Fallon Impact Report

Transportation of Spent Nuclear Fuel by Highway to Yucca Mountain

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Executive Summary

If a high-level waste repository opens at Yucca Mountain, south of Fallon on US 95, a large number of truck shipments of nuclear waste are expected on US 95. Truck shipments of nuclear waste through Fallon would lead to a radiation dose to the public even if the transport is incident-free, because no shielding material can reduce direct gamma radiation by 100 %. As a result, residents, drivers, pedestrians and workers will get a radiation dose, which depends on the recipient's exposure proximity and duration. Depending on the population estimate, the population dose due to incident-free transportation of the entire waste that is planned to pass Fallon is as high as 9.45 person-rem. Even though this dose and the resulting population risk are relatively small, it nevertheless increases the risk to develop cancer.

In case of a severe accident involving a nuclear shipment, the dose to individuals and the population will be much higher. In contrast to incident-free transportation, such an accident would cause both acute and long-term exposures, because radioactive particulates would be dispersed in the environment and continue to lead to radiation exposures. A severe transportation accident leading to a release of radioactive particulates is possible and credible. It could be caused by high impact, long duration fire or sabotage. Such an accident would lead to high radiation exposures due to inhalation (acute dose) and ground shine (long-term dose). Additional exposure to radiation would arise from ingestion of food, water and soil, even though the dose due from the ingestion pathway is very small in comparison to the inhalation and ground shine pathways. However, since food produced in the Fallon area is exported to and consumed in large parts of Nevada and California, an accident in Fallon could have health impacts throughout the region, if this food source is not interdicted.

Without remediation and assuming a long-term exposure of 50 years, about 10 % of the present population of Fallon would develop fatal cancer as a consequence of the accident. This means that either a thorough remediation or a permanent evacuation will have to take place. In order to comply with EPA's Protective Action Guide (PAG) or CERCLA cleanup standards, an area of 39 - 193 km^2 would have to be remediated. We have not calculated the radiation exposure of clean-up workers, and the economic costs of such an accident, which would be considerable. DOE shipments are insured under Price-Anderson insurance, but the timing of the payouts is problematic since this requires a Congressional authorization.

Local government could undertake several measures. Shipping casks should be designed to withstand all likely accidents that could take place on highways or by rail. Casks are presently designed to withstand a 30 mph crash into an unyielding object, and a fire of 1,475° F for 30 minutes and in any case are not physically tested. Pressure by local government could be brought to bear on Congress and federal agencies to improve the safety of shipping containers. Several mitigating actions can be undertaken on the local level. Emergency personnel should be trained and equipped to handle radiation-related accidents, so that the hazard can be quickly evaluated and emergency measures, including evacuation and interdiction of the food supply, taken.

Introduction

Background

In the event that the proposed geologic repository at Yucca Mountain, Nevada, begins accepting waste, the State of Nevada will have the option of designating preferred routes for transportation of spent nuclear fuel and high-level radioactive waste to the facility. There is evidence that if truck shipments are used to transfer spent fuel to Yucca Mountain, the State of Nevada will designate US95 as a preferred route, connecting Interstate 80 with the Yucca Mountain site. Churchill County would be affected by this potential route, with its largest city and County seat, Fallon, located at the intersection of US50 and US95.

Previous studies by Churchill County have estimated the likely number of truck shipments through the city of Fallon. In this study, we use these estimates to predict the incident-free doses likely to be incurred by residents near the roadway, motorists sharing the roadway with the shipments, and transients lodging near the roadway. Also, we calculate the dose resulting from a severe accident involving a nuclear shipment.

City of Fallon and Surroundings

Fallon is located 60 miles east of Reno and 70 miles east of the California border at the junction of Highways 50 and 95A, with US95 forming its main street running straight from north to south. Its elevation is 4,500 feet above sea level. Fallon had a population of 7,536 in 2000[1]. According to the Churchill County Impact Report[2], the corridor population in 1999 (the population within 1 mile of US95 or US50) is estimated to be 11,483 for the US95 corridor. Almost the entire population of the US 95 corridor resides within 4 miles of Fallon. This corridor population is expected to grow to 14,261 by 2010 and to 20,251 by 2020[3]. We assume the same population growth ratio for Fallon and Churchill County and calculate a projected population for 2010 and 2020 (Table 1).

Table 1. Population estimates for Churchill County

Year	City of Fallon	US95 corridor	Churchill County
1999/2000	7,536	11,483	23,982
2010	9,359	14,261	29,784
2020	13,290	20,251	42,294

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[1] US Census 2000.

[2] Massey R, RCS, *Churchill County Impact Report*, August 2001, p. 15

[3] *Ibid*

Number of Shipments Expected to Pass Through Fallon

The most variable estimate concerns the number of shipments expected to travel the US95 corridor en route to Yucca Mountain. Estimates will vary depending on the expected number of truck vs. rail shipments, the number of shipments expected to take the US95 route rather than another alternative, etc.

The Churchill County Impact Report estimates that 5,450 truck shipments would traverse Fallon on US95 under the Proposed Action in the Yucca Mountain EIS, which calls for shipments of 63,000 MTHM of CSNF to the facility from 2010 through 2033. If the expansion of Yucca Mountain (known as Modules I and II) is approved, the Churchill County Impact Report estimated the number of shipments to increase to 19,193 between the years 2010 and 2048.

It is possible that shipments from California would use US50 to Fallon, and then turn south on US95. We have not included this possibility in our report. If trucks were indeed to take this route, then the incident-free dose would be greater. The severity of an accident would remain unchanged, since we apply bounding assumption for the accident location upwind from the town (see below). But the simultaneous use of two routes in Fallon would increase the likelihood that at the time of an accident, the wind would indeed blow towards town, as predicted in the model.

Incident-Free Dose Calculation

For the calculation of expected doses to the population of Fallon under routine shipment conditions, the RISKIND[4] computer program was used. In the following, we present the calculation of the most important input parameters.

Population and Population Density

Only persons living within 1 mile of the proposed shipment routes were considered in this calculation. It was also assumed that all shipments proceed on US95 through Fallon, and none take US 50 or US 50A.

Because almost the entire population of the US95 corridor within Churchill County lives in Fallon, we limit the incident-free dose calculation to a 7-mile stretch that includes Fallon and its immediate surroundings. We neglect any dose to the corridor population outside this 7-mile-stretch. We obtain the population density by dividing the corridor population by 14 square miles, or about 36 km^2.

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[4] USDOE, Argonne National Laboratory, RISKIND-A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel, ANL/EAD-1, November 1995.

In addition to the corridor population, we include the transient tourist population, and the "on-link" population of motorists.

According to the Churchill County Impact Report, about 200,000 visitors stay overnight in local motels and RV parks in Fallon each year. Nearly all of these facilities are within 1 mile of the highway. Therefore, we assume a steady visitor population in Fallon of 200,000/365, or 548 per day. No credit is taken for the likely increase in this figure with time.

An estimate of the "on link" population (average number of people in the street that is exposed to radiation from transportation casks) is made based on traffic figures given in the Churchill County Impact Report. These are given for the years 1999 and 2020, so interpolation was used to estimate the traffic density for 2010. The densities are based on the average of the densities in Table 2-6 of the Impact Report for traffic on US95 in the center of Fallon (north and south). These estimates are given in Table 2.

Table 2. Traffic through Fallon

Year	Estimated Average Daily Traffic (one way)
1999	10,550
2010	19,010
2020	26,700

It will be assumed that vehicles contain an average of 2 persons for the dose calculations.

RISKIND Inputs

The RISKIND computer program was used to calculate the incident-free dose to the maximally exposed individual (MEI) and to the population of Fallon and immediate surroundings as a result of a shipping campaign through the city. Table 3 shows the inputs used in RISKIND. The program has to be run separately to calculate the dose to the MEI in rem/y and total rem, and to the population in person-rem/y, and total person-rem.

Dose to the Maximally Exposed Individual (MEI)

The Maximally Exposed Individual is assumed to be located at the intersection of Williams and North Maine Streets, between 15 and 30 feet from the road, for every shipment. 4 separate calculations will be performed, to consider a person at both distances, both indoors and outdoors. It is assumed that the MEI will be exposed to a stopped shipment for 2 minutes per shipment, as he/she waits at the traffic light, and that the MEI will be exposed to every shipment. For passing shipments, it is assumed that the trucks will travel at 10 mph near the intersection.

RISKIND calculates the dose per truck. We therefore multiply this dose with 5,450 – 19,193 to obtain the total dose in mrem, and divide this dose by 24 and 39 y to calculate the annual dose in mrem/y for the "Proposed Action" and "Modules I&II" alternatives, respectively. Table 4 shows the annual and lifetime dose of the MEI.

Table 3. Input parameters used for RISKIND for incident-free transport

Variable	Value	Comments
Distance from shipping route	15 feet to 1 mile	Exposure at distances greater than 1 mile is not significant
Corridor resident population density (persons/km^2)	316.7 (1999), 393.3 (2010), 558.5 (2020)	Based on a 2 x 7-mile-corridor, and corridor pop. from Table 1
Tourist population density (persons/km^2)	511	Average of 548 tourists, distributed over 2x7 miles
Distance traveled	7 miles	Calculated dose for inside Fallon separately from elsewhere in Churchill County
Fraction of population indoors	0	Used to obtain upper-bound, no-shielding estimate
1-way traffic density (vehicles/hour)	621 (1999); 1,118 (2010); 1,113 (2020)	Based on 17-hour day, average of traffic density on US95 in both directions
People per vehicle	2	
Number of stops	1	
Stop duration	2 minutes	Assumed stop time in Fallon for traffic lights
Number of people exposed during stop	50	20 people in nearby cars or pedestrians, 30 in nearby businesses/residences
Exposure Distance, stopped truck	2 to 90 meters	Assumption; RISKIND defaults
Average vehicle speed	25 mph	Posted speed limit in Fallon
# lanes 1-way	2	
Lane width	3.7 meters	Assumption

Table 4. Dose to the Maximally Exposed Individual (MEI) from incident-free transportation (mrem)

Dose	**Scenario**	**Dose at different locations** 15 ft, outdoors	15 ft, indoors	30 ft, outdoors	30 ft, indoors
Yearly Dose	Proposed Action	25.7	10.1	7.9	3.1
	Modules I&II	55.7	21.8	17.1	6.7
Lifetime Dose	Proposed Action	617	241	189	75
	Modules I&II	2,173	850	666	263

Population Dose Results

Again, RISKIND calculates the population dose per truck, and we therefore multiply the output with 5,450 – 19,193 trucks to obtain the total dose in person-rem. For the annual dose in person-rem/y, we divide the total dose by 24 and 39 years for the “Proposed Action” and “Modules I&II” scenario, respectively.

The incident-free dose to the population is given in Table 5 for the city of Fallon and immediate surroundings, based on the three population projections from 1999, 2010, and 2020. It is broken down into categories of persons: residents, tourists, and those sharing the roadway with the shipment. Unlike the dose to the maximally exposed individual, which describes a worst-case scenario for a single person, the population dose is the expected average dose that is received by the population in Fallon and surroundings. This is the reason why the annual population dose is less than the annual dose to the MEI.

Table 5. Incident-free dose rate to the population (person-rem/year), using population estimates from 1999, 2010 and 2020

Receptors	**Annual dose (person-rem/y)**			**Total dose (person-rem)**		
	1999	**2010**	**2020**	**1999**	**2010**	**2020**
			Proposed Action Scenario			
Off-link residents	0.0159	0.0198	0.0282	0.382	0.474	0.676
Tourists	0.0003	0.0003	0.0003	0.006	0.006	0.006
On-Link	0.0570	0.0570	0.0570	1.368	1.368	1.368
Stop Lights	0.0263	0.0263	0.0263	0.632	0.632	0.632
Total dose	0.099	0.103	0.112	2.39	2.48	2.68
Expected LCF	0.0001	0.0001	0.0001	0.0024	0.0025	0.0027
			Modules I and II scenario			
Off-link residents	0.0344	0.0428	0.0610	1.344	1.670	2.380
Tourists	0.0006	0.0006	0.0006	0.022	0.022	0.022
On-Link	0.1235	0.1235	0.1235	4.817	4.817	4.817
Stop Lights	0.0571	0.0571	0.0571	2.226	2.226	2.226
Total dose	0.216	0.224	0.242	8.41	8.74	9.45
Expected LCF	0.0002	0.0002	0.0002	0.0084	0.0087	0.0094

In addition to the dose in person-rem, we also calculate the number of expected latent cancer fatalities (LCF) due to such a radiation dose. The Yucca Mountain FEIS used a population dose-to-cancer conversion factor of 2000 person-rem per latent cancer fatality. This number is based on a conversion factor of 0.0005 latent cancer fatalities per person-rem[5], which is a recommendation by the International Commission on Radiological Protection (ICRP)[6]. This ICRP report uses a Dose and Dose Rate Effectiveness Factor (DDREF) of 2 for exposure to low doses of radiation, which effectively cuts the probability of developing cancer from a given population dose in half. More recent data on cancer risk at low doses among Atomic Bomb survivors[7] suggest that using this DDREF may underestimate the actual risk from low radiation dose exposure. Without the DDREF, the radiation dose that on average causes one fatal cancer in an irradiated population is 1,000 rem. This radiation dose is called the *fatal cancer dose*.

The fatal cancer dose depends both on gender and age. Values for the estimated cancer dose, i.e. the dose that on average causes one fatal cancer, vary from source to

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[5] USDOE, 2002. *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*. pp 6-37.
[6] ICRP (International Commission on Radiological Protection) 1991. *1990 Recommendations of the International Commission on Radiological Protection*. Volume 21, No. 1-3 of *Annals of the ICRP*. ICRP Publication 60. New York, New York: Pergamon Press. TIC: 235864. pp 20-22.
[7] Pierce and Preston, 2000. "Radiation-Related Cancer Risks at Low Doses among Atomic Bomb Survivors." *Radiation Research* 154, 178-186.

source. Depending on the model used, the cancer dose is very low for children and extremely high for older people (Gofman)[8], or more stable across the ages (BEIR V[9], Pierce[10]). For male 1-y-olds, Gofman[11] gives a cancer dose of 65 rem. This dose increases to 200 rem at age 20, and 538 rem at age 40. After that, the cancer dose sharply increases, reaching 2,000 rem at age 46 and 13,434 at age 50. For higher ages, the cancer dose is even higher. This is due to the Gofman model, which contends that cancer incidence has a peak percent occurrence value 40 years after irradiation.

Other authors assume different models, and, as a consequence, obtain different results. The cancer dose for 5-y-old males, as given by BEIR V[12], is 858 rem. This dose reaches 1,041 by the age of 20, and 2,008 rem by the age of 40. The highest cancer dose given is for age 65, with a value of 3,448 rem. Pierce et al[13] provide similar numbers that are somewhat lower for young ages (556 rem at age 10) and higher for older males (3,781 rem at age 65), but the increasing trend of the cancer dose with age is evident in the results from all authors.

These numbers, taken together, support the fatal cancer dose of 1,000 rem obtained by not including the DDREF applied by ICRP. Using this result, we divide the total dose in Table 5 by 1,000 rem and obtain the number of expected LCF.

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[8] Gofman JW, *Radiation & Human Health*, Sierra Book Club, 1981.

[9] National Academy of Sciences, *Health Effects of Exposure to Low Levels of Ionizing Radiation*, BEIR V (Committee of the Biological Effects of Ionizing Radiation), National Academy Press, 1990.

[10] Pierce DA, Shimizu Y, Preston DL, Vaeth M and Mabuchi K, *Studies of the Mortality of Atomic Bomb Survivors, Report 12, Part I. Cancer: 1950-1990*, Radiation Research 146, 1-27, 1996.

[11] Gofman 1981, p. 285-88.

[12] BEIR V, p. 175.

[13] Pierce 1996, p. 13.

Dose due to a Severe Accident

In this section, we calculate the dose to individuals (in rem) and to the population (in person-rem) due to a severe accident involving a nuclear transportation cask, and the expected latent cancer fatalities. In a “severe accident”, the cask is breached open upon impact or a long-duration fire, and radionuclides are released to the environment.

Selection of a Hypothetical Accident Location

When performing a consequence assessment, it is vital to consider whether a severe accident could occur at a specific location. The location must have the characteristics necessary to produce a severe accident (e.g., high speeds, high drop-offs, steep gradients, potential for long-duration fire, presence of bridge abutments, etc.). Based on truck accident statistics, we know that out of 50,000 truck shipments, several hundred accidents of varying severity will take place over the lifetime of the repository. Pinpointing the exact location and exact conditions surrounding a proposed accident is clearly impossible.

For the case of a truck shipment, a severe accident would require a fairly high-speed collision, something that could likely not be accomplished on the city streets of Fallon. Instead, a location at the very edge of the town was selected. There are relatively few areas near the city of Fallon where a truck accident could be severe enough to result in the release of radioactive material. There are no highway overpasses or rocky outcroppings which could lead to the potential for a high-speed impact onto a rigid surface. Some concrete structures exist on the side of the highways, but none appear to be massive enough to have the potential to breach the cask. A long duration fire is also possible and could be caused by a collision with a gasoline tanker or explosion at a gas station. It could also be caused by sabotage.

The most likely location for a severe truck accident leading to a breach of the confinement involving impact would be a concrete structure associated with the bridge over the canal that forms the southern boundary of the town, or with the canals running parallel to the highway. While the major canals near the highway are composed of relatively soft materials and would not be likely to cause a severe breach of the spent fuel containment, there exist smaller canals, which are concrete-lined. In addition, the canals are crossed by box culvert bridges, which are made of reinforced concrete. It is conceivable that a truck traveling on US95 could lose control, leave the highway, and impact the concrete beam of a canal overpass at relatively high speed, especially if the canal is dry. While the likelihood of such an event is considered to be very low, it is used for bounding purposes.

Also for bounding purposes, we locate the accident at the northern edge of Fallon. Due to the meteorological assumptions (see below), this accident location would lead to the most significant doses to the population. The location at the northern border of the town is also a reasonable worst-case scenario, because the waste is transported north-south on US95. Traffic is generally much faster while entering a town than while leaving it. This means that transports carrying nuclear wastes are moving fast at the northern edge, whereas the trucks entering Fallon from the south are returning from Yucca Mountain and are therefore empty.

In the case of shipments from California on US50 to Fallon, the worst-case accident scenario would remain unchanged, since there is no additional risk from transports along US50 that is not already included in the accident analysis due to transports along US95. The countryside both north and west of Fallon is flat, i.e. a severe accident requires man-made obstacles at the entrance of Fallon for shipments along both highways. Because we apply a wind direction from north, as discussed in the following section, an accident located at the northern edge of Fallon involving a truck traveling south on US95 would have more severe consequences than one located at the western edge, involving a truck traveling east on US50. However, since north is the most predominant, but of course not the only wind direction, the likelihood that an accident happens upwind from Fallon increases if both US95 and US50 are used for nuclear shipments.

Another possibility for a severe accident may arise from the proximity of the Hawthorne Army Ammunition Depot. Ammunition is trucked to Fallon Naval Air Station (FNAS) on US95. The potential for a severe accident could exist if a collision occurred between a truck carrying explosives and ammunition and a spent fuel truck, if some of the explosives were to detonate, possibly breaching the spent fuel confinement and leading to a significant release of radioactive material, perhaps in a fire. Accidents involving explosive military equipment (ammunition, missiles, bombs etc) have occurred several times. On August 4, 1985, in Checotah, Oklahoma, an automobile collided with a tractor-semi trailer transporting bombs. The collision caused a fire and resultant explosions. The Army Corps estimated that 371 residences within a radius of 6,200 feet were damaged; 22 homes needed major reconstruction and 11 homes needed to be rebuilt. The explosion also destroyed a fire truck, 2 eastbound lanes of I-40, the right shoulder of the highway. Approximately 3,382 tons (1,700 cubic yards) of material was used to fill the crater. Other accidents involving explosives: Roseville, California, April 28, 1973 (18 RR boxcars of bombs) and Benson, Arizona, May 24, 1973 (12 RR boxcars of bombs). The Safety Board has also investigated two other munitions accidents: August 1, 1984 Navy torpedo overturned at the intersection of two major highways in Denver. Enough fuel spilled to cause an explosion, but the fire department put out the fire before an explosion. And May 10, 1985, a tractor trailer carrying munitions struck a parked vehicle on I-85 near Bonnieville, KY resulting in a fiery accident. C-4 plastic explosives ignited and burned intensely, but did not explode. In addition, on June 4, 1971, an automobile collided with a tractor-trailer transporting non-military explosives near Macon, Georgia. Gasoline and diesel fuel leaked from the vehicle fuel tanks, a fire quickly engulfed both vehicles and the cargo exploded. Two firemen, a wrecker-operator and 2 bystanders were killed and 33 persons injured. We consider this accident a possible, but less likely scenario, and we therefore do not include it in our dose calculations.

Severity of an Accident

Once an accident location was chosen, the most severe accident that could plausibly occur at the site was estimated. It is important to note that the current-generation truck casks, which will likely be shipping fuel to the proposed repository at Yucca Mountain, have never been physically tested. Thus, the estimates of cask response to severe accident conditions are subject to error.

We base our cask response assumptions on the conclusions drawn from the Modal Study[14,15], with important exceptions as discussed below. We decided not to use the release estimates from the more recent NRC-commissioned study on spent fuel transportation risks, NUREG/CR-6672, for a number of reasons. The NUREG/CR-6672 estimates (1) are non-conservative, (2) contain many assumptions within accident scenarios which are subject to significant scientific criticism, and (3) provoke issues we have raised concerning its methodology and have yet to be addressed (Lamb, M., and Resnikoff, M., "Review of NUREG/CR-6672, Reexamination of Spent Fuel Shipment Release Estimates," prepared on behalf of Clark County, Nevada, October 2000). Until these matters are addressed, we will continue to use the previous study with certain modifications.

The accident severity was determined by examining the types of conditions that could plausibly occur at the location chosen. To begin, we classified the twenty cask response regions developed in the Modal Study into 6 release groups, as had been done by the Department of Energy in the DEIS for the Yucca Mountain facility. Structural response to accident conditions was determined in the Modal Study by an estimate of the percentage strain on the cask inner wall during duress. A category 5 accident, for example, was one in which the cask inner strain caused by impact conditions was between 2% and 20%. The Modal Study predicted this to occur at speeds of 20-60 mph, depending on cask type, orientation, and surface hardness. This type of accident is reasonable considering the conditions at the postulated accident location.

The most severe accident severities require long-duration, hot fires (causing the cask mid-thickness temperature to exceed 1050°F), or strain rates exceeding 30%. These are truly catastrophic accident conditions. It is unlikely that the current-generation truck cask could achieve the 30% strain rates necessary for classification as a category-6-accident at locations in Fallon. Also, for a sustained, hot fire, large quantities of fuel are needed. It is unclear where such fuel could originate in the accident postulated in Fallon, unless a fuel truck slams into a nuclear transportation truck, which is extremely unlikely, since the accident location is off the highway, or a fire occurs at a gas station. Therefore, we consider this event not credible and omit it in our accident analysis.

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[14] NUREG/CR-4829. Fisher *et al. Shipping Container Response to Severe Highway and Rail Accident Conditions*. Lawrence Livermore National Laboratory, 1987.

[15] NUREG/CR-6672. Sprung *et al. Reexamination of Spent Fuel Shipment Risk Estimates*. Sandia National Laboratories, 2000.

Spent Fuel Release Fraction Estimates

Below is a more detailed discussion of the various estimates made in determining the release fraction.

Fuel Inventory

We use the assumptions made by DOE in the Final Environmental Impact Statement (FEIS) for the proposed Yucca Mountain Facility[16]. The FEIS included a dose calculation for the MEI due to an accident or an attack on a fuel transport.

The FEIS assumes that fuel from a pressurized water reactor (PWR) is shipped in GA-4 truck casks, which have a diameter of 0.508 m and a length of 4.4 m. There are 4 assemblies of 424 kg each of uranium per cask (4 PWR fuel assemblies). The average age of the spent fuel is 15 years, with an assumed burnup of 50,000 MWD/MTU.

Fuel Matrix

For a release of radioactive materials from a cask to take place, three barriers must be breached - fuel matrix, rod cladding, and cask. When fuel is heated in reactors, a percentage of volatile radionuclides, such as cesium, will migrate out of the fuel matrix under the influence of temperature gradients and concentrate in the fuel-clad gap, the space between the fuel pellet and the surrounding tube (see PNL-10540, 1995. Gray and Wilson, *Spent Fuel Dissolution Studies, FY1994 to 1994*. Pacific Northwest Laboratories, p vi.). This “gap cesium” inventory is directly related to the release fraction in the event of an accident because it can be released in the event of any cladding breach. Almost all of the cesium released in the event of a spent fuel shipping accident will be this “gap cesium.” For the fuel matrix, the Modal Study assumes 0.3% of the cask inventory of cesium will be present between the cladding and the fuel pellet. However, we believe that the estimate made by Gray et al (9.9% gap cesium inventory) is on more solid experimental ground. Assuming the cesium release fraction is directly proportional to the gap inventory, we intend to increase the release fraction posted in the Modal Study by a factor of 33. For particulates and gases, other release fractions apply, as discussed below.

In addition, the Modal Study does not adequately consider CRUD spallation in the event of an accident. CRUD resides on the external surfaces of fuel assemblies and it is more easily dislodged and dispersed in a severe accident. We will assume an independent estimate for this source term, using the average CRUD surface density given for PWR reactors in the RISKIND User’s Manual.

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[16] USDOE, 2002. 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. (Cited here as YMFEIS)

Cask Opening

The Modal Study assumes all material within the cavity is released if a leak path exists, and it further assumes a leak path exists for any accident with maximum strain greater than 0.2%. According to the Modal Study, Category 5 accidents produce greater than a 2% strain on the cask inner wall. The Modal Study estimated that a 2% strain on the cask inner wall could occur in an end-on impact with an unyielding target at a velocity of 46 mph. For a truck cask, a 30% strain on the cask inner wall could occur in an end-on impact with an unyielding target at a velocity of 76 mph (Modal Study, p. 7-5). A 2% strain assuming a side impact with a train sill (or similar immovable object such as a bridge abutment) could occur at a speed of 20 mph. In our opinion, these accident speeds are plausible at the chosen accident location.

Rod Cladding Breach

A rod cladding breach could be caused by an impact or internal rod pressure due to high temperature. Since we do not assume a hot fire in an accident in Fallon, as discussed above, we concentrate on breach due to impact.

The Modal Study assumes the rods are most susceptible to breach in an end-on impact (p. 8-7). Fig. 8-3 of that study shows that 3% break occurs in an impact resulting in 0.2% strain (at an acceleration < 40g), 10% break in an impact resulting in 2% strain (40-100g), and 100% break in an impact resulting in 30% strain, >100g. However, other studies (in particular, the one relied on by Holtec in its SAR for the HI-STAR 100 cask)[17] show that a sideways impact greater than 63g is sufficient to shatter the cladding. All impact accidents we consider here have a deceleration greater than 63g, so we assume 100% of the cladding is shattered by impact.

Postulated Release Fractions

For the postulated fractions of radioactive inventory released, we take the results from the Modal Study for accidents corresponding to severity category 5, correcting for cesium and CRUD, as is presented in the following table:

Table 6: Postulated Severe Truck Accident Release Fractions

Inert gas	Iodine	Cesium	Ruthenium	Particulates	CRUD
3.3E-01	2.5E-03	6.6E-03	2.7E-05	2.00E-05	1

Meteorological Conditions

It is impossible to predict the exact meteorology at the location of a postulated accident. In fact, the choice of a specific meteorological profile is rather arbitrary for a consequence assessment.

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[17] UCID-21246. Chun, Witte and Schwartz, “Dynamic Impact Effects on Spent Fuel Assemblies.” Lawrence Livermore National Laboratory, 1987.

For the dose to the maximally exposed individual in the centerline of the plume, we calculate the dose that would not be surpassed in 95 % of all weather conditions. This means that for the individual dose, we did not input the wind speed and direction, but used average weather data and took the results for 95%-weather conditions.

For the population dose calculation, we have decided to use average weather data from the closest available monitoring station. There is not a single predominant wind direction. The most predominant wind direction between January 2001 and February 2002 was north[18]. The average wind speed in this period was[19] 2.35 mph or 1.06 m/s.

We assume that an accident happens at the northern edge of the city. This is a plausible scenario, since spent fuel trucks entering the town from north most probably travel at a higher speed than those exiting the town in the south. (Trucks entering Fallon from the south are not presumed to carry any nuclear waste). If we also assume a wind direction from N, then this accident scenario is not only plausible, but at the same time the bounding worst-case scenario, since all of the contamination would be blown across the town.

For the Pasquill stability class (measure of the air mixing or diffusion ability of meteorological conditions), we apply Class D.

Exposure Times

Our analysis assumes an acute exposure time of 24 hours. The choice of this length of time was made based on research into evacuation times for disaster situations along with the unique challenges presented by the postulated Fallon accident.

It is assumed that the postulated accident is severe enough to prevent evacuation along US95 going north from Fallon. This effectively cuts off 1/4 of the evacuation pathways. Second, the meteorological conditions assumed at the time of the accident are such that the plume generally travels toward the south, paralleling US95. Given the choice, residents would most likely choose to vacate the area in a direction away from the plume, making evacuation to the south on US95 unlikely. US50, leaving Fallon east and west, would be the most likely means of egress for persons living in Fallon. Those living east of US95 would probably go east, whereas those living west would evacuate west in order not to pass through a high radioactive field in the center of town. Therefore, Fallon would have a relatively limited number of egress routes in the event of the postulated accident, which would result in relatively difficult evacuation conditions.

A 24-hour evacuation time estimate is appropriate for a township such as Fallon. While it may be possible that an evacuation could take place in a shorter period of time, this would require significant emergency planning above that which currently exists in many small towns.

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[18] http://www.gpick.com/wea, accessed on April 18, 2002

[19] ibid

For the long-term exposure, we calculate the dose to individuals and the population after 1 and 50 years. The nature of the long-term exposure is different from that of acute exposure. Whereas the acute radiation dose is mainly due to inhalation of radioactive airborne particulates, direct gamma radiation from deposited particulates (ground shine) is the most important factor for long-term exposure.

Methodology

In addition to RISKIND, the computer program HotSpot[20] was used to obtain contaminant plumes for later inclusion onto a map of Fallon and its surroundings. Besides calculating an incident-free dose (see above), RISKIND is also designed to provide risks and consequences of spent fuel shipping accidents. HotSpot was developed at Lawrence Livermore and is used to estimate levels of radioactive contamination following an accident. Both use standard Gaussian plume dispersion equations to estimate airborne concentrations and ground deposition of radionuclides.

We calculate the dose for individuals living at different distances downwind from the accident in the centerline of the contamination plume, and for the population living within the contamination plume calculated with HotSpot.

The dose calculation for individuals was carried out exclusively with RISKIND. Also, we used RISKIND to calculate the released radionuclides that served as an input for HotSpot for the population dose calculation.

The population dose was calculated by superimposing acute-dose-isopleths onto a map of Fallon and its surroundings. With the average dose (rem) between two isopleths, and the respective population density (persons/km^2) and area (km^2), we calculated the population dose in person-rem. Population densities and areas were taken from the U.S. Census 2000 for the City of Fallon and Churchill County. Areas and population densities between plumes, inside and outside of Fallon, were calculated using the plume maps.

HotSpot provides estimates of ground deposition and acute dose only. However, because acute and long-term dose are directly proportional, we used correlation factors derived from RISKIND to multiply with the acute population dose in order to obtain the long-term population dose.

Table 7 shows the parameters that were used as inputs for RISKIND and HotSpot. Most values were taken from the Yucca Mountain Final Environmental Impact Statement (YM FEIS), Chapter 6 and Appendices A and J. For parameters that we did not specify here, we used default values.

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[20] "Hotspot Health Physics Code, Version 1.06." Lawrence Livermore National Laboratory. Steven G. Homann, contact.

Table 7. Inputs into RISKIND and HotSpot

Parameter	Value	Comments
RISKIND:		
Acute exposure	24 h	Estimated evacuation time
Long-term exposure	1 and 50 y	Exposure range
Shielding	none	Default
Food pathway	off	Not enough information
Water pathway	off	Not enough information
Cask dimensions	length 4.4 m, radius 0.508 m	From YM FEIS
Burnup	50,000 MWD/MTU	From YM FEIS
Cooling time	15 y	From YM FEIS
Total uranium in cask	1.696 MT	YM FEIS; 4 assemblies of 424 kg
Cask cavity surface area	39 m2	Default
Crud surface activity	140 micCi/m2	From YM FEIS
Mixing height	400-1600 m	Default
Temperature	283 K	Default
Anemometer height	10 m	Default
Rainfall	none	Default
Release height	1 m	Default
Release fractions:		
Particulates	0.00002	Modal Study
Ru	0.000027	Modal Study
Cs	0.0066	Value form Mod.St., multiplied by 33
I	0.0025	Modal Study
Gas	0.33	Modal Study
Heat release	500 ca/s	Default for accident without heavy fire
HotSpot:		
Dispersion model	General plume	
Released radionuclides	2.5 Ci of Sr-90; 1,210 Ci of Cs-137; 0.219 Ci of Pu-238; 0.0145 Ci of Pu-239; 0.0251 Ci of Pu-240; 0.101 Ci of Pu-241; 0.152 Ci of Cm-244	Output from RISKIND
Deposition velocity	1 cm/s	Output from RISKIND
Wind speed	1.1 m/s	Average wind speed 2001-2002
Wind direction	N	Most frequent monthly dominant direction in 2001-2002 (see text)
Stability class	D	Most frequent stability class

Results

Receptors and pathways

In a severe truck accident, airborne radioactive particulates would be released and transported downwind. The population downwind would then inhale these particulates and receive a radiation dose. Particulates would settle on the ground, plants and surface streams. Radiation emanating from the ground (ground shine) due to gamma rays would also give rise to a radiation dose that increases with the ground concentrations and the length of time a person remained in the contaminated area. Because we lack detailed data about hydrological aspects and food production/consumption in Fallon, we exclude the dose due to ingestion of contaminated water and food from the analysis.

RISKIND calculates a radiation dose to individuals who live straight downwind from the accident along the plume centerline, at different distances. We chose the distances of 50m, 100 m, 200 m, 500 m, 1 km, 2 km, 5 km, 10 km, 20 km and 50 km.

Dose to individual

The acute (24 h) dose in rem to an individual directly downwind from the accident location was calculated for 95 % of all weather conditions. This means that there is only a chance of 5 % that the dose would even be higher, due to extreme weather. The results are shown in Table 8. All calculated doses are without any remediation. The very high long-term doses dictate a cleanup or a permanent evacuation, since they are not acceptable. The question remains as to what area has to be remediated. We discuss this matter below in the section, “population dose”.

Table 8. Dose to Individual living downwind from accident

Distance downwind (km)	Acute Dose (rem)	1-y-Dose (rem)	50-y-Dose (rem)
0.05	543	4,890	90,800
0.1	188	1,690	31,400
0.2	107	960	17,800
0.5	40.8	367	6,820
1	13	117	2,180
2	3.54	31.9	592
5	0.66	5.92	110
10	0.18	1.63	30.2
20	0.05	0.44	8.25
50	0.01	0.09	1.72

Obviously, the acute dose cannot be avoided by remediation. Therefore, assuming immediate and perfect remediation, this is the minimum dose that individuals living along the center of the contamination plume would receive in case of a category-5-accident.

Acute dose to the population

The next step was to superimpose plume diagrams on the map of Fallon to estimate the amount and extent of contamination and dose. Plumes for acute dose and ground deposition concentration were obtained from the HotSpot computer model and plotted onto the ArcView map shown in Figures 1-4. Appendix A include maps generated by the Churchill County geographic information system (GIS) and a summary analysis of potential land use impacts resulting from an accident.

Because the population density inside of Fallon is very different from that outside, we differentiate between the city and the (rural) surroundings. In Figure 1, the rectangle denominated Area F encloses almost all of Fallon City. The rectangle measures about 3.15 by 3.68 km and has a surface of 11.59 km^2. Using the population estimates from Table 1, we arrive at a population density in Fallon of 650, 807 and 1,146 people per km^2 for the years 2000, 2010 and 2020, respectively (Table 9). The population density of Churchill County, excluding Fallon, is 1.27, 1.57 and 2.23 p/km^2, respectively.

Table 9. Population density of Fallon and surroundings

Region	Pop.2000	Pop.2010	Pop.2020	Area (km^2)	Dens.2000 (p/km^2)	Dens.2010 (p/km^2)	Dens.2020 (p/km^2)
Churchill County	23,982	29,784	42,294	13,011	1.84	2.29	3.25
Fallon	7,536	9,359	13,290	11.59	650.10	807.37	1,146.48
Churchill C. excl. Fallon	16,446	20,425	29,004	12,999	1.27	1.57	2.23

The population dose (person-rem) is calculated by multiplying the average dose (rem) of a dose zone with the respective population (persons). The dose zones are the areas between two neighboring dose isopleths. The dose zone population is calculated from the population density and the surface of each dose zone. The isopleths of the highest acute doses are completely inside of the area F, whereas the ones with acute doses below 500 mrem are partially outside. By measuring the plumes on the map and applying basic geometric calculations of ellipse segments, we calculate the area of each dose zone inside and outside Area F (Table 10).

Table 10. Acute dose to the population

Dose zone between isopleths	Av. Dose in dose zone (rem)	Surface of dose zone			Acute population dose[a]		
		Total (km^2)	within Area F (km^2)	outside Area F (km^2)	2000 (person-rem)	2010 (person-rem)	2020 (person-rem)
inside 100	>100	0.003	0.003	0	195.031	242.210	343.944
100 to 50	75	0.003	0.003	0	146.273	181.658	257.958
50 to 10	30	0.024	0.024	0	468.075	581.304	825.466
10 to 5	7.5	0.031	0.031	0	151.149	187.713	266.557
5 to 3	4	0.039	0.039	0	101.416	125.949	178.851
3 to 2	2.5	0.060	0.060	0	97.516	121.105	171.972
2 to 1	1.5	0.170	0.170	0	165.776	205.879	292.352
1 to 0.5	0.75	0.370	0.370	0	180.404	224.044	318.148
0.5 to 0.4	0.45	0.200	0.133	0.067	38.947	48.368	68.684
0.4 to 0.3	0.35	0.300	0.083	0.217	18.982	23.573	33.475
0.3 to 0.2	0.25	0.700	0.211	0.489	34.448	42.781	60.750
0.2 to 0.1	0.15	2.000	0.131	1.869	13.129	16.305	23.154
outside 0.1	<0.1	N/A	N/A	N/A	omitted	omitted	omitted
Total					1,611	2,001	2,841

a: Dose calculated with population density estimates for 2000, 2010 and 2020

Long-term population dose and latent cancer fatalities

1-year and 50-year long-term dose estimates were made for the combined dose due to inhalation, ground shine, and cloud shine. For long-term population doses, ground shine due to deposited cesium is the major contributor. Other potential pathways, namely food and water ingestion, were not included in this calculation. Instead, this is discussed later on in this paper.

The methodology of arriving at population dose estimates utilizes the fact that long-term dose estimates are directly proportional to acute dose estimates. Estimating a long-term dose estimate then simply becomes an exercise in finding the correct multiplier. This was done using RISKIND, which provides estimates of both acute and long-term dose. Examining the dose estimates at given distances, it was determined that a 1-year long term dose was 35 times greater than the corresponding acute dose, and a 50-year dose was 485 times greater than the acute dose. The results for the long-term population dose estimates are given in Table 11.

To calculate the number of expected latent cancer fatalities (LCF), we again divide the population dose by 1,000 rem, as was done in the incident-free dose calculation.

Table 11. Latent cancer fatalities due to population dose

Exposure time	**Population estimate**		
	2,000	**2,010**	**2,020**
Acute population dose in 24 h (rem)	1,611	2,001	2,841
LCF	1.6	2.0	2.8
Long-term population dose in 1 y (rem)	56,390	70,031	99,446
LCF	56	70	99
Long-term population dose in 50 y (rem)	781,405	970,432	1,378,036
LCF	781	970	1,378

The long-term population doses are theoretical doses to which the population would be exposed if no remediation and/or evacuation took place. If a severe accident takes place in 2020, no cleanup takes place and people live in Fallon for another 50 years, then the expected latent cancer fatalities are 1,378. This would be about 10 % of Fallon's population in the year 2020. From this it follows that evacuation and remediation is absolutely necessary in the case of a category-5-accident involving a nuclear waste shipment.

In case of a full evacuation, followed by perfect remediation, the population dose would effectively be the acute dose, with an estimated number of latent cancer fatalities of 1.6 – 2.8 cases. This is 0.02 % of the respective city population of Fallon. However, perfect remediation is not possible. Therefore, the acute dose and the corresponding LCF have to be understood as a lower bound. Due to the necessarily imperfect remediation, the actual population dose in case of an accident would be higher in any case.

Estimated area requiring remediation

There is currently no universally accepted decontamination level for areas subjected to radioactive contamination. However, there are a few general guidelines. For example, the Environmental Protection Agency set a cleanup level at an above background effective dose of 15 mrem/year for Superfund sites[21], including exposures from all pathways. The Nuclear Regulatory Commission specifies a cleanup level of 25 mrem/y in its Radiological Criteria for License Termination. The EPA has also issued a Protective Action Guide[22] that states the doses in any single year after the first must not exceed 0.5 rem and that the cumulative dose over 50 years (including the 1st and 2nd

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[21] OSWER 9200.4-18, "Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination," Aug. 22, 1997.

[22] EPA 400R-92-001. "Manual of Protective Action Guides and Protective Actions for Nuclear Incidents." US EPA Office of Radiation Programs, 1992.

years) must not exceed 5 rem. For this analysis, we will use both the EPA criteria for Superfund sites and the EPA Protective Action Guides to estimate the area requiring remediation.

Looking at Fig. 4 and Table 12, for the first year after the postulated accident, we see that a person living along the 1.5 mrem acute-dose-isopleth would receive a yearly dose of 53 mrem due to ground shine, cloud shine, and inhalation. If instead we take the 50-year individual dose and divide by 50 to get an average annual long-term dose, the last plotted isopleth (1 mrem acute dose) corresponds to an average yearly dose of 15 mrem/y, the same as the EPA cleanup level for superfund sites. Therefore, according to this threshold, the entire area under the 1.5 mrem acute-dose-isopleth will have to be remediated. This corresponds to a total area of 193 km^2. Most of this area is outside of Fallon, but the EPA cleanup standards are valid also outside of the city.

This is clearly a prohibitive cleanup action. In addition to the vast region outside of Fallon that would have to be remediated, a major part of the city would have to be scraped - buildings, streets, grass, and so on. We have not estimated here the considerable economic costs of evacuating and remediating the Fallon area, including the cost of waste disposal, lost business and property devaluation, though we have made estimates for urban areas for the State of Nevada.

Using the EPA Protective Action Guides, Table 12 shows that the locations on the 10 mrem acute-dose isopleth correspond to a first-year dose of 0.35 rem and 4.85 rem over 50 years, just below the Protective Action Guide limit. Hence, the area that would require remediation is 39 km^2. Thus, the area needing clean up is somewhere between 39 and 193 km^2.

Table 12. Area in need of remediation

Isopleth of acute dose (rem)	Total area within isopleth (km^2)	1-y-dose on isopleth (rem)	50-y-dose on ispopleth (rem)	Average annual dose for 50-y-dose (rem)
100	0.003	3,500	48,500	970
50	0.006	1,750	24,250	485
10	0.030	350	4,850	97
5	0.061	175	2,425	49
3	0.10	105	1,455	29
2	0.16	70	970	19
1	0.33	35	485	10
0.5	0.7	18	243	5
0.4	0.9	14	194	4
0.3	1.2	10.5	145.5	2.9
0.2	1.9	7.0	97.0	1.9
0.1	3.9	3.5	48.5	1.0
0.05	8.3	1.75	24.25	0.49
0.01[a]	**39**	**0.35**	**4.85**	**0.10**
0.0015[b]	**193**	**0.053**	**0.728**	**0.015**
0.0010	264	0.035	0.485	0.010

a: Boundary of region in need of remediation using EPA Protective Action Guides levels
b: Boundary of region in need of remediation using EPA Superfund cleanup level

Ingestion of soil, water and food

In our analysis, we neglected the dose due to ingestion of contaminated soil, water and food. The Fallon area sits in the middle of the Newlands Irrigation Project, which covers about 60,000 acres of surface irrigated crop land. This area produces vegetables, corn, alfalfa and more. About 13,000 milking cows are kept in the area, and the Newlands Project provides about 1/3 or the milk consumed in northern Nevada and the eastern slope of the Sierra Nevada in California. In addition, the area produces meat for local and regional consumption. In short, agriculture is very important in the Fallon area, and its products are not only used locally, but also distributed in a large region. Large-spread ground contamination due to a severe transportation accident would therefore have impacts in an area much larger than Churchill County.

Hotspot does not calculate a dose due to ingestion pathway. We use the RESRAD computer code to calculate this dose. As the main input into RESRAD, we use the ground contamination output from Hotspot. Similar to dose isopleths that are defined by all points with the same acute dose (in rem), Hotspot also calculates surface contamination isopleths (in $\mu Ci/m^2$). As a bounding scenario, we assume that this contamination is contained within the uppermost 15 cm of the soil (default plant root depth) with a soil density of 1.5 g/cm^3, and calculate a soil concentration in pCi/g soil. This value can be inserted into RESRAD. As another bounding assumptions, we apply a thickness of the unsaturated zone of 2 m, which would be the case with a shallow aquifer.

We calculate the dose due to ingestion of food, water and soil for a point located on the 100 µCi/m^2 isopleth, which covers an area of 0.84 km^2. The resulting soil concentration is (100 µCi / 0.15 m^3) 667 µCi/m^3 or 444 pCi/g. We obtained each radionuclide's soil concentration by calculating its fraction of the total released activity, using the release totals Table 7. 99.75 % of the total contamination is due to Cs-137, 0.2 % due to Sr-90, and the remaining fraction is due to all other released radionuclides. Using RESRAD default parameters, the first-year dose due to ingestion of contaminated food, water and soil is 40.6 mrem. This dose is also the maximum annual dose. The dose is exclusively due to water-independent pathways. The groundwater pathway does not contribute to the total dose until >100 years after the accident, at which point the total dose is very small.

In comparison, the first-year dose due to ground shine on the 400 mrem acute-dose-isopleth, which is encloses an area comparable in size to that of the 100 µCi/m^2-isopleth, is 14 rem (Table 12). This means that the dose due to inhalation and ground shine is about 350 times greater than that due to ingestion of food, water and soil. The ingestion dose is therefore negligible for local residents in comparison to the acute dose (mainly inhalation) and long-term dose (mainly ground shine) that they will receive in case of an accident. However, the dose due to ingestion of food is "exported" to other regions, i.e. it reaches people that live far away from the accident location, if agricultural production is not halted after an accident or the contaminated region remediated. Since remediation would be necessary in any case due to the otherwise unacceptable population dose and resulting LCF as presented in Table 11, we do not consider the export of contaminated food as an important health risk to the region. However, it is another argument for the necessity of large-scale remediation in case of an accident involving a nuclear shipment in Fallon.

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