ANALYSIS OF MAXIMUM REASONABLY FORESEEABLE ACCIDENTS FOR THE YUCCA MOUNTAIN DRAFT ENVIRONMENTAL IMPACT STATEMENT (DEIS)

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ABSTRACT

Accidents could occur during the transportation of spent nuclear fuel and high-level radioactive waste. This paper describes the risks and consequences to the public from accidents that are highly unlikely but that could have severe consequences. The impact of these accidents would include those to a collective population and to hypothetical maximally exposed individuals (MEIs). This document discusses accidents with conditions that have a chance of occurring more often than 1 in 10 million times in a year, called “maximum reasonably foreseeable accidents”. Accidents and conditions less likely than this are not considered to be reasonably foreseeable.

INTRODUCTION

The *Draft Environmental Impact Statement (DEIS) for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE 1999) analyzed transportation accident scenarios that would have annual probabilities exceeding 1 in 10 million (10^{-7}) and that would have the highest consequences. The RISKIND code was used to estimate population dose (person-rem) and dose to hypothetical MEIs (rem) that would occur as a consequence of these accidents. The analysis converted these doses to estimated numbers of latent cancer fatalities using the risk factor of 5.0E-04 fatal cancers per person-rem, as recommended by the International Commission on Radiological Protection (ICRP 1991).

The RISKIND program was selected for this analysis because it has been used for analogous calculations in other environmental impact statements and assessments.

Maximum reasonably foreseeable impacts from accident scenarios for the transportation of spent nuclear fuel and high-level radioactive waste would be characterized by extremes of mechanical (impact) forces, heat (fire), and other conditions that would have maximal reasonably foreseeable consequences. The mechanical forces and heat that are part of these accident scenarios exceed the design limits of transportation cask structures and materials. The performance of transportation casks may be demonstrated through a combination of physical tests and mathematical analyses (Fischer et al. 1987). In addition, these forces and heat would be applied to the structures and surfaces of a cask in a way that would cause the greatest damage and be most likely to result in release of radioactive materials to the environment. The most severe accident scenarios presented in the Yucca Mountain DEIS would release radioactive material.

A new methodology to reexamine spent fuel shipment risk estimates (Sprung et al. 2000) will be evaluated for use in the Yucca Mountain Final Environmental Impact Statement (FEIS).

The Yucca Mountain DEIS analyzed two transportation scenarios: the mostly legal-weight truck scenario and the mostly rail scenario. To evaluate the impacts of maximum reasonably foreseeable accidents on exposed populations for each of these scenarios, the 20 most populous urbanized areas in the United States were identified. These data, along with the population density around the Las Vegas area (including tourists), were estimated and were used to develop the basis for an urbanized area demographics model for use in evaluating consequences of these maximum reasonably foreseeable accidents to an urban population.

ESTIMATE OF THE LIKELIHOOD OF MAXIMUM REASONABLY FORESEEABLE ACCIDENTS

For an accident to be "reasonably foreseeable", the product of the following four parameters must exceed $1x10^{-7}$ [DOE Green Book (DOE 1993)].

?? Expected accidents
?? Conditional probability of an accident severe enough to cause a release of radioactive material
?? Likelihood of an accident occurring in a populated area
?? Probability of particular weather conditions being in effect when an accident occurs

The number of accidents expected annually is the product of the cumulative shipment distance and the applicable state-specific accident rate (Saricks and Tompkins, 1999). The state-specific accident rates (accidents per kilometer of vehicle travel) used in the analysis included accident statistics for commercial motor carrier operations for the Interstate Highway System, other U.S. highways, and state highways for each of the 48 contiguous states (Saricks and Tompkins 1999). The analysis also used average accident rates for railroads in each state. Thus, the data reflects accident and fatality rates that apply to commercial motor carriers and railroads.

Conditional probabilities for classes of severe accidents that could lead to releases of radioactive materials were estimated based upon the selection of transportation accident scenarios according to a methodology developed by the Nuclear Regulatory Commission (NRC) in Fischer et al. 1987. Fischer et al. is often referred to as the "Modal Study". The Modal Study developed 20-accident severity categories based on the combination of mechanical stress (impact) and thermal stress (fire) incident upon a spent nuclear fuel-shipping container during an accident. Figure 1 is a diagram of accident severity categories showing the conditional probabilities for truck and rail for each combination of mechanical and thermal stress. In terms of potential to release radioactivity to the environment, the most severe of reasonably foreseeable accidents would be in one of the eight categories of very severe accidents. The fractions and characteristics of radioactive materials that would be released in an accident were estimated to be the same for these eight categories. That is, for a shipment of spent nuclear fuel the amount and characteristics of radioactive material assumed to be released in a Category R(4,1) accident would be the same as those for an accident in Category R(4,2), R(4,3), R(4,4), R(4,5), R(1,5), R(2,5), or R(3,5). Therefore, the conditional probabilities of occurrence of these categories can be summed and the sum used to calculate a collective probability for the most severe of the accidents addressed in this analysis. Thus, the conditional probability of a truck accident of the greatest severity that is analyzed would be 0.0000098 per accident event (about 1 chance in 100,000 per accident).

Table 1 presents the release fractions for severity category 6 accidents. These release fractions are based upon best engineering judgment. Release fractions are shown for groups of radionuclides. All of the radionuclides in a particular group exhibit very similar physical and chemical behavior, which determines the release fraction. That is, all radionuclides released as fine particulate matter, for example, will exhibit essentially the same behavior in an accident involving a release.

Structural response (maximum strain on inner shell, percent)		R (x,1)	R (x,2)	R (x,3)	R (x,4)	R (x,5)
S_3 (30)	P_t P_r	R (4,1) 1.532×10^{-7} 1.786×10^{-9}	R (4,2) 3.926×10^{-14} 3.290×10^{-13}	R (4,3) 1.495×10^{-14} 2.137×10^{-13}	R (4,4) 7.681×10^{-16} 1.644×10^{-13}	R (4,5) $< 1 \times 10^{-16}$ 3.459×10^{-14}
S_2 (2)	P_t P_r	R (3,1) 1.7984×10^{-3} 5.545×10^{-4}	R (3,2) 1.574×10^{-7} 1.021×10^{-7}	R (3,3) 2.034×10^{-7} 6.634×10^{-8}	R (3,4) 1.076×10^{-7} 5.162×10^{-8}	R (3,5) 4.873×10^{-8} 5.296×10^{-8}
S_1 (0.2)	P_t P_r	R (2,1) 3.8192×10^{-3} 2.7204×10^{-3}	R (2,2) 2.330×10^{-7} 5.011×10^{-7}	R (2,3) 3.008×10^{-7} 3.255×10^{-7}	R (2,4) 1.592×10^{-7} 2.531×10^{-7}	R (2,5) 7.201×10^{-8} 1.075×10^{-8}
	P_t P_r	R (1,1) 0.994316 0.993962	R (1,2) 1.687×10^{-5} 1.2275×10^{-3}	R (1,3) 2.362×10^{-5} 7.9511×10^{-4}	R (1,4) 1.525×10^{-5} 6.140×10^{-4}	R (1,5) 9.570×10^{-6} 1.249×10^{-4}
			T_1 (500)	T_2 (600)	T_3 (650)	T_4 (1,050)

Thermal response (lead mid-thickness temperature, ?F)

Legend

R(x,y) = The label used to identify the cell in the accident response matrix located at the x row from the bottom of the matrix and y column from the left of the matrix. Thus, (R1,1) is the identifier for the cell in the lower left corner of the matrix.

P_t = Probability of occurrence assuming a truck accident occurs

P_r = Probability of occurrence assuming a rail accident occurs

Source: Fischer et al. (1987).

Figure 1. Probability matrix for mechanical forces and heat in transportation accidents

Table 1. Fractions of selected radionuclides in commercial spent nuclear fuel projected to be released from casks in transportation accidents for severity category 6 accidents

Cask response region	**Release fraction**[a]				
	Inert gas	**Iodine**	**Cesium**	**Ruthenium**	**Particulates**
R(1,5),R(2,5),R(3,5),R(4,5), R(4,1),R(4,2),R(4,3),R(4,4)	$6.3?10^{-1}$	$4.3?10^{-2}$	$2.0?10^{-3}$	$4.8?10^{-4}$	$2.0?10^{-5}$

a. Source: Fischer et al. (1987).

The likelihood of an accident occurring in a specific population area depends on the percentage of travel that occurs in urban, suburban, and rural areas. For this analysis, urban and suburban areas were combined to determine distance traveled in urbanized areas. Rural areas were treated separately; they typically comprise more than 80 percent of route travel but have low population densities.

At present, about 10 years before shipments could begin, DOE has not determined the specific routes it would use to ship spent nuclear fuel and high-level radioactive waste to the proposed repository. Nonetheless, this analysis used current regulations governing highway shipments and historic rail industry practices to select existing highway and rail routes to estimate potential routing distances. The route characteristics used were the transportation mode (highway or railroad) and, for each of the modes, the total distance between an originating site and the repository. In addition, the analysis estimated the fraction of travel that would occur in rural, suburban, and urban areas for each route. The fraction of travel in each population zone was determined using 1990 census data to identify population-zone impacts for route segments. The highway routes were selected for the analysis using the HIGHWAY (Johnson et al. 1993a) computer program and routing requirements of the Department of Transportation for shipments of Highway Route-Controlled Quantities of Radioactive Materials (49 CFR 397.101).

Rail transportation routing of spent nuclear fuel and high-level radioactive waste shipments is not regulated by the Department of Transportation. As a consequence, the routing rules used by the INTERLINE computer program (Johnson et al. 1993b) assumed that railroads would select routes using historic practices. Because the routing of rail shipments would be subject to future, possibly different practices of the involved railroads, DOE could use other rail routes. DOE has determined that the HIGHWAY and INTERLINE programs are appropriate for calculating routes and related information for use in transportation analyses (Maheras and Pippen 1995).

The analyses of accident consequences assumed that during and following severe accidents, radioactive materials would be released from casks into the atmosphere, where the materials would be carried by wind. Because it is not possible to predict specific locations where transportation accidents would occur, the analysis used data that describe average atmospheric conditions across the continental United States. These data can be found in Section 10 of the *Environmental Baseline File for National Transportation* (TRW 1999). Averages of data from 177 meteorological data collection locations and the RISKIND computer program (Yuan et al. 1995) were used to estimate the dispersion of radioactive materials potentially released into the atmosphere in severe accidents. The RISKIND computer program used the meteorological information to estimate the consequences of maximum reasonably foreseeable accidents.

National average, or expected, meteorological conditions (Pasquill Stability Class D dispersion conditions and 4.47 meters per second wind speed) are an average over the six Pasquill stability classes and the range of possible wind speeds consistent with those classes, and can be assumed to be the conditions expected to prevail during all accidents. Thus, the analysis assumed that the probability of average meteorological conditions occurring would be 1.0.

Very stable meteorological conditions (represented by Pasquill Stability Class F + G and 0.89 meter per second wind speed) occur nationally approximately 10 percent of the time. These conditions lead to the least dilution of airborne material, and therefore to the largest consequences for a given release for the exposed population. The analysis assumed that the probability of these conditions occurring during an accident would be 0.10.

POPULATION DENSITIES USED IN CONSEQUENCE ANALYSIS

The *Environmental Baseline File for National Transportation* (TRW 1999) identifies the 20 most populous urbanized areas in the United States. Because the DEIS was published before the 2000 Census was taken, the analysis used the computer software CensusCD+Maps (Geolytics 1998) to project the population of the Las Vegas metropolitan area for the year 2000. The average daily population of visitors to Las Vegas was added to the Las Vegas population data estimated using the CensusCD+Maps software. The analysis assumed the visitor population in the Las Vegas metropolitan area would be concentrated in the 16-kilometer (10-mile) diameter core of the city. The Las Vegas data were used in the analysis along with the population distributions of the 20 largest U.S. cities to estimate the distribution of population in urbanized areas in the United States. The urbanized area population data were used in the analysis to evaluate the consequences of maximum reasonably foreseeable accidents and sabotage events. Table 2 presents the list of the 20 largest urbanized areas in the United States and Las Vegas, Nevada.

Table 2. The population of the top 20 urbanized areas in the United States (plus Las Vegas)

Urbanized area	Population (0 – 80 km)
New York	16,745,143
Los Angeles	11,995,083
Chicago	7,997,522
Philadelphia	7,417,369
Detroit	4,645,291
San Francisco	5,343,862
Washington	5,590,633
Dallas	3,923,686
Houston	3,680,606
Boston	5,998,075
San Diego	2,530,629
Atlanta	3,099,872
Minneapolis	2,648,573
Phoenix	2,184,434
St. Louis	2,566,376
Miami	3,446,036
Baltimore	5,520,605
Seattle	2,983,686
Tampa	2,792,637
Pittsburgh	2,969,521
Las Vegas	1,464,995[a,b]

a. Includes average visitor population of 292,000.

b. Obtained from CensusCD+Maps? software (Geolytics 1998) using longitude and latitude coordinates of (36.17432, 115.15408) as input

The analysis of consequences of maximum reasonably foreseeable accidents used the demographics model estimates (using 1990 U.S. Census Data) from 0 to 80 kilometers (0 to 50 miles) for the largest 20 urbanized areas (plus Las Vegas) in the United States. Each of the concentric rings from

0 to 50 miles (0 to 5 miles, 5 to 10 miles, 10 to 15 miles, 15 to 20 miles, 20 to 25 miles, and 25 to 50 miles) was analyzed separately using the RISKIND code and summed to determine the total accident consequence impact.

Table 3 presents a summary of the population density data average of the largest 20 urbanized areas (plus Las Vegas) in the United States.

Table 3. Average top 20 urbanized area population information 0 to 80 kilometers (plus Las Vegas, Nevada)

Radius (km)	Area of circle (km^2)	Population inside concentric ring	Population density (persons/ km^2)	Concentric ring distance	Population inside ring	Area of ring (km^2)	Population density (persons/ km^2)
8.05	203.33	553,025	2,720	0 to 8.05	553,025	203.33	2,720
16.09	813.32	1,509,941	1,857	8.05 to 16.09	956,917	609.99	1,569
24.14	1829.97	2,282,968	1,248	16.09 to 24.14	773,027	1,016.65	760
32.18	3253.28	2,891,397	889	24.14 to 32.18	608,429	1,423.31	427
40.23	5083.26	3,359,718	661	32.18 to 40.23	468,321	1,829.98	256
80.45	20333.02	5,025,935	247	40.23 to 80.45	1,666,217	15,249.76	109

RADIOACTIVE CONTENTS OF CASKS FOR ANALYZING CONSEQUENCES OF MAXIMUM REASONABLY FORESEEABLE ACCIDENTS

The analysis based its calculation of maximum consequences on typical pressurized water reactor spent nuclear fuel described in Appendix A of the Yucca Mountain DEIS. Pressurized water reactor fuel makes up the largest part of the inventory that would be shipped to the repository under the Proposed Action. Calculations were also calculated for other types of materials, including boiling water reactor spent nuclear fuel, DOE spent fuel, and high-level waste. The calculations demonstrate that the PWR fuel provides the bounding impacts.

Appendix A of the Yucca Mountain EIS lists radionuclide inventories for each material type analyzed. The release fractions for each type of material are described in Table 1. The analysis used estimates of releases (cask inventory times release fractions) to the atmosphere as a source term and the RISKIND computer code (Yuan et al., 1995) to calculate radiological consequences to hypothetical MEIs and populations. The consequences were estimated for rural and urbanized area populations postulated to live within 80 kilometers (50 miles) of the location of a severe accident.

ANALYSIS RESULTS FOR MAXIMUM REASONABLY FORESEEABLE ACCIDENTS

Accident consequences are presented in Table 4 for typical pressurized water reactor spent nuclear fuel. The results are for a category 6 severe accident during legal-weight truck or rail transportation in an urbanized area under neutral and stable atmospheric conditions for shipments of pressurized water reactor spent nuclear fuel. This material represents about half of the material shipped and would result in the release of the most radioactivity based on radionuclide content and form (spent nuclear fuel or high-level radioactive waste).

The RISKIND calculations provided estimates of population dose (person-rem) and dose to hypothetical MEIs (rem). The analysis converted these doses to estimated numbers of latent cancer fatalities using the risk factor of 5.0E-04 fatal cancers per person-rem recommended by the International Commission on Radiological Protection (ICRP 1991).

Table 4. Maximum reasonably foreseeable rail and truck accident consequences (urbanized area)

Population ring	**Population dose (person-rem)**			
	Stability class D (50%)		**Stability class F (95%)**	
	Rail accident	**Truck accident**	**Rail accident**	**Truck accident**
1 (0 to 8 km)	13,400	2,050	58,100	8,900
2 (8 to 16 km)	2,690	413	2,600	398
3 (16 to 24 km)	829	127	267	41
4 (24 to 32 km)	345	53	43	7
5 (32 to 48 km)	167	26	9	1
6 (48 to 80 km)	287	44	2	0
Total (person-rem)	17,718	2,712	61,061	9,347
Total (LCFs)	8.9	1.4	30.5	4.7

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