rigs are unlikely to be located in urban areas and because the DOT routing rules require using urban bypass routes.

Table 12 Collective Doses to Residents near Truck Stops (Person-Sv)

Origin	Destination	Type	Persons/km² (persons/mi²)	Number of Stops	Dose
MAINE YANKEE	ORNL	Rural	19.9 (51.5)	1.14	7.4×10^{-7}
		Suburban	395 (1023)	0.93	1.0×10^{-5}
	Deaf Smith	Rural	18.6 (48.2)	2.47	1.5×10^{-6}
		Suburban	371 (961)	1.6	1.7×10^{-5}
	Hanford	Rural	15.4 (39.9)	4.33	2.2×10^{-6}
		Suburban	325 (842)	1.5	1.4×10^{-5}
	Skull Valley	Rural	16.9 (43.8)	3.5	1.9×10^{-6}
		Suburban	333 (861)	1.3	1.2×10^{-5}
KEWAUNEE	ORNL	Rural	19.8 (51.3)	0.81	5.2×10^{-7}
		Suburban	361 (935)	0.59	6.0×10^{-6}
	Deaf Smith	Rural	13.5 (35.0)	2.0	8.6×10^{-7}
		Suburban	339 (878)	0.52	5.0×10^{-6}
	Hanford	Rural	10.5 (27.2)	3.4	1.2×10^{-6}
		Suburban	316 (818)	0.60	5.4×10^{-6}
	Skull Valley	Rural	12.5 (32.4)	2.6	1.1×10^{-6}
		Suburban	325 (840)	0.44	4.1×10^{-6}
INDIAN POINT	ORNL	Rural	20.5 (53.1)	0.71	4.7×10^{-7}
		Suburban	388 (1005)	0.71	7.8×10^{-6}
	Deaf Smith	Rural	17.1 (44.3)	2.3	1.3×10^{-6}
		Suburban	370 (958)	1.2	1.3×10^{-5}
	Hanford	Rural	13.0 (33.7)	4.1	1.8×10^{-6}
		Suburban	338 (875)	1.1	1.1×10^{-5}
	Skull Valley	Rural	14.2 (36.8)	3.3	1.5×10^{-6}
		Suburban	351 (909)	0.93	9.3×10^{-6}
IDAHO NATIONAL LAB	ORNL	Rural	12.4 (32.1)	3.1	1.3×10^{-6}
		Suburban	304 (787)	0.72	6.3×10^{-6}
	Deaf Smith	Rural	7.8 (20.2)	2.3	5.8×10^{-7}
		Suburban	339 (878)	0.35	3.4×10^{-6}
	Hanford	Rural	6.5 (16.8)	0.43	9.0×10^{-8}
		Suburban	200 (518)	0.57	3.2×10^{-6}
	Skull Valley	Rural	10.1 (26.2)	0.42	1.4×10^{-7}
		Suburban	343 (888)	0.11	1.1×10^{-6}

OCCUPATIONAL DOSES

Radiation doses to workers are limited in accordance with the regulations in 10 CFR Part 20, which states maintaining worker exposure to ionizing radiation "as low as is reasonably achievable" (ALARA). ALARA applies to occupational doses since workers could be exposed to much larger doses than the general public.

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

Table 13 summarizes the occupational doses. All doses are reported per hour except for the truck stop worker (reported for the maximum truck stop time) and the rail classification yard workers. All doses are individual doses (Sv) except for the railyard worker collective doses.

Table 13 Occupational Doses and Dose Rates from Routine Incident-Free Transportation

Cask and route type	Train crew in transit: 3 people; person-Sv/km	Truck crew in transit 2 people; person-Sv/km[a]	Escort: Sv/hour[a]	Inspector: Average Sv per 8 inspections[c]	Truck stop worker: Sv per stop	Rail classification yard workers: person-Sv /stop
Rail-Lead rural/suburban	$4.3x10^{-7}$		$5.8x10^{-6}$			$1.5x10^{-5}$
Rail-Lead urban	$7.2x10^{-7}$		$5.8x10^{-6}$			[b]
Rail-Steel rural/suburban	$3.3x10^{-7}$		$4.4x10^{-6}$			$1.1x10^{-5}$
Rail-Steel urban	$5.5x10^{-7}$		$4.4x10^{-6}$			[b]
Truck - DU rural/suburban		$3.8x10^{-7}$	$4.9x10^{-9}$	$1.5x10^{-3}$	$6.7x10^{-6}$	
Truck - DU urban		$3.6x10^{-7}$	$4.9x10^{-9}$			

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

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

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

Doses to rail crew and rail escorts are similar. Spent fuel may be transported in dedicated trains so that both escorts and train crew are assumed to be within a distance of one railcar length of the railcar carrying the spent fuel. Escorts in the escort car are not shielded because they must maintain line-of-sight to the railcar carrying spent fuel. Train crew members are in a crew compartment and were assumed to have some shielding, resulting in an estimated dose about 25 percent less than the escort. The largest collective doses are to railyard workers. The number of workers in railyards is not constant and the number of activities that brings these workers into proximity with the shipment varies as well. This analysis assumes the dose to the worker doing an activity for each activity (e.g., inspection, coupling and decoupling the railcars, moving the railcar into position for coupling). The differences between doses in the Rail-Lead case and the Rail-Steel case reflect differences in cask dimensions and in external dose rate.

Truck crew members are shielded so that they receive a maximum dose of 2.0×10^{-5} Sv/hr (2.0 mrem/hr). This regulatory maximum was imposed in the RADTRAN calculation. Truck inspectors generally spend about 1 hour within 1 meter of the cargo (Weiner and Neuhauser, 1992), resulting in a relatively large dose. An upper bound to the duration of a truck refueling stop is about 50 minutes (0.83 hours) (Griego et al., 1996). The truck stop worker whose dose is reflected in Table 13 is assumed to be outside (unshielded) at 15 meters from the truck during the stop. Truck stop workers in concrete or brick buildings are shielded from any radiation.

SUMMARY AND CONCLUSIONS

The individual and collective doses calculated are for a single shipment and, even though overestimated, they are uniformly very small. Individual doses are comparable to background doses and are less than doses from m medical diagnostic procedures. Collective doses are orders of magnitude less than the collective background dose, as shown in Figure 10 for an example shipment from Maine Yankee to ORNL. This route assumes ten inspection stops at state boundaries. The NRC recommends that collective doses (average doses integrated over a population) only be used for comparisons (NRC, 2008). The proper comparison for collective doses is between the background collective dose plus the shipment dose and the background dose if there is no shipment. The collective dose, however, is *never* zero in the absence of a shipment.

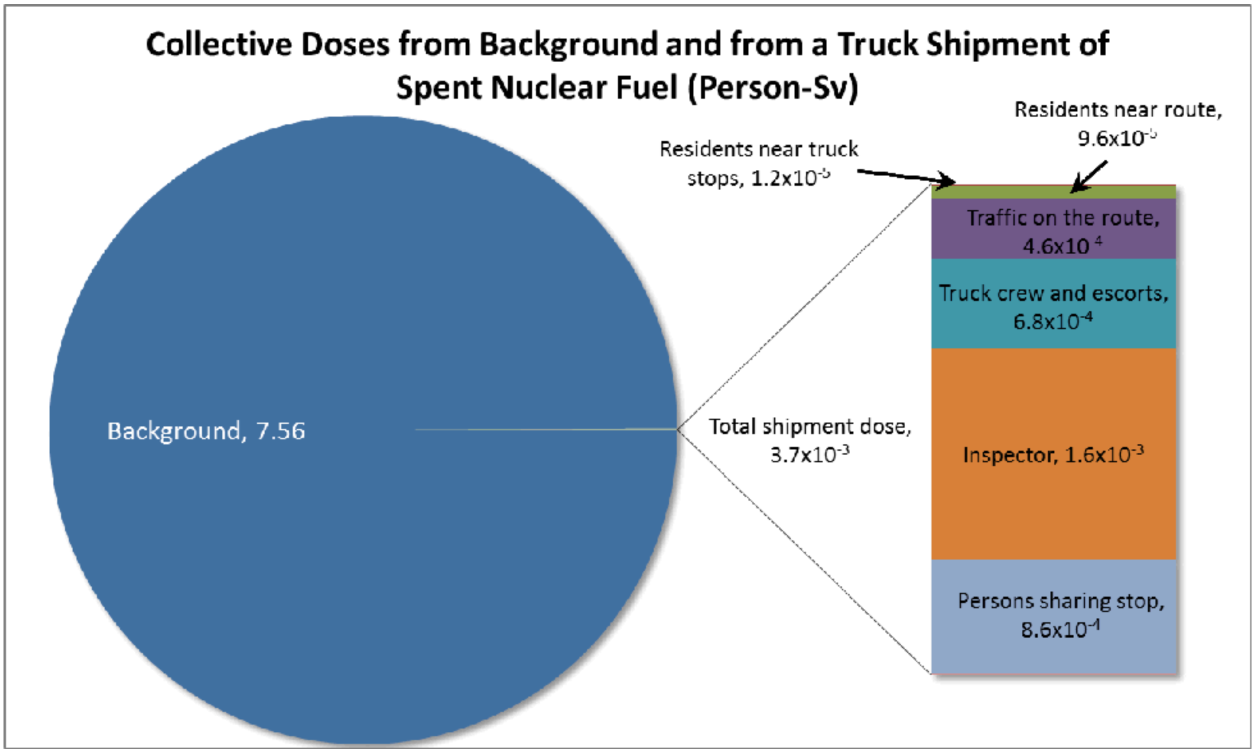

Figure 10 Collective doses from background and from Maine Yankee to ORNL truck shipments of spent nuclear fuel (person-Sv) (1 Sv=10^5 mrem)

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