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REEXAMINATION OF SPENT FUEL SHIPMENT RISK ESTIMATES

J. R. Cook
U. S. Nuclear Regulatory Commission
Washington DC 20555
Phone: (301)415-8521
Fax: (301)415-8555
Email: jrc1@nrc.gov

J. L. Sprung
Sandia National Laboratories*
Albuquerque NM 87185-0718
Phone: (505)844-0134
Fax: (505)844-0244
Email: jlsprun@sandia.gov

ABSTRACT

The risks associated with the transport of spent nuclear fuel by truck and rail have been reexamined [1] and compared to results published in NUREG-0170 [2] and the Modal Study [3]. The full reexamination considered transport of PWR and BWR spent fuel by truck and rail in four generic Type B spent fuel casks. Because they are typical, this paper presents results only for transport of PWR spent fuel in steel-lead steel casks.

Cask and spent fuel response to collision impacts and fires were evaluated by performing three-dimensional finite element and one-dimensional heat transport calculations. Accident release fractions were developed by critical review of literature data. Accident severity fractions were developed from Modal Study truck and rail accident event trees, modified to reflect the frequency of occurrence of hard and soft rock wayside route surfaces as determined by analysis of geographic data. Incident-free population doses and the population dose risks associated with the accidents that might occur during transport were calculated using the RADTRAN 5 transportation risk code. The calculated incident-free doses were compared to those published in NUREG-0170. The calculated accident dose risks were compared to dose risks calculated using NUREG-0170 and Modal Study accident source terms.

The comparisons demonstrated that both of these studies made a number of very conservative assumptions about spent fuel and cask response to accident conditions, which caused their estimates of accident source terms, accident frequencies, and accident consequences to also be very conservative. The results of this study and the previous studies demonstrate that the risks associated with the shipment of spent fuel by truck or rail are very small.

INTRODUCTION

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) [2]. That EIS provides the regulatory basis for issuance of general licenses for transportation of radioactive material under 10 CFR 71. Based in part on the findings of NUREG-0170, the NRC's 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."

In 1996 the NRC decided to reexamine the risks associated with the shipment of spent power reactor fuel by truck and rail. The reexamination was initiated (1) because many spent fuel shipments are expected to be made during the next few decades, (2) because these shipments will be made to facilities along routes and in casks not specifically examined by NUREG-0170, and (3) because the risks associated with these shipments can be estimated using new data and improved methods of analysis. This paper summarizes and the full report [1] documents the methodology and results of the study that performed this reexamination of the risks of transporting spent fuel from commercial reactor sites to possible interim storage sites and/or permanent geologic repositories.

OVERVIEW OF NUREG-0170 AND THE MODAL STUDY

NUREG-0170 estimated the radiation doses and latent cancer fatalities that might be associated with the transportation of 25 different radioactive materials by plane, truck, train, and ship or barge. The estimates were made using Version 1 of the RADTRAN code (RADTRAN 1) [4], that was developed specifically to perform the NUREG-0170 study. One of the 25 radioactive materials examined by NUREG-0170 was spent power reactor fuel.

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For spent fuel shipments that occur without accidents (incident-free transport), radiation doses were estimated for two population groups: (1) shipment workers (e.g., the truck or train crew, cask handlers, and persons who inspect the cask, truck, or train) and (2) members of the general public who would be exposed to low levels of radiation, because they lived near the shipment route or came near the cask while traveling on the route. For transportation accidents, release of radioactive material from spent fuel to the environment, the probability of these releases, and the population doses and radiation-induced latent cancer fatalities that such releases might cause were estimated.

The influence of accident severity on accident consequences was examined by dividing all accidents into eight categories according to their severity. Because "little information relating the response of packages to accident environments" [5] was available in 1975, release of radioactive materials to the environment as a result of accidents was examined using two release models that were constructed largely by expert judgement. The first model, Model I [6], assumed [7] that "zero release occurs up to the regulatory test level and that the packaging fails catastrophically in all environments that exceed that level." 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 [8], becoming equal for catastrophic accidents to the release specified for all severe accidents by Model I.

Because the NUREG-0170 spent fuel accident source terms were not developed by examining the response of spent fuel and spent fuel casks to severe accident conditions, NRC had the response of generic steel-lead-steel truck and rail spent fuel casks to collision and fire accident conditions examined by the performance of finite element impact and thermal heat transport calculations. The results of these calculations were published in 1987 in NUREG/CR-4829, "Shipping Container Response to Severe Highway and Railway Accident Conditions," which is usually called the Modal Study [3]. Although that study did not perform any consequence calculations, comparison of the probabilities and magnitudes of the accident source terms developed for that study to those developed for NUREG-0170 allowed the authors of the Modal Study to conclude that the risks per spent fuel shipment for shipments by both truck and rail were "at least 3 times lower that those documented in NUREG-0170" [9].

METHODOLOGY

For this study, the risks associated with the transport of spent fuel were estimated using Version 5 of the RADTRAN code [10, 11]. Risks were estimated (1) for incident-free transport, (2) for transportation accidents so severe that they result in the release of radioactive materials from the cask to the environment, and (3) for less severe accidents that cause the cask shielding to be degraded but result in no release of radioactive material (Loss of Shielding accidents).

Based on prior sensitivity studies [12,13,14], RADTRAN 5 input parameters were divided into three groups: (1) source term parameters (severity and release fractions); (2) other input parameters that strongly influence RADTRAN estimates of radiation dose, which were collectively called other "more important parameters"; and (3) RADTRAN input parameters that have little impact on estimates of radiation dose, which were collectively called "less important parameters." Central (best) estimate values were selected for each of the "less important" parameters, e.g., breathing rate.

For the source term parameters, review of studies of transportation accidents, in particular the Modal Study [3], 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 fractions specify the fraction of all possible accidents that are represented by each of the representative accidents. Severity fraction values were estimated by review of the accident event trees, accident speed distributions, and accident fire distributions that were developed for the Modal Study [3]. Because only impact onto a very hard surface can result in the release of radioactive materials during a collision accident, 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 [15] and Geographic Information System (GIS) methods of analysis [16].

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., noble gases, volatiles, particulates) that might escape from a failed spent fuel rod to the cask interior, and (c) the fraction of the amount of each radioactive material 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 relatively low speed impacts [17] and then comparing the scaled rod strains to a strain failure criterion [17]. Heating of the cask by a hot long duration fire to rod burst rupture temperatures was assumed to fail all unfailed rods (those not failed by collision impact). Rod-to-cask release fractions were estimated by review of literature data, especially the experimental results of Lorenz [18, 19, 20]. Cask-to-environment release fractions were based on MELCOR [21] fission product transport calculations [22] that estimated the dependence of these release fractions on the cross-sectional area of the cask leak path through which the release to the environment occurs.

Specifications for generic steel-lead-steel truck and rail casks and for a generic steel-DU-steel truck cask and a generic monolithic steel rail cask were developed from literature data

[23]. The response of these generic casks to severe collisions (e.g., seal leak areas) was examined by performing three-dimensional finite element calculations for 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 degradation 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 seal leakage and rod burst rupture were estimated by performing one-dimensional heat transport calculations.

For the other "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, 200 sets of parameter values were constructed by sampling these distributions using a structured Monte Carlo sampling technique called Latin Hypercube Sampling (LHS) [14, 24]. This procedure generated one set of 200 parameter values for spent fuel transportation by truck and a second set for transportation by rail. Each set included parameter values for 200 representative highway or railway routes that traversed the length and breadth of the continental United States but had no specific origins or destinations.

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. Finally, 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.

RESULTS

Seven sets of RADTRAN calculations are described in the full report [1]. Each set of calculations developed estimates of the radiological consequences and risks that are associated with the shipment of power reactor spent fuel. Two types of consequences and risks were estimated, those that are associated with the occurrence of accidents during the shipment and those associated with shipments that take place without the occurrence of accidents. The calculations examine four generic cask designs, two shipment modes, two sets of routes, and three sets of accident source terms. The four generic cask designs examined are steel-lead-steel truck and rail casks, a steel-DU-steel truck cask, and a monolithic steel rail cask. The two shipment modes are truck and rail. The two sets of routes are (a) 200 representative truck or rail routes selected by LHS sampling of route parameter distributions and (b) for each mode, four illustrative real routes plus the NUREG-0170 shipment route. The three sets of accident source terms are the NUREG-0170 [2] source terms, the Modal Study source terms [3], and the new source terms developed by this study.

Calculational sets one and two examined spent fuel transportation by truck and rail using the 200 sets of other "more important" truck or rail input parameter values that were constructed by LHS sampling of the real-world distributions of the values of these parameters. Sets three and four examined transportation by truck and rail over the four "illustrative" truck or rail routes and the NUREG-0170 truck or rail route. Comparison of the results of these illustrative route calculations to the results obtained for the calculations that used the 200 representative routes showed that the results obtained for the "illustrative" real routes fall within the range of the results obtained for the representative routes. Set five examined the influence of NUREG-0170 exposure pathway modeling on accident consequence predictions. And sets six and seven compared the accident consequence predictions developed using the accident source terms developed by this study to those developed using the accident source terms developed by the Modal Study [3] and NUREG-0170 [2].

The full study provides results for transport of PWR and BWR spent fuel by truck or rail in four generic casks. In this paper, results are presented only for the six RADTRAN 5 calculations that examined transport of PWR spent fuel in steel-lead-steel truck or rail spent fuel casks. These results are typical of those obtained for BWR spent fuel and/or transportation in other generic casks. Each of the six calculations discussed here used the set of "less important" values for all RADTRAN 5 input parameters assigned central estimate values. Each calculation used the 200 other "more important" truck or rail parameter values, that were generated by LHS sampling. Thus, these calculations differed only in the source terms used (i.e., NUREG-0170 source terms, Modal Study source terms, or the source terms developed by this study), and the set of exposure pathways modeled (the calculations that used Modal study source terms or the source terms developed by this study examined all exposure pathways; the calculations that used NUREG-0170 source terms calculated exposures only for the inhalation pathway because only the inhalation pathway was examined by the NUREG-0170 study).

Table 1 Comparison of NUREG-0170 Incident-Free Doses (person-rem) to the Incident-Free Doses Developed by this Study[a]

Study	Year	Mode	Number of Shipments	Doses (person-rem)			
				Multiple Shipments		Single Shipment	
				Hand/Stor[b]	Other[c]	Hand/Stor[b]	Other[c]
NUREG-0170	1975	Truck	254	52.06	41.74	0.205	0.164
NUREG-0170	1985	Truck	1530	313.6	251.4	0.205	0.164
This Study		Truck	2489[d]	Not Calc.[e]	110	Not Calc.[e]	0.0441
NUREG-0170	1975	Rail	17	7.227	0.553	0.425	0.0325
NUREG-0170	1985	Rail	652	277.4	20.60	0.425	0.0316
This Study		Rail	100.5[d]	Not Calc.[e]	2.040	Not Calc.[e]	0.0203

a. Modal Study incident-free doses are not presented because the Modal Study did not perform any consequence calculations.
b. Handler + storage doses.
c. Crew + on-link + off-link + stop doses.
d. Average number of shipments per year required to ship the full 1994 spent fuel inventory over 30 years in steel-lead-steel truck and rail casks.
e. NUREG-0170 assumed that intermodal cask transfers and temporary storage of the cask would occur during cask shipments; this study assumed that they would not occur and therefore did not calculate any handling/storage doses.

Table 1 compares the NUREG-0170 incident-free truck and rail doses to the incident-free doses developed by this study. Because the NUREG-0170 doses were developed for all of the spent fuel shipments expected to occur in 1975 or 1985, doses for single shipments are calculated by dividing the 1975 or 1985 doses by the number of spent fuel shipments that NUREG-0170 estimated would occur during these years. For single shipments, Table 1 shows that the sum of the other incident-free doses (i.e., crew, on-link, off-link, and stop doses) developed by this study for spent fuel transport by truck with two-person crews is about one-fourth of the sum of the corresponding NUREG-0170 truck doses. It also shows that the sum of this study's incident-free doses for transport by rail is about two-thirds of the sum of the corresponding NUREG-0170 rail doses. The similarity of these incident-free results is not surprising, because both studies assume that the surface dose rates of spent fuel transportation casks are somewhat below the regulatory limit and both use along-route population densities and the population densities at rest stops that are not very different. Table 1 also shows that shipment of the 1994 spent fuel inventory at a constant number of shipments per year over 30 years leads to average yearly population doses for transport by truck and rail that are respectively about half and one-tenth of the NUREG-0170 estimates for 1985.

Figures 1 and 2 present the accident dose CCDFs generated by these calculations. CCDFs are plots of the chance of obtaining a result equal to or larger than the consequence value that corresponds to the probability. For example, in Figure 1, the NUREG-0170 Model I CCDF shows that the probability per shipment of an accident that leads to a population dose $\geq$ 10 person-rem is estimated to be 10^{-4} (0.0001). Figures 1 and 2 both present four CCDFs: the NUREG-0170 Model I CCDF, the NUREG-0170 Model II CCDF, the Modal Study CCDF, and the CCDF developed by this study. In each figure, the highest lying CCDF is the NUREG-0170 Model I CCDF, the next highest is the NUREG-0170 Model II CCDF, the next is the Modal Study CCDF, and the lowest lying CCDF is the CCDF developed by this study.

Table 2 Comparison of Mean Accident Population Dose Risks (person-rem) Calculated Using NUREG-0170 Model I and Model II Source Terms and Modal Study Source Terms to Those Calculated Using the Source Terms Developed by this Study

Study	Truck Accidents	Train Accidents
NUREG-0170 Model I[a]	1.3E-2	1.9E-2
NUREG-0170 Model II[a]	7.7E-4	4.9E-4
Modal Study[b]	1.3E-4	1.9E-3
This Study[b]	8.0E-7	9.4E-6

a. Calculated assuming exposures only by the inhalation pathway.
b. Calculated assuming exposures by all exposure pathways.

The area under each CCDF represents the expected risk from a single shipment of spent fuel for the calculation that generated the CCDF. Table 2 presents these expected accident population dose risks. Thus, Table 2 allows the expected dose risks calculated using the new truck and train accident source terms developed by this study to be compared to those calculated using NUREG-0170 Model I and Model II and Modal Study source terms. Because source term magnitudes

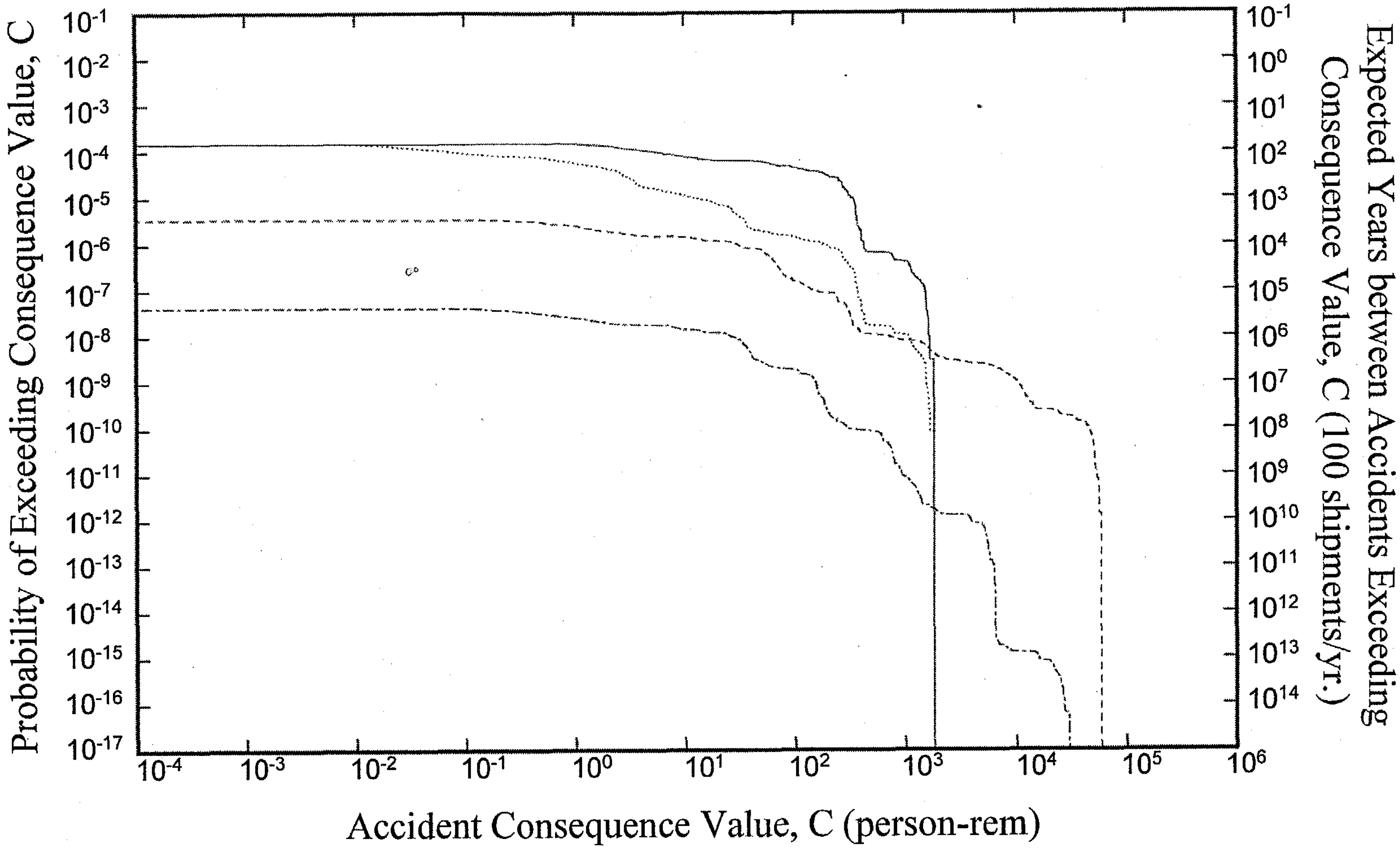

Figure E.1 Mean truck accident population dose risk CCDFs for calculations that compared the source terms developed by NUREG-0170, the Modal Study, and this study. Each RADTRAN 5 calculation assumed transport in a steel-lead-steel truck cask over each of the 200 representative truck routes and each calculation generated results for all of the 19 representative truck accident source terms.

——— NUREG-0170 accident release inventory, NUREG-0170 Model I release fractions, only inhalation pathways

. . . . . . NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, only inhalation pathways

- - - - - PWR inventory, 20 Modal Study source terms, all exposure pathways

-.-.-.-.- PWR inventory, 19 truck accident source terms developed for this study, all exposure pathways

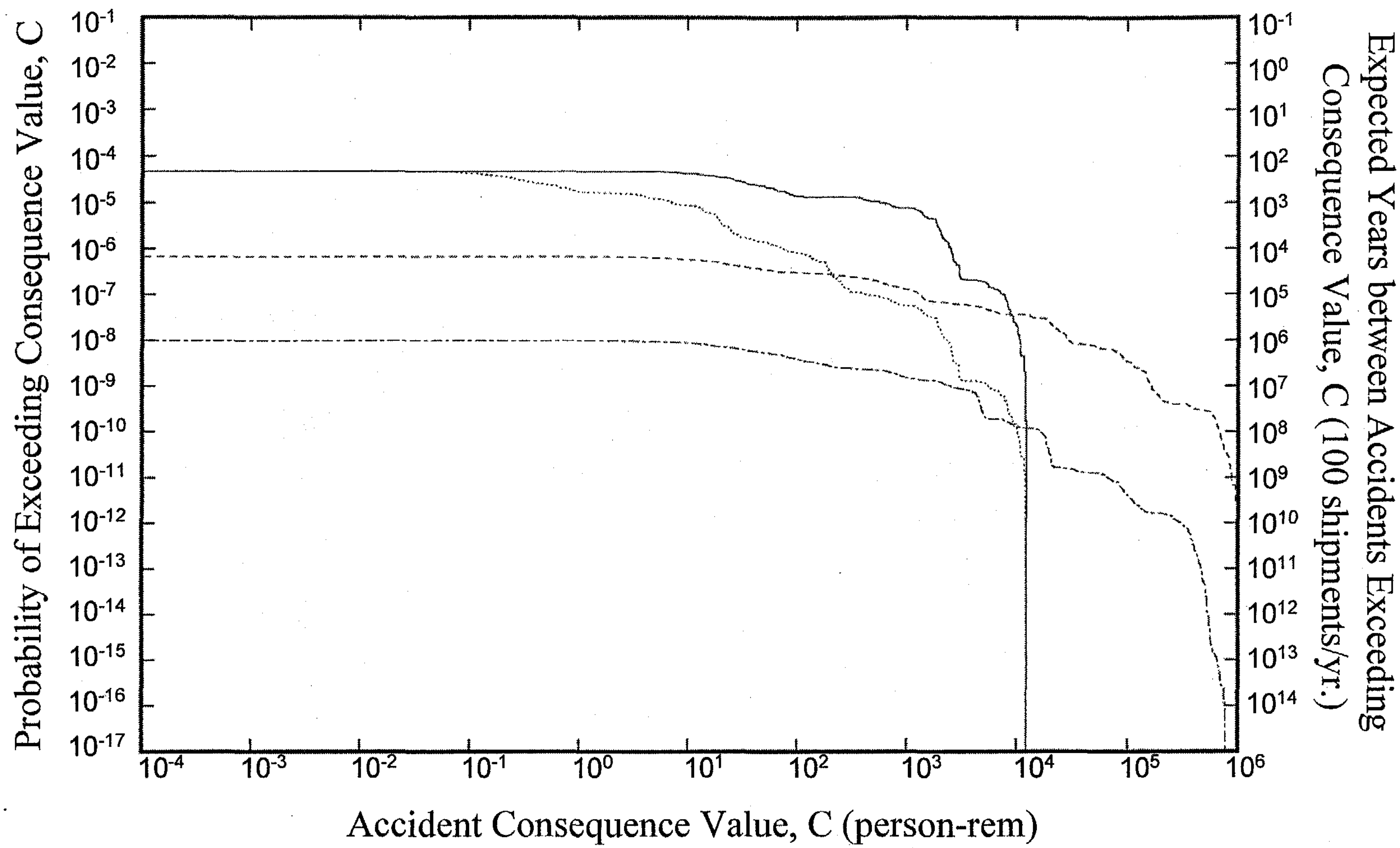

Figure E.2 Mean rail accident population dose risk CCDFs for calculations that compared the source terms developed by NUREG-0170, the Modal Study, and this study. Each RADTRAN 5 calculation assumed transport in a steel-lead-steel rail cask over each of the 200 representative rail routes and each calculation generated results for all of the 21 representative rail accident source terms.

———— **NUREG-0170 accident release inventory, NUREG-0170 Model I release fractions, only inhalation pathways**

. . . . . . **NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, only inhalation pathways**

------------ **PWR inventory, 20 Modal Study source terms, all exposure pathways**

-.-.-.-.- **PWR inventory, 21 train accident source terms developed for this study, all exposure pathways** directly reflect spent fuel and cask response to accidents, the results presented in this table and in Figures 1 and 2 display the effects of the different treatments of spent fuel and spent fuel casks made by each study.

Comparison of the results presented in Tables 1 and 2 shows that the ratio of this study's estimates of single shipment mean incident-free dose risks to this study's single shipment mean accident dose risks is about $5x10^4$ for truck and about $2x10^3$ for rail. Thus, single shipment incident-free dose risks, which are quite small, greatly exceed single shipment accident dose risks.

Inspection of Table 2 shows that the expected accident population dose risks stand in the following order and have the following relative magnitudes when normalized to the NUREG-0170 Model I result:

Truck Accidents

NUREG-0170 Model I (1.0) > NUREG-0170 Model II (0.06)
> Modal Study (0.01) > This Study (0.00006)

Rail Accidents

NUREG-0170 Model I (1.0) > Modal Study (0.1)
> NUREG-0170 Model II (0.03) > This Study (0.0005)

The relative ordering of these accident results is entirely consistent with the assumptions made by each study regarding the probability of radionuclide leakage from the cask during transportation accidents and the magnitude of the source terms generated by accidents of differing severities. Because both Model I and Model II in NUREG-0170 assumed that spent fuel casks might release a portion of their contents when subjected to the loads that characterize minor accidents, the fraction of all truck and train accidents predicted by these models to cause releases is very large and extremely conservative. Similarly, because the NUREG-0170 Model I assumed that all cask leaks led to the release of the entire NUREG-0170 accident inventory (the largest amount of radioactive material expected to be released during a severe accident), the mean accident population doses calculated using the NUREG-0170 Model I for truck and rail accidents are quite large. When, as was done by the Modal Study, cask failure and thus source term probabilities and magnitudes are estimated from the response of the cask shell to mechanical and thermal loads, both source term probabilities and most source term magnitudes decrease. Consequently, relative to the NUREG-0170 Model I result, mean accident population dose risks for rail and truck are decreased respectively by one and two orders of magnitude. When, as was done by this study, cask release and thus source term probabilities and magnitudes are estimated by examining the response of cask closures and spent fuel rods to impact loads and the burst rupture of spent fuel rods due to heating by fires, cask release is found to be even less likely and retention of particles and condensable vapors by deposition onto cask interior surfaces is found to be substantial. Accordingly, source term probabilities and most source term magnitudes, except those for the most severe accidents examined, decrease further. Consequently, relative to the Modal Study result, expected (mean) accident population dose risks for both rail and truck are each further decreased by about two orders of magnitude.

Source term magnitudes for the most severe accidents examined by the Modal Study and this study are larger than the largest source term magnitude postulated in NUREG-0170. They are larger because the product of the cask inventory and the largest accident release fractions developed by this study is larger than the largest source term examined by NUREG-0170. Nevertheless, although the largest source terms developed by the analyses performed by the Modal Study and this study are larger than the largest NUREG-0170 source term, the accident risks posed by these source terms are substantially smaller because these source terms are so very improbable.

CONCLUSIONS

These results and additional results presented in the full report [1] lead to the following conclusions:

- The single cask truck shipment expected incident-free population doses developed by this study are about one-quarter of those in NUREG-0170.
- The single cask rail shipment expected incident-free population doses developed by this study are about two-thirds of those in NUREG-0170.
- The use of very conservative cask failure criteria in NUREG-0170 caused its estimates of the fraction of all accidents that release radioactive materials to be much too large and thus very conservative.
- The NUREG-0170 estimate of the largest source term that might be released from a failed spent fuel cask during an unusually severe transportation accident is significantly lower than the largest source terms calculated using Modal Study release fractions or the release fractions developed by this study. However, the risks associated with these larger source terms are lower than the risk of the largest NUREG-0170 source term because these larger source terms are so very improbable.
- The source terms developed by the Modal Study and by this study, which reflect the complexities of rod failure and cask response to transportation accident impact and thermal loads, yield estimates of expected (mean) spent fuel transportation accident population doses that are orders of magnitude smaller than those developed by the NUREG-0170 study.

Overall, the results of this study confirm the validity of the NUREG-0170 estimates of spent fuel incident-free population doses. The results also show that the NUREG-0170 estimates of spent fuel accident population dose risks were very conservative, as was believed to be true when NUREG-0170 was published [25].

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