POTENTIAL EXPOSURES AND HEALTH EFFECTS FROM SPENT FUEL TRANSPORTATION[a]

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ABSTRACT

The radiation exposures and consequent health effects associated with normal operations and postulated accidents during transportation of spent fuel have been analyzed and evaluated and the results have been summarized in the Final Environmental Assessments issued by DOE. For normal, accident-free transport of spent fuel, radiation exposures arise from both gamma and neutron sources within the spent fuel cask. The neutrons result from the spontaneous fission of transuranic nuclides in the spent fuel. The neutron dose flux component was modeled using DISNEL,a generalized, one-dimensional, multi-energy group neutronics code. Computer program PATHRAE-T was then developed from the EPA code PATHRAE and was employed to determine the total, combined dose field, including both ground and sky scatter of neutrons and gamma photons for any position around a truck or rail spent fuel cask. Four activity classes, viz., caravan, traffic obstruction, resident and pedestrian proximity, and servicing of the cask transport vehicle were reviewed for maximum individual exposure assessments. Projected doses for typical activities under maximum exposure conditions were 6 mrem or less per event.

A spent fuel rail cask containing up to 14 PWR spent fuel assemblies could conceivably be involved in a variety of rail related transportation accidents. PATHRAE-T was used to estimate doses from rail cask accidents involving the release of radioactive nuclides although a release from such accidents is highly unlikely. The maximum individual exposure, primarily due to inhalation, is about 10 rem and occurs about 70 meters downwind. Ground deposited nuclides account for 99 percent of the population dose. The maximum population dose accident could result in 22 latent health effects for the urban population who, during the same period, would experience about 410,000 cancer fatalities from all other causes. The same case rail cask accidents were also evaluated for a maximum water pathway contamination scenario. The nuclide contaminated plume was assumed to be transported over a large reservoir used for domestic and agricul-tural water. This accident could result in a 63,000 person-rem dose causing about 13 latent health effects in the absence of any natural and industrial processes for nuclide removal from the water.

INTRODUCTION

The extensive use of nuclear power will eventually result in significant quantities of spent fuel which must be shipped by truck or rail from the point of generation or temporary storage to a designated nuclear waste repository. This activity has the potential for increasing radiation exposures of individuals above their normal background levels in the near vicinity of the transportation route. The transportation casks that will be employed to ship spent fuel must satisfy the regulatory and safety design requirements imposed by appropriate governmental agencies. It has been assumed here that the maximum dose rate 2 meters from the outer edges of the transport conveyance is no greater than 10 mrem per hour regardless of the type of ionizing radiation and the shielding material composition and configuration assumed. This dose rate is the present U.S. Department of Transportation Regulation(1) for such shipping casks. This regulation eliminates the need to employ precise specifications for cask composition and configuration which are still being developed.

GAMMA RADIATION EXPOSURES

The spent fuel transported in a truck or rail cask can be represented by an equivalent uniform line source of gamma radiation with a length equal to a typical pressurized water reactor (PWR) fuel assembly. The mathematical expression for the dose rate H is then given by the following equation(2).

$$H(r,z) = \frac{S\ B(r,z)}{4\ r}\ \mathrm{Tan}^{-1}[(L/2+z)/r]+\mathrm{Tan}^{-1}[(L/2-z)/r]$$

where

S = effective line gamma radiation source strength (mrem-m/hr)

$B(r,z)$ = effective gamma buildup factor (dimensionless)

L = length of the line radiation source (m)

r,z = the radial and axial position from the source center (m)

The radiation buildup factor $B(r,z)$ is defined as the ratio of the total gamma dose rate to the direct gamma dose rate, i.e., the total dose rate due to collided and uncollided photons divided by that due only to uncollided photons. The buildup factor accounts for those photons that are scattered by the atmosphere and those scattered by the ground(3). The buildup factor is assumed to be given by

$$B(r,z) = 1 + B(\mathrm{atmosphere}) + B(\mathrm{ground}).$$

Although both components arise primarily due to Compton scattering of photons, the greater atom density of the ground over the atmosphere makes ground scattering more important.

NEUTRON RADIATION EXPOSURES

Spent fuel contains transuranic elements which are produced as a result of neutron capture in uranium (and thorium, if present). Many of these nuclides (viz., uranium, neptunium, plutonium, curium, etc.)

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undergo spontaneous fission resulting in the emission of neutrons. A predominant neutron emitter encountered in spent fuel from light water reactors is the isotope (Cm-244) which has a half-life for alpha emission of 18.1 years. A typical PWR spent fuel element 5 years out of the reactor contains about 600 curies of Cm-244 which decays predominantly by alpha emission and 0.00013 percent of the time by spontaneous fission, emitting neutrons with a standard fission energy spectrum. The energy dependent neutron flux field from the spontaneous fission neutron emitters was calculated for a current, standard U.S. PWR spent fuel cask using DISNEL(4), a generalized, one dimensional, multiple energy group, neutronics code. The neutron equivalent dose rate H(r) was determined as follows

$$\dot{H}(r) = \sum_i \phi_i(r)\, DF_i$$

where

r = position vector

$\dot{H}(r)$ = neutron dose rate (mrem/hr)

$\phi_i(r)$ = neutron flux for the ith energy group (neutrons/m^2-sec)

DF_i = dose conversion factor for the ith energy group (mrem-m^2-sec/neutron-hr)

DOSE RATE FIELD FROM NORMAL TRANSPORT

A program entitled PATHRAE-T(5) has been developed to provide the total dose rate field arising from neutrons and gamma photons for any position around a truck or rail cask. For 5 year old spent fuel in a cask with a wet neutron shield and dry fuel cavity, the dose rate distribution for the typical U.S. truck cask(6) is 65 percent gamma and 35 percent neutron. Figure 1 shows the dose rate field obtained from PATHRAE-T surrounding a spent fuel truck cask. Isodose lines are given in units of microrem per minute as functions of distance from the center of the

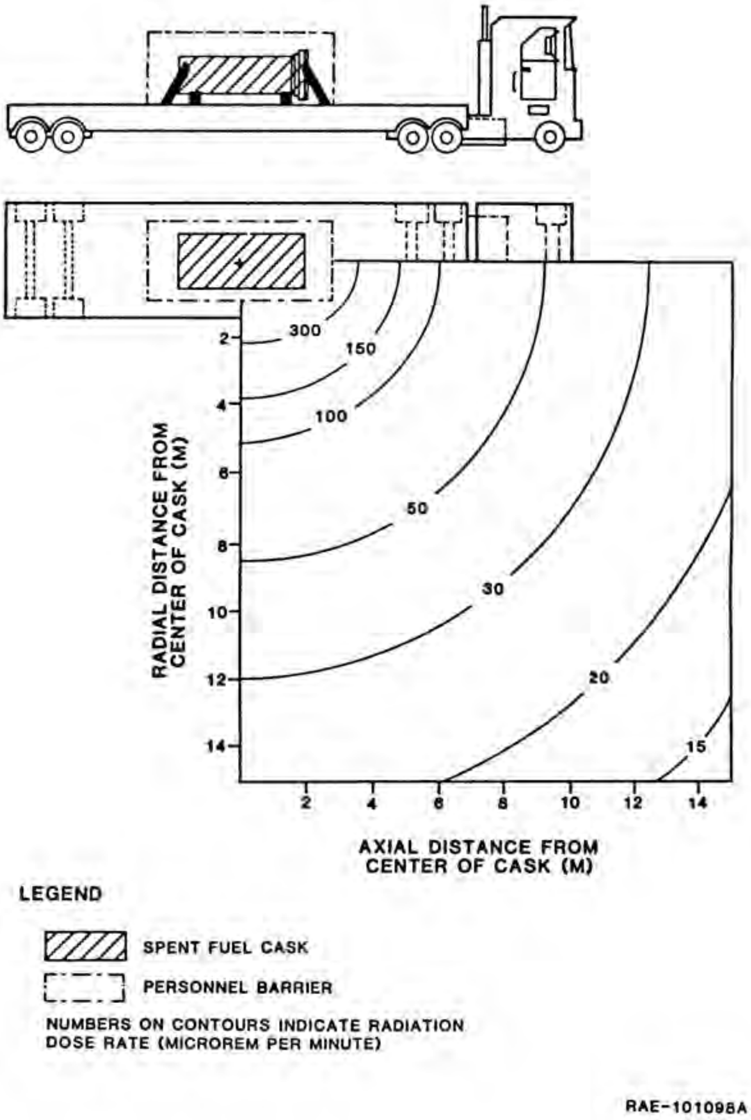

Fig. 1. Radiation Isodose Map for Truck Transport.

cask. Because of symmetry of the field, only one quadrant is shown. The radiation dose rate at the trailer's front or rear wheels is about 100 microrem per minute, while the dose rate outside the cab door of the tractor is about 50 microrem per minute. Table I provides tabulations of maximum individual exposure events which might occur within the radiation field of a spent fuel cask in normal transport.

TABLE I

Projected Maximum Individual Exposures From Normal Spent Fuel Transport by Truck Cask[a]

Description (Service or Activity)	Distance to Center of Cask	Exposure Time	Maximum Dose Rate and Total Dose
<u>Caravan</u> Passengers in vehicles in adjacent lanes to cask vehicle	10 m	30 min	40 rem/min 1 mrem
<u>Traffic Obstruction</u> Passengers in stopped vehicles adjacent to the cask vehicle stopped due to obstruction	5 m	30 min	100 rem/min 3 mrem
<u>Residents and Pedestrians</u> Slow transit (traffic control devices, area with pedestrians)	6 m	6 min	70 rem/min 0.4 mrem
Truck stop for driver's rest	40 m	8 hrs (overnight)	6 rem/min 3 mrem
Slow transit through area with with homes, businesses, schools, etc.	15 m	6 min	20 rem/min 0.1 mrem
<u>Truck Servicing</u> Refueling (100 gallon capacity)	7 m (at tank)		60 rem/min
- 1 nozzle from 1 pump		40 min	2 mrem
- 2 nozzles from 1 pump		20 min	1 mrem
Load inspection/ enforcement	3 m (near personnel barrier)	12 min	160 rem/min 2 mrem
Tire change of repair	5 m	50 min	100 rem/min 5 mrem
State weight scales	5 m	2 min	80 rem/min 0.2 mrem

Most of these potential exposure events will not occur with each spent fuel shipment. Furthermore, the distances and exposure times are chosen to represent unlikely, extreme values which in combination result in maximum credible individual exposures. Four classes of normal spent fuel transportation exposure are postulated for both truck and rail casks. The first class is the caravan scenario, which includes all exposures arising from events in which people are traveling along the same transportation route as the spent fuel cask. For example, passengers in vehicles traveling ahead, to the side, or behind the truck cask might be subject to exposures. For this scenario class, the minimum nominal distance between the passengers and the cask is estimated at 10 meters for a maximum exposure time of 30 minutes. From Figure 1 the dose rate at about 10 meters from the truck cask is about 40 microrem per minute. Therefore, the maximum individual dose is estimated to be

$$40 \text{ microrem/min} \times 30 \text{ min} = 1200 \text{ microrem}$$

or about 1 mrem for the truck caravan scenario. This dose estimate neglects shielding afforded by passenger vehicles and is believed to be conservatively high. Furthermore, the probability of such an occurrence (i.e., to remain within 10 meters of the cask for 30 minutes) is very low and is very unlikely to be experienced by the same exposed individual more than once. Traffic obstructions which result in stopping or significant slowing of the transportation cask constitute the second class of exposures. The occurrence of an obstruction for 30 minutes which results in a 5 meter separation between the truck cask and an exposed individual is recognized as highly conservative and unlikely to be repeated for the same exposed individuals. The dose rate of 100 microrem per minute at 5 meters from the truck cask for a 30 minute exposure results in a maximum individual dose of 3 mrem. Another class of individual exposures results from the transit of the cask through areas where pedestrians and residents are located within the radiation field of the cask. Slow transit events assume average cask transport speeds less than 1 mph through these areas. Resulting doses are 3 mrem or less. The final class of individual exposure events during normal transport operations are those associated with the servicing of the cask transporter. Doses here are 5 mrem or less.

POTENTIAL RADIATION EXPOSURES FROM RAIL CASK ACCIDENT

Spent fuel rail casks each containing up to 14 PWR spent fuel assemblies could conceivably be involved in a variety of rail related transportation accidents. However, to date there has never been a transportation accident involving spent fuel which has resulted in a release of radioactive material to the environment(7). In fact, no release of radioactive material has ever occurred from any package designed as an accident-resistant package. Thus, for future accidents involving rail casks, the most likely outcome will be that no radioactive material will be released from the cask. This is true even if the accident involves derailment and overturn of the rail cask car with detachment of the spent fuel cask from the car. Numerous experimental tests to date have demonstrated the integrity of such casks. The probability of a release of radioactivity from a rail cask accident has been estimated to be no greater than 2 occurrences per million rail transport accidents. Nevertheless, the consequences of a set of maximum credible accidents which result in radioactive material release have been examined.

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[a] These exposures should not be multiplied by the expected number of shipments to a repository in an attempt to calculate total exposures to an individual; the same person would probably not be exposed for every shipment, nor would these maximum exposure circumstances necessarily arise during every shipment.

There are numerous physical mechanisms(8) which can contribute to the release of radioactive materials from spent fuel in a transport cask. These mechanisms, each of which have distinct, quantifiable processes associated with them are 1) impact rupture which results in the release of radioactive material due to mechanical disruption and failure of the fuel cladding followed by depressurization of the fuel rod; 2) burst rupture which results in a release due to external heating which produces internal pressures in the fuel sufficient to deform and burst the cladding and fuel rod; 3) rapid oxidation resulting from heating, combined with diffusion and leaching which can enhance the release of radioactive material from the spent fuel. With the failure of the protective cladding, severe heating combined with air flow over the exposed uranium dioxide fuel may further oxidize the fuel, resulting in macroscopic cracking and increased release of fission products. The release of crud is associated with the liberation of certain radionuclides which are not fission products generally, but have deposited on fuel assemblies from corrosion products and trace contaminant deposition. A total, catastrophic failure with full breaching of the cask is not considered credible. However, some casks have employed valves for access to the cask interior and could be breached by valve failure during a credible accident scenario. Furthermore, leakage past the cask closure seals or even a small breach due to a stress crack in the cask wall are considered credible, although no experimental tests have ever indicated such a failure mode. The set of accident scenarios examined for radiation dose consequences is considered to include the worst credible scenario for radioactive material releases which might occur from an air cooled rail cask. In this worst case scenario, the rail cask and its spent fuel assemblies may suffer impact rupture, or impact and burst rupture, or a combined impact and burst rupture accompanied by rapid oxidation due to severe heating from a combustible fuel supported fire. Table II provides a tabulation of the major radioactive nuclides and their inventory in a rail cask containing 14 PWR spent fuel assemblies, each 5 years old. On the basis of projected, worst case rail accidents for an air-cooled rail cask, the credible releases of nuclides to the environment and the fraction of this environmental release that is respirable have been estimated(8). These releases are tabulated for each accident class, viz., impact, burst with impact and, finally, rapid oxidation accompanying burst and impact rupture. The nuclides listed in the table have been found to have the greatest human health consequences and are used to characterize the total nuclide inventory. The PATHRAE-T computer code can be used to calculate whole body dose equivalents to individuals or population groups under diverse hydrological, climatic and demographic conditions. The code employs a standard Gaussian puff atmospheric dispersion model and the radiation doses are assumed to result from the following exposure pathways: 1) inhalation of gaseous and airborne particulate nuclides from the release plume; 2) direct gamma ray exposure from nuclides in the atmosphere; 3) direct gamma ray exposure from nuclides deposited on the ground from atmospheric transport; 4) inhalation of airborne particulate nuclides resuspended in the atmosphere from distributed ground dust; and 5) human ingestion of water contaminated with nuclides deposited on surface water and soil. Radiation exposures arising from the consumption of food grown on contaminated land were found to be negligible and were ignored.

Table III and IV indicate the estimated radiation doses for maximally exposed individuals and the general population received by persons located generally downwind of the accident. The location for the maximum individual exposure occurs at a position about 70 meters directly downwind from the point of release and results in a maximum individual dose of about 10 rem. This dose is considered to have no immediate health consequences and only a small increase in the probability of incurring cancer in later years. Table IV shows that nuclides deposited upon the ground account for 99 percent or more of the population dose, since inhalation and plume exposures occur only during the passage of the airborne nuclides. Exposures from ground deposition continue for the entire 50 year period of residency assumed in the analysis. For the urban population density a worst case rail cask

TABLE II

Environmental Releases and Respirable Fractions of Nuclides
in Spent Fuel Rail Accident

		Environmental Release (Ci)			Respirable Fraction		
Nuclide	Cask Inventory (Ci)	Impact	Impact and Burst	Impact, Burst and Oxidation	Impact	Impact and Burst	Impact, Burst and Oxidation
Co-60 (crud)	645	8.06	8.06	8.06	0.05	0.05	0.05
Kr-85	42,700	512	4,360	4,780	1.00	1.00	1.00
Sr-90	417,000	0.0042	0.379	0.379	0.05	0.05	0.05
Ru-106	114,000	0.0011	0.104	4.67	0.05	0.05	0.05
I-129	0.213	0	0	0.001	0.05	1.00	0.12
Cs-134	192,000	0.0019	34.6	326	0.05	1.00	0.15
Cs-137	613,000	0.0061	110	1,040	0.05	1.00	0.15
Pu-239	2,870	0.0	0.0026	0.0026	0.05	0.05	0.05
Totals	1.38x106	520	4,513	6,159	512 Ci	4,505 Ci	4,990 Ci

TABLE III

Maximum Individual Radiation Dose Estimates For Rail Cask Accidents

Accident Class	Dose (mrem)			
	Inhalation	Plume Gamma	Ground Gamma	Dust Inhalation
Impact	180	11	12	0.0001
Impact and Burst	6100	71	91	0.004
Impact, Burst and Oxidation	9000	550	710	0.0006

accident with impact and burst rupture enhanced by oxidation could result in up to 22 latent health effects (latent health effects are possible fatal cancers and genetic defects over the succeeding two generations) if the nuclides deposited on the ground are not cleaned up or other measures to reduce radiation exposure are not implemented. For the rural population density the same accident could result in up to 0.035 latent health effects. These health effects may be put into perspective by considering cancer fatalities from all other sources over 50 years. The same urban and rural populations would experience about 470,000 and 730 cancer fatalities respectively from all other cancer causes. Clearly the severe but credible rail cask accident does not contribute significantly to the number of cancer fatalities in the region impacted.

POPULATION EXPOSURES THROUGH THE WATER PATHWAY

The worst case rail cask spent fuel accidents were considered in a setting which maximized radiation exposure from the water pathway. The plume of radioactive material was assumed to be transported over a large reservoir that was wider than the transverse extent of the plume. The reservoir was assumed to have a surface area of 400,000 square meters (about 100 acres) and to contain about 3.8 million cubic meters (about 1 billion gallons) of water. The plume from the release passes over the reservoir as it travels from 100 meters to about 1400 meters downwind of the release point. The nuclides deposited on the water surface are assumed to become thoroughly mixed and remain suspended within the reservoir water. The contaminated water is used solely for domestic purposes by the surrounding population. Table V provides estimates of the population doses that would result from this worst case accident. The impact, burst and oxidation class accident results in a maximum of about 13 latent health effects. The probability that such a worst case accident would occur near a major reservoir and that prevailing weather conditions would combine to result in significant water contamination is extremely small. Furthermore, it is reasonable to assume that normal water treatment processes, combined with monitoring and emergency actions, would significantly reduce doses to the affected populations. The water from the accident model reservoir could supply about 100,000 people for a year. This same population would experience about 9,600 cancer fatalities from other causes over 50 years.

TABLE IV

50-Year Population Dose Estimates For Spent Fuel Rail Cask Accidents
No Cleanup of Deposited Nuclides

Accident Class	Urban Area (3860 people/km^2)				Rural Area (6 people/km^2)			
	Inhalation	Plume Gamma	Ground Gamma	Total	Inhalation	Plume Gamma	Ground Gamma	Total
Impact								
Dose (person-rem)	3.1	0.33	940	940	0.005	0.0005	1.5	1.5
Latent Health Effects[a]				0.19				
Impact and Burst								
Dose (person-rem)	110	2.2	13,000	13,100	0.16	0.0034	21	21
Latent Health Effects[a]				2.7				0.0042
Impact, Burst and Oxidation								
Dose (person-rem)	150	17	110,000	110,000	0.24	0.027	170	170
Latent Health Effects[a]				22				0.035

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[a] Latent Health Effects (LHE) estimates are based on 1 person-rem = 2x10-4 LHE.

TABLE V

Population Radiation Exposure From Water Ingestion For Severe But Credible Spent Fuel Rail Cask Accidents

Accident Class	Total Release from Rail Cask (Ci)[a]	Population Dose Effects From Water Ingestion
Impact	8.07	180 person-rem 0.036 LHE[b]
Impact and Burst	153	6900 person-rem 1.4 LHE[b]
Impact, Burst and Oxidation	1379	63,000 person-rem 13 LHE[b]

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[a] The noble gas Kr-85 is omitted because of its negligible uptake by a surface water body.

[b] Latent health effects (LHE) estimates are based upon 1 person-rem = $2x10^{-4}$ LHE.

CONCLUSION

Situations that could result in radiation exposure during normal transport of spent fuel result in doses of the order of 5 mrem or less. This represents less than 2 weeks of natural background radiation. Furthermore, these exposures are not likely to be repeated to the same individuals. A person(s) responding to a worst case rail cask accident could receive a dose of 10 rem if no protective equipment was worn and the individual remained within the contaminated cloud of radionuclides during the entire release. However, the consequences of this radiation exposure are probably less than those hazards arising from smoke inhalation and injury from the severe fire assumed. The maximum population dose from the worst case rail accident could result in up to 22 latent health effects but monitoring and land cleanup would be inevitable and would greatly reduce these effects. A worst case rail cask accident which contaminates a water pathway could result in up to 13 latent health effects but reasonable surveillance and water treatment operations would significantly reduce this impact. It is concluded that spent fuel from nuclear power operations can be safely transported for disposal with risks no greater than those associated with other general industrial activities.

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