1. INTRODUCTION

1.1 NUREG-0170

In September of 1977, the Nuclear Regulatory Commission (NRC) issued a generic environmental impact statement (EIS), titled "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," NUREG-0170, that covered the transport of all types of radioactive material by all transport modes (road, rail, air, and water) [1-1]. That EIS provided the regulatory basis for continued issuance of general licenses for transportation of radioactive material under 10 CFR 71. Based in part on the findings of NUREG-0170, NRC staff concluded (1) that "the average radiation dose to the population at risk from normal transportation is a small fraction of the limits recommended for members of the general public from all sources of radiation other than natural and medical sources and is a small fraction of natural background dose" and (2) that "the radiological risk from accidents in transportation is small, amounting to about one-half percent of the normal transportation risk on an annual basis" [1-2]. In addition, the NRC Commission concluded that "present regulations are adequate to protect the public against unreasonable risk from the transport of radioactive materials" (46 FR 21629, April 13, 1981) and stated that "regulatory policy concerning transportation of radioactive materials be subject to close and continuing review."

1.2 NUREG-0170 Spent Fuel Transportation Risks

NUREG-0170 estimated the radiation doses and latent cancer fatalities that might be associated with the transport of 25 different radioactive materials by plane, truck, train, and ship or barge. The 25 materials were chosen to encompass 90 percent of all shipments in the United States and 90 percent of the activity contained in shipments. The estimates were made using Version 1 of the RADTRAN code (RADTRAN 1) [1-3], which was developed specifically to support the performance of the NUREG-0170 study.

One of the 25 radioactive materials examined by NUREG-0170 was spent nuclear power reactor fuel. For spent fuel shipments that occur without accidents (incident-free transport), radiation doses were estimated for members of the general public who would be exposed to radiation, for example, because they lived near the shipment route, and also for workers (e.g., crew, handlers, inspectors). Release of radioactive materials from spent fuel to the environment as a result of transportation accidents, the probability of these releases, and the latent cancer fatalities that such releases might cause were also estimated.

Spent fuel transport risks were estimated for shipment by truck and by train over a generic highway and a generic rail route [1-4]. Table 1.1 describes attributes of these two generic routes. Radiological consequences (population doses for incident-free transport and expected numbers of latent cancer fatalities for transportation accidents) were estimated for spent fuel shipments expected to occur during 1975 and 1985. Tables 1.2 and 1.3 respectively present the incident-free and accident consequences estimated for these spent fuel shipments.

Table 1.1 NUREG-0170 Spent Fuel Truck and Train Route Data

Parameter	Truck Route	Rail Route
Route Length (km)	2530	1210
Fraction Urban	0.05	0.05
Fraction Suburban	0.05	0.05
Fraction Rural	0.9	0.9
Population Densities (people km^{-2})		
Urban	3861	3861
Suburban	719	719
Rural	6	6
Shipments per year (single cask)		
1975	254	17
1985	1530	652

Table 1.2 NUREG-0170 Annual Incident-Free Spent Fuel Transportation Doses (person-rem)

Incident-Free Shipment Doses	Truck		Train	
	1975	1985	1975	1985
Crew	31.3	188	0.68	2.6
Handlers	50.8	306	6.8	261
Storage	1.26	7.6	0.427	16.4
General Public				
Off-Link[a]	3.8	22.9	0.175	6.69
On-Link[b]	1.88	11.3	0.222	8.53
Stops[c]	4.82	29.0	0.089	3.44
Total Population Dose	93.8	565	7.78	298

a. Residents living by the transport route.
b. Travelers exposed while traveling in cars, buses, or trains.
c. Travelers exposed at rest stops.

Table 1.3 Expected (Mean) Latent Cancer Fatalities Predicted in NUREG-0170 to be Caused by Truck and Train Accidents that Occur during Spent Fuel Transport

Year	Release Model	Truck	Train	Truck + Train
1975	I	0.047	0.021	0.068
1985	I	0.29	0.8	1.09
1975	II	NA	NA	0.0000356
1985	II	NA	NA	0.000422

For calculations of radiological consequences that might be caused by accidents, accidents were divided into eight categories (Categories I through VIII) of increasing severity. Because "little information relating the response of packages to accident environments" [1-5] was available in 1975 for spent fuel and other highly radioactive materials shipped in Type B packages, release of radioactivity as a result of accidents was examined using two release models. The first model, Model I [1-6], assumed [1-7] that "zero release occurs up to the regulatory test level and that the packaging fails catastrophically in all environments that exceed that level." The amounts of each radionuclide that were assumed [1-8] to be released to the environment by this "catastrophic" failure are presented in Table 1.4. Thus, Model I assumed that the radioactive release specified in Table 1.4 would take place whenever a Type B spent fuel package was subjected to mechanical or thermal loads in excess of the mechanical and thermal loads encountered during package certification tests [1-9]. Because the Model I cask release behavior was considered to be unrealistic, a second release model (Model II) was formulated. In Model II, for accidents that exceed the regulatory test level, release fractions increased more gradually with accident severity [1-10], becoming equal for catastrophic accidents to the release specified for all severe accidents by Model I.

Table 1.5 shows that the Model I and Model II release fractions are used for both truck and train accidents. Model I and Model II release fractions are the same for accident categories I, II, V, VI, VII, and VIII and differ only for categories III, and IV. Finally, Table 1.3 shows that accident consequences are substantially decreased if, as is done in Model II, release is assumed to increase with increasing accident severity.

Table 1.4 Inventory (Ci) Assumed in NUREG-0170 to be Released to the Environment from a Type B Spent Fuel Cask as a Result of an Accident

Fission Products	Truck Cask	Rail Cask
Kr-85	1700	10,900
I-131	0.022	0.138
Volatiles as Cs-137	200	1280

1.3 Need for Reevaluation of NUREG-0170 Spent Fuel Transportation Risks

While NUREG-0170 was an important analysis that delineated transportation risks in the context of the information available at that time, its results were developed using rather simple models and limited data. In the interim, there has been significant growth in analytical capabilities and data. While the casks and the specific routes for spent fuel movements have not yet been designated, it is clear that the generic cask and routes used in NUREG-0170 are now less than typical. For example, spent fuel may soon be shipped in the dual-purpose or multi-purpose canisters (MPCs) from commercial reactors to Interim Spent Fuel Storage Installations and/or Centralized Storage Facilities in addition to shipment to a permanent geologic repository. In fact, the Office of Nuclear Material Safety and Safeguards (NMSS) has received several applications for dual-purpose (storage and transport) spent fuel casks, and additional applications

Table 1.5 NUREG-0170 Model I and Model II Severity and Release Fractions for Spent Fuel Transport by Truck and Rail

Accident Category	Severity Fractions[a] Models I and II		Release Fractions Truck and Rail	
	Truck	Rail	Model I	Model II
I	0.55	0.50	0.0	0.0
II	0.36	0.30	0.0	0.0
III	0.07	0.18	1.0	0.01
IV	0.016	0.018	1.0	0.1
V	0.0028	0.0018	1.0	1.0
VI	0.0011	1.3×10^{-4}	1.0	1.0
VII	8.5×10^{-5}	6.0×10^{-5}	1.0	1.0
VIII	1.5×10^{-5}	1.0×10^{-5}	1.0	1.0

a. Fraction of accidents that fall into this severity range

are expected in the near future. In addition, many improvements have been made to the risk assessment models implemented in the RADTRAN code since the initial version of that code was used to estimate spent fuel transportation risks for NUREG-0170, and a major study of the response of spent fuel casks to severe transportation accidents, "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, often called the Modal Study, has been published [1-11].

Because new data and analytical methods were now available to apply to the analysis of power reactor spent fuel transportation risks, and because spent fuel is likely to be shipped to facilities along routes and in casks not specifically examined by NUREG-0170, the NRC decided the conclusions reached in NUREG-0170 should be reexamined in order to determine if the risks of the spent fuel shipments that are expected to take place during the next few decades are bounded by the risk estimates published in NUREG-0170. Accordingly, this report documents the methodology and results of a reevaluation of the risks of transporting spent fuel from commercial reactor sites to possible interim storage sites and/or permanent geologic repositories.

1.4 Study Objectives

This study had three objectives:

- Estimation of the radiological and non-radiological, routine and accident, transportation risks associated with the anticipated spent fuel shipments and determination of whether those risks are bounded by the estimates and projections of spent fuel shipment risks published in 1977 in NUREG-0170.

- Examination of any outstanding spent fuel transportation issues or environmental concerns not resolved by NUREG-0170 and the Modal Study.

- Documentation of the approach, data, and computational methods used to reestimate spent fuel transportation risks in detail sufficient to allow other transportation experts to fully understand the analyses performed, and preparation of a summary of the results in a form accessible to concerned citizens.

1.5 General Approach

The risks associated with the transport of spent fuel were estimated using Version 5 of the RADTRAN code [1-12, 1-13]. As in NUREG-0170, risks were estimated for incident-free transport and also for transportation accidents severe enough to cause radioactive material to be released from the cask to the environment.

Based on prior sensitivity studies [1-14, 1-15, 1-16], RADTRAN 5 input parameters were divided into three groups:

- Source term parameters (accident severity fractions and their corresponding accident release fractions),

- Other "more important" parameters that strongly influence RADTRAN estimates of radiation dose (for values within their likely range), and

- "Less important" parameters which have little impact on estimates of radiation dose (for values within their likely range).

For each of the "less important parameters," e.g., breathing rate, central (best) estimate values were selected. For each of the more important parameters (e.g., route lengths, population densities, accident rates, durations of truck stops, and cask surface dose rates), distributions of parameter values were constructed that reflected the likely real-world range and frequency of occurrence of the value of each parameter. Next, for both truck and rail analyses, 200 sets of the other "more important" parameter values were constructed by sampling these distributions using a structured Monte Carlo sampling technique called Latin Hypercube Sampling [1-16, 1-17].

For the source term parameters, review of studies of actual transportation accidents, in particular the Modal Study [1-11], allowed representative sets of truck and train accidents and their impact and fire environments to be defined. This analysis developed 19 representative truck accidents and 21 representative train accidents. Severity fraction and release fraction values were estimated for each representative accident.

Severity fraction values were developed by a review of the accident event trees, accident speed distributions, and accident fire distributions that were published in the Modal Study [1-11]. New event tree frequencies of occurrence of route wayside surfaces (e.g., hard rock; concrete, soft rock, and hard soil; soft soil; water) were developed using Department of Agriculture data [1-18] and Geographic Information System (GIS) methods of analysis [1-19].

Release fractions were estimated as the product of (a) the fraction of the rods in the cask that are failed by the severe accident, (b) the fraction of each class of radioactive materials (e.g., particulates) that might escape from a failed spent fuel rod to the cask interior, and (c) the

fraction of the amount of radionuclides released to the cask interior that is expected to escape from the cask to the environment. Rod failure during high speed collision accidents was estimated by scaling rod strains calculated for low speed impacts and then comparing the scaled rod strains to a strain failure criterion [1-20]. Heating of the cask by a fire to rod burst rupture temperatures was assumed to fail all unfailed rods. Rod-to-cask release fractions were estimated by review of literature data, especially the experimental results of Lorenz [1-21, 1-22, 1-23]. Cask-to-environment release fractions were based on MELCOR fission product transport calculations [1-24] that estimated the dependence of these release fractions on the size (cross-sectional area) of the cask failure that allows the release to the environment to occur.

Specifications for two generic truck and two generic rail spent fuel casks were developed from literature data [1-25]. Cask damage (e.g., seal leak areas) during severe collisions was estimated from the results of finite element calculations that modeled impacts onto an unyielding surface at various impact speeds. Unyielding surface impact speeds were converted to equivalent impact speeds onto yielding surfaces (e.g., soft rock) by considering the energy that would be absorbed by the yielding surface, increasing the energy of the unyielding surface calculation by that amount, and converting the new total energy to an initial impact speed. Seal leakage and rod burst rupture temperatures due to heating during fires were estimated from literature data. The durations of engulfing optically dense fires needed to produce large seal leak areas and rod failure by burst rupture were estimated by performing one-dimensional heat transport calculations.

By taking all possible combinations of the single set of central estimate values for the "less important" RADTRAN input parameters, the 200 sets of other "more important" truck parameter values, and the 19 sets of representative truck accident severity and release fraction values, input for 3800 single-pass RADTRAN 5 truck spent fuel transportation calculations was developed for each generic truck cask. Similarly, by taking all possible combinations of the set of "less important" parameter values, the 200 sets of other "more important" rail parameter values, and the 21 sets of representative rail accident severity and release fraction values, input for 4200 single-pass RADTRAN 5 rail spent fuel transportation calculations was developed. Application of standard statistical methods to the results of these 3800 truck or 4200 rail transportation calculations then allowed the results to be displayed as Complementary Cumulative Distribution Functions (CCDFs) and estimates of the expected (mean) result for radiological consequences (e.g., population dose) to be calculated. Finally, the results of these RADTRAN 5 calculations were compared to the results of RADTRAN 5 calculations that used the spent fuel source terms (severity fractions and release fractions) developed by the NUREG-0170 study [1-1] and those developed by the Modal Study [1-11] and differences in predicted risks are discussed.

1.6 References

[1-1] "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," NUREG-0170, U.S. Nuclear Regulatory Commission, Washington, DC, December 1977.

[1-2] Ref. [1-1], Summary and Conclusions, p. vii.

[1-3] J. M. Taylor and S. L. Daniel, "RADTRAN: A Computer Code to Analyze Transportation of Radioactive Material," SAND76-0243, Sandia National Laboratories, Albuquerque, NM, April 1977.

[1-4] Ref. [1-1], Vol.1, pp. 1-17, 4-16, 4-23, A-13, and E-4.

[1-5] Ref. [1-1], p. 5-20.

[1-6] Ref. [1-1], p. 5-22.

[1-7] Ref. [1-1], p. 5-21.

[1-8] Ref. [1-1], p. A-14.

[1-9] Code of Federal Regulations, Volume 10, Part 71.73 (10 CFR 71.73).

[1-10] Ref. [1-1], p. 5-23.

[1-11] L. E. Fischer, et al., "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, Lawrence Livermore National Laboratory, Livermore, CA, February 1987.

[1-12] K. S. Neuhauser and F. L. Kanipe, "RADTRAN 5, Technical Manual," Sandia National Laboratories, Albuquerque, NM (in preparation, draft available on request).

[1-13] K. S. Neuhauser and F. L. Kanipe, "RADTRAN 5, User Guide," Sandia National Laboratories, Albuquerque, NM (draft available on the RADTRAN web site).

[1-14] G. S. Mills, K. S. Neuhauser, and F. L. Kanipe, "RADTRAN 4 Truck Accident Risk Sensitivity Analysis," Proceedings of Waste Management 95, WM Symposia, Tucson, AZ, 1995a.

[1-15] G. S. Mills and K. S. Neuhauser, "Sensitivity Analysis for RADTRAN 4 Input Parameters," 88th Annual Meeting of the Air & Waste Management Assoc., San Antonio, TX, 1995.

[1-16] G. S. Mills, et al., "Application of Latin Hypercube Sampling to RADTRAN 4 Truck Accident-Risk Sensitivity Analysis," Proceedings of the 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95), IAEA, Vol. 4, p. 705, 1995.

[1-17] G. D. Wyss and K. H. Jorgensen, "A User's Guide to LHS: Sandia's Latin Hypercube Sampling Software," SAND98-0210, Sandia National Laboratories, Albuquerque, NM 1998.

[1-18] State Soil Graphics (STATSGO) Data Base, available on the Internet at ftp.ftw.nrcs.usda.gov/pub/statsgo.

[1-19] ARC/INFO Coverages and Arc View Project, K. C. Bayer Digital Map of the U.S., purchased from Geologic Data Systems, Inc., 1600 Emerson St., Denver, CO 80218.

[1-20] T. L. Sanders, et al., "A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements, Appendix III, Spent Fuel Response to Transport Environments," SAND90-2406, Sandia National Laboratories, Albuquerque, NM, November 1992.

[1-21] R. A. Lorenz, et al., "Fission Product Release from Highly Irradiated LWR Fuel," NUREG/CR-0722, Oak Ridge National Laboratory, Oak Ridge, TN, February 1980.

[1-22] R. A. Lorenz, et al., "Fission Product Release from Simulated LWR Fuel," NUREG/CR-0274, Oak Ridge National Laboratory, Oak Ridge, TN, July 1978.

[1-23] R. A. Lorenz, et al., "Fission Product Source Terms for the LWR Loss-of-Coolant Accident," NUREG/CR-1288, Oak Ridge National Laboratory, Oak Ridge, TN, July 1980.

[1-24] J. L. Sprung, et al., "Data and Methods for the Assessment of the Risks Associated with the Maritime Transport of Radioactive Materials: Results of the SeaRAM Program," SAND97-2222, Sandia National Laboratories, Albuquerque, NM, August 1997.

[1-25] "Shipping and Storage Cask Data for Commercial Spent Nuclear Fuel," JAI Corp., July 1996.