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RISK OF TRANSPORTING SPENT NUCLEAR FUEL BY TRUCK

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Spent nuclear fuel has been routinely transported from reactor plants to storage and reprocessing facilities for over 25 years. During this time over 3600 shipments of spent fuel have been made. The safety record for these shipments has been excellent. As the nuclear industry grows, it is expected that the number of shipments made annually will increase. To help insure the continued health and safety of the general public, research programs have been instituted to improve the level of understanding of the safety-related aspects of transporting nuclear materials. Pacific Northwest Laboratory (PNL) is currently conducting a transportation research program for the Transportation Branch of DOE's Division of Environmental Control Technology. One of the objectives of this program is to assess the risk of transporting energy materials for current and future shipping systems. This paper presents preliminary results of a study to assess the risk of transporting spent nuclear fuel by truck.(1)

Risk, as used in the context of this paper, is the product of the probability of a release of radioactive material to the environment and the consequences resulting from the release. The risk methodology used to evaluate the risk in shipping spent fuel was initially applied to the shipment of plutonium by truck(2) and has subsequently been applied to the transport of other energy materials.(3,4) The methodology includes: 1) a description of the spent fuel transport system, 2) identification of potential release sequences, 3) evaluation of the probabilities and consequences of the releases, and 4) calculation and assessment of the risk. The system description includes projected industry characteristics, amounts to be shipped, shipping package descriptions, material characteristics, transport mode, transport routes used and weather and population distribution information. Release sequences are identified by fault tree analysis techniques. Releases are evaluated using package failure data, normal transport and transport accident environment data and mathematical models for material dispersion and resultant health effects. This information is combined to calculate the shipping system risk which is compared to other known risks. The data may be further analyzed to determine the primary contributors to the risk and identify possible methods for reducing the risk, if the current risk level is judged by society to be unacceptable.

SHIPPING SYSTEM DESCRIPTION

The analysis was based on the spent fuel shipping requirements for a nuclear industry consisting of 100 nuclear reactors of 1000 Megawatt electrical capacity. This level is expected to be reached in the early to mid-1980s. The amount of fuel shipped per year from the 100 reactors was estimated to be 1854 MT of heavy metal.(5)

Spent nuclear fuel may be either stored or reprocessed and used as additional reactor fuel. The reprocessing of spent nuclear fuel is currently the subject of national and international debate. At the present time, reprocessing has been indefinitely suspended in the United States. For completeness, two spent fuel shipping scenarios were examined: the "once through" fuel cycle and fuel reprocessing. In the "once through" fuel cycle, fuel elements are used in a power reactor, shipped to an intermediate storage facility, and eventually placed in a permanent disposal facility. Federal repositories for spent fuel and radioactive wastes are not projected to be in operation until after the mid-1980s, so only shipments to interim storage were considered for this case. Four interim spent fuel storage facilities were assumed to be in operation in the United States in the reference year. These were assumed to be located at Morris, IL, Barnwell, SC, Oak Ridge, TN, and Hanford, WA. At the present time, no reprocessing facilities are operating in the United States. For the reprocessing case, all spent fuel was assumed to be shipped from the reactor to fuel reprocessing plants located at Barnwell, SC, and Oak Ridge, TN.

Estimated shipping route distances from reactors to spent fuel storage facilities or fuel reprocessing plants were determined using a model shipping system. Existing and proposed reactors[6] were grouped according to type (PWR or BWR) and location, and distances from these groups to the nearest assumed interim storage or reprocessing facility were calculated. Estimates of the amounts of spent fuel shipped per year from each reactor group were made based on the number, size and type of reactors in each group. From these amounts, the number of assemblies shipped and the number of shipments by truck were calculated. It was assumed that 20% of the spent fuel transported during the reference time period is shipped by truck. Table 1 shows the shipping characteristics assumed for the study.

For this study spent fuel was assumed to be shipped in a typical water filled truck cask designed to transport one PWR or two BWR fuel assemblies. The reference cask used for the study is pictured in Figure 1. The cask is lead shielded and water filled with a borated water neutron shield. Impact limiters of stainless steel-sheathed balsa wood are placed at each end of the cask to provide protection from impact damage. The approximate loaded cask weight is 23 MT, the overall length 544 cm (214 in.) and the diameter 96 cm (39 in.). Cask overpressure protection is provided by a rupture disk assembly which vents to atmosphere if the cavity pressure exceeds 76 atm.

TABLE 1. Summary of Shipping Characteristics for Spent Fuel by Truck in Mid-1980s

Amount Spent Fuel Per Shipment (MTHM)	PWR 0.461 BWR 0.189
Material Shipped Per Year (MTHM)	380
Age of Fuel at Shipment (Time after Discharge from Reactor in Days)	180
Number of Assemblies Shipped per Year by Truck	PWR 550 BWR 670
Number of Shipments Per Year by Truck	885
Average Shipment Distance (km):	
Once Through Fuel Cycle	690 (430 mi)
Reprocessing Fuel Cycle	930 (580 mi)
Accident Probability (number/km)	1.5×10^{-6}

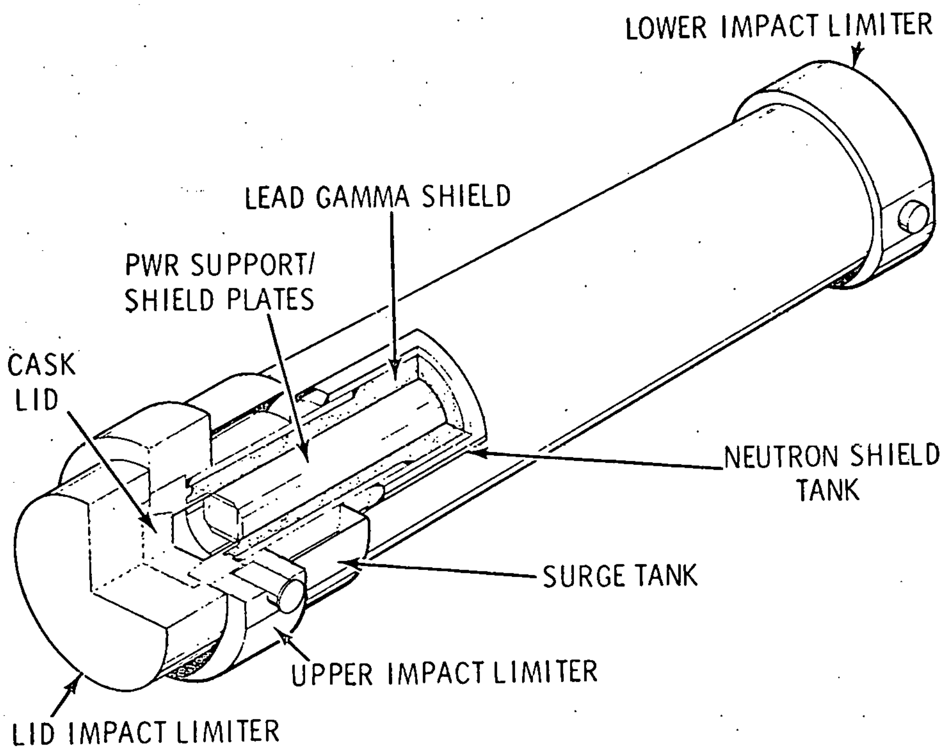

FIGURE 1. Reference Spent Fuel Shipping Cask

RELEASE SEQUENCE IDENTIFICATION

The next step in the risk assessment was to identify possible ways that releases could occur (release sequences) from a truck cask in an accident. Fault tree analysis was used to identify combinations of conditions which could result in a release. Releases of radioactive material were postulated and the series of events which would have to occur to cause the releases were examined. Figure 2 shows the top of the fault tree that was developed for this study. The PNL computer code ACORN(7) was used to plot the fault tree. The top event on the tree is the postulated release of radioactive material to the environment during spent fuel shipment. The major modes of failure were found to be through release of material from one of the main components of the cask: the cask lid, closure seal, cask wall, pressure relief device, drain valve or the vent valve. Detailed fault trees for the failure of each of these cask components were then developed. Release of radioactive material from each component was postulated to occur from 1) accident forces that fail the component and the fuel and 2) failure of the component from accident forces or substandard packaging conditions resulting in a loss of cavity coolant. Both the cask component and the fuel may fail from the same accident event or they may fail from different events. Loss of coolant failure sequences may result in release of radioactivity in the cavity coolant itself or coolant activity plus fission products escaping from overheated fuel rods. The contribution to the failure sequences of packaging closure errors, cask construction flaws or changes in the package condition from normal transport forces were also considered.

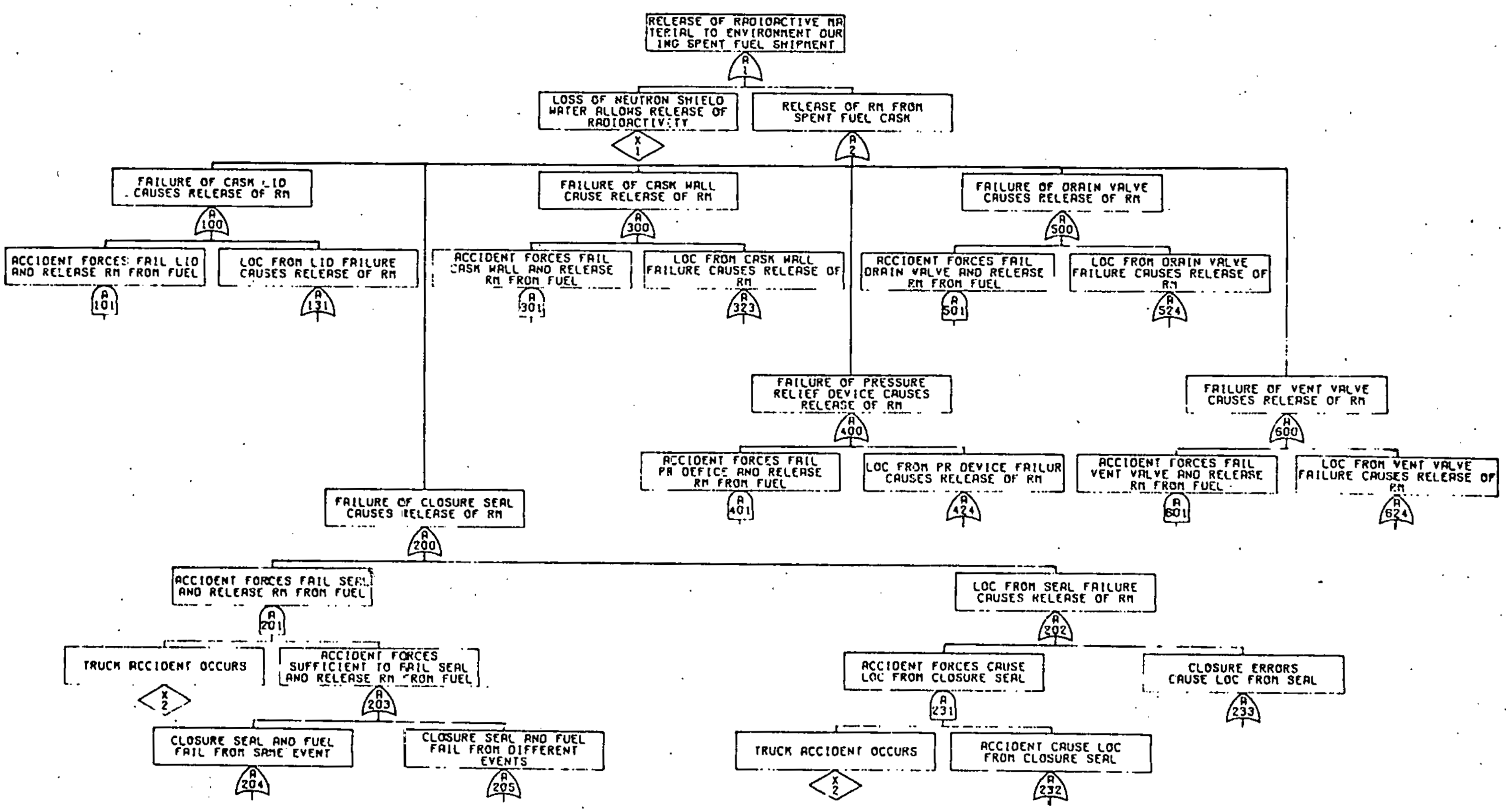

FIGURE 2. Top of Fault Tree for the Shipment of Spent Fuel by Truck

Each of the fault tree branches for the different cask components were developed down to basic events which can be assigned failure probabilities. The fault tree provides a compact notation for identifying and summarizing several thousand release sequences. Release sequences contained in the fault tree were identified with the MFAULT[8] fault tree analysis code.

RELEASE SEQUENCE EVALUATION

After the release sequences have been identified, the occurrence frequency (release sequence probability) and the amount of radioactivity released (release fraction) are estimated for each release sequence and the potential consequences of the release are determined. The release sequence probabilities are determined by estimating the occurrence frequency of each of the basic events in the fault tree. The fault trees were developed to a point where data on basic events could be obtained through either analysis or survey. The estimated basic event probabilities were determined using package closure data, cask failure thresholds and transport accident data.

Facilities routinely receiving spent fuel were surveyed to determine the condition of the casks during transport. The probabilities developed from the results of the survey were used for events involving package closure errors and the effect of normal transit forces on the cask.

The probability of package failure in an accident was developed by combining truck transportation accident environment data with estimates of the response of the package to stresses produced in truck accidents. Package response to the most significant stresses imposed in highway accidents was estimated in terms of failure thresholds. A failure threshold is the level of applied thermal or mechanical stresses that produce a release of radioactivity in an accident. Accident environment information developed by Sandia Laboratories[9] was the primary basis for estimating the probability of producing forces in an accident that exceed the package failure thresholds.

Package failure threshold estimates were obtained using mathematical analysis, engineering estimates and the results of a full scale test of a water cooled truck cask.[a] Detailed analysis and experimental tests were beyond the scope of this study. Two barriers to release of radioactive material are present for the spent fuel cask. These barriers are the fuel rod cladding and the spent fuel cask body. Relatively small amounts of activity are present in the cavity coolant and are released if the cask body is breached. All larger releases of radioactivity from the cask must breach both the fuel and the cask. Failure thresholds were derived for both the fuel and cask. The most significant types of accident-imposed stresses which affect the spent fuel cask and fuel were determined to be: end impact, side impact, fire, and impact followed by fire. The responses of the cask and fuel to each type of stress associated with the accident environment were calculated independently. Puncture failure information was obtained from accident environment data that relates failure frequency to the equivalent steel thickness of the cask. The forces produced by immersion were determined not to be significant for truck transportation of spent fuel.

The amount of radioactive material released to the environment for each release sequence is conveniently expressed as a release fraction the fraction of the cask inventory released by that sequence of events. The release fractions used in this study were developed from the results available in existing literature on releases from spent fuel. Published literature reported only experimental accident simulations and known chemical and physical responses of the spent fuel. Because no actual accidental release data is available, engineering judgment was required to arrive at realistic release estimates.

Radioactive material is available for release from the truck cask under postulated accident conditions in the form of vapors, liquids and aerosols. Vapors consist of noble fission gases and elements volatilized from the fuel at elevated temperatures. The cavity coolant represents

[a] Personal communication with M. Huerta on Preliminary Test Results, Sandia Laboratories, Albuquerque, NM, August 1977.

the only potential liquid release. Aerosols are released as a result of vaporizing contaminated cavity coolant or the release of fines from the fuel pellets. In order to be available for release from the truck cask, the activity must first escape the fuel rods into the cask cavity. Four mechanisms have been identified which may lead to significant release from the fuel rods.

1. Gas Gap Release is the energetic venting of pressurized gases from the fuel element plenum and pellet cladding gap. High temperature creep or mechanical forces can cause the necessary cladding rupture. Available for release are noble gases, volatile halogens and entrained particulates which have migrated from the fuel matrix during irradiation.

2. Vaporization Release is the volatilization of low melting point fission products and their gaseous transport to the cask cavity. If the high temperature environment occurs before fuel cladding rupture, then a driving force for release is the venting of fuel cladding internal pressure. Cesium is a primary constituent of the semi-volatile elements.

3. Leaching of fission products from the fuel pellets requires direct contact of aqueous cask cavity coolant. Leached activity escapes the cask with the cavity coolant.

4. Oxidation of some fraction of the UO_2 fuel pellets to U_3O_8 may take place in the unlikely event of a large cask rupture. A cask breach large enough to allow flowing air to contact the fuel is necessary for this type of release. Material released would be in the form of noble gases, volatilized fission products and sub 10 μm particulates.

The release sequences developed from the fault tree were divided into eight different categories based on postulated accident conditions, and release fractions were assigned to each category. For each accident category, release fractions were developed for five different classes of radioactive material. Those classes were noble gases, Iodine, Cesium and Ruthenium, Actinides, and all other significant mixed fission products. Table 2 shows the accident categories and the associated release fractions. Fuel rod overheating resulting from accidents involving a fire that lasts long enough to cause release of the cavity coolant or a loss of cavity coolant from other accident forces results in the largest potential releases. This occurs because pressurized creep rupture of the cladding expels much more activity than less energetic venting following an impact type failure of the fuel.

RISK CALCULATION AND ASSESSMENT

The consequences of the postulated releases of radioactive material from spent fuel following an accident are dependent on the type of release, the population distribution near the accident, the weather conditions at the time of release and assumptions about the health effects of the material that is released. This assessment included a probabilistic treatment of the weather and population distributions along the shipping routes. Weather information was obtained by averaging actual data from 26 reactor sites throughout the country. Population distribution information was obtained by dividing the U.S. into four population zones and assigning a representative population distribution to each zone using census data projected to the 1980s. The number of accidents in each zone was then estimated based on the shipping distance in that zone. Radiation doses to the public from the releases were calculated for each of the population and weather distributions using standard atmospheric dispersion and inhalation models. The health effects from this population dose were estimated using information developed in the BEIR[10] report. These estimates are believed to be conservative.

The shipping system risk is determined by multiplying the probability of a release sequence occurring by the estimated consequences for each weather and population distribution (adjusted for the fraction of accidents occurring in each population zone for each weather condition) and summing over all release sequences. This calculation was carried out for both the "once-through" and reprocessing fuel cycles. The risk spectrum for the once-through cycle for the number of shipments projected for the mid-1980s is presented in Figure 3. The risk spectra for

TABLE 2. Accident Release Fractions of Radioactive Material to the Atmosphere From the Truck Transport of Spent Fuel

Accident Case	Release Mechanisms	Fractional Release of Cask Activity: Noble Gases (Kr, Xe)	Iodine	Fission Products	AOFP[a]	Actinides
1. Small undetected leak of cavity coolant	Leaching	-[b]	--	Cs 3.6×10^{-8}	--	--
2. Slow leak of cavity coolant due to gasket failure	Leaching	--	--	Cs 1.2×10^{-9}	--	--
3. Impact and slow leak of cavity coolant	1. Gap activity 2. Leaching	0.3	0.1	Cs 4.2×10^{-8}	6.5×10^{-9}	5.3×10^{-9}
4. Severe cask impact with a rapid loss of cavity coolant	1. Gap activity 2. Volatilization 3. Oxidation	0.31	0.12	Cs 3.0×10^{-4} Ru 1.0×10^{-4}	1.5×10^{-6}	1.0×10^{-6}
5. Cask involved in a 1010°C fire	1. Gap activity 2. Volatiles	0.3	0.1	Cs 1.5×10^{-4}	1×10^{-5}	1×10^{-5}
6. Cask impact followed by a 1010°C fire	1. Gap activity 2. Volatilization 3. Leaching	0.3	0.1	Cs 1.6×10^{-4}	2×10^{-6}	1.5×10^{-6}
7. Severe cask impact followed by a 1010°C fire	1. Gap activity 2. Volatilization 3. Oxidation	0.31	0.12	Cs 3.1×10^{-4} Ru 1.0×10^{-4}	1.5×10^{-6}	1×10^{-6}
8. Rapid loss of cavity coolant due to cask closure device failure	1. Gap activity 2. Volatiles	0.3	0.1	Cs 1.5×10^{-4}	1×10^{-5}	1×10^{-5}

(a) All Other Fission Products.

(b) Indicates negligible activity released (RF < 10^{-10}).

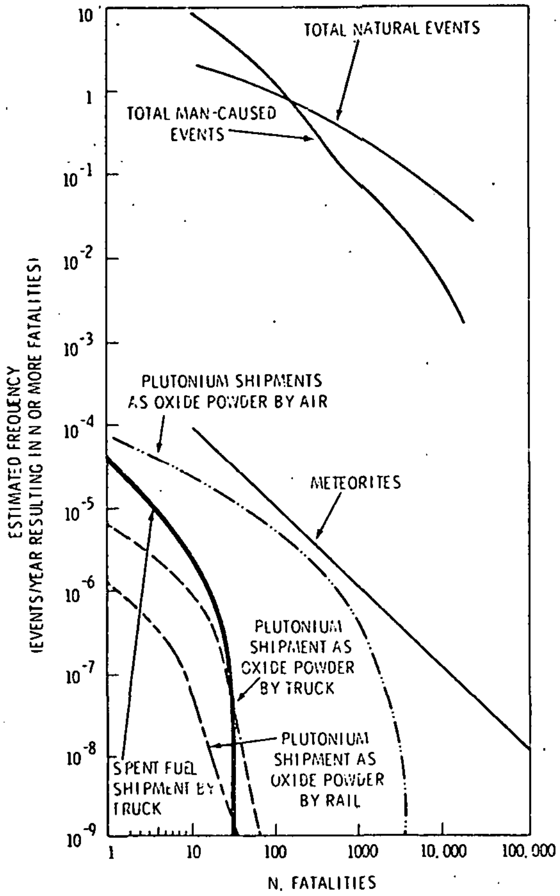

FIGURE 3. Risk Spectrum for Shipment of Spent Fuel to Interim Storage and Other Risk Spectra

transportation of other radioactive materials and for other risks in society are included in the figure for comparison. The curves indicate that the risk to society from transporting spent fuel by truck is much less than the risk from natural events or from other man-caused events. The spent fuel shipping risk is comparable to the risk of transporting uranium hexafluoride by truck and train[4] and plutonium by truck and train and less than the risk of transporting plutonium by cargo aircraft.[3] For the 1980's shipping levels used in this study, a truck carrying spent fuel would be expected to be involved in a minor accident once every 1.1 years. An accident that resulted in one or more latent cancer fatalities is estimated to occur once in 17,500 years. The risk for the reprocessing scenario is about 20% less than the risk shown for the once-through fuel cycle. Although the average shipping distance for the reprocessing case is larger, the risk is somewhat lower because the shipping routes, on average, are through less populated sections of the country.

Sensitivity studies were performed to determine the most important contributors to the risk. Impact forces were found to contribute to about 69% of the releases, failure by fire contributed to approximately 28% and non-standard package conditions to only about 3% of the releases. To illustrate the sensitivity of the risk to the release fractions, it was assumed that all release fractions were increased by a factor of ten. This case represents an upper limit example since the release fractions used in the base case analysis are believed to be conservative. This was shown to increase the risk by a factor of eight which indicates that the risk of spent fuel shipment is significantly dependent on the amount of material released in an accident. Conservative extensions of existing data were used in the analysis to determine the release fractions. Additional data on the fractions of radioactivity released under simulated accident conditions could increase the certainty of the risk evaluation.

Two possible methods for reducing the risk of transporting spent fuel by truck were investigated. Modifying the reference cask to reduce the effects of fire by replacing the rupture disk with a pressure relief valve was found to reduce the risk level by 24%. It was found that a significant method of reducing the risk would be to store the fuel longer than 2 years before shipment. The heat generation rate in the spent fuel would then be low enough to prevent fuel failure by overheating with no cavity coolant in the cask. Sensitivity analysis showed that shipping only fuel that had been cooled two years or longer would reduce the risk level 82%.

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