# NUREG/CR-6672: BACKGROUND, OBJECTIVES, AND ANALYSIS STRUCTURE

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## ABSTRACT

Because a large number of spent fuel shipments to an interim or permanent repository may take place in the near future, during the summer of 1996, the U.S. Nuclear Regulatory Commission asked Sandia National Laboratories to reexamine the risks associated with shipping spent fuel by truck and rail. The results of this study were documented in NUREG/CR-6672 [1], "Reexamination of Spent Fuel Shipment Risks." This paper describes why this study was performed, the study objectives, and the structure of the analyses conducted to develop the route, source term, and other input data required by RADTRAN 5 [2,3], the transportation risk assessment code that was used to estimate the non-accident and accident risks associated with truck and rail shipments of spent nuclear fuel. In particular, the analysis structure shows how the following data were used to estimate severity and release fractions for 21 hypothetical source terms for severe truck or severe rail accidents:

(a) Modal Study accident event trees, fire duration distributions, and speed distributions;
(b) rod failure fractions, which were estimated by scaling rod strains for a 30 mph impact to higher speeds and comparing the scaled strains to a strain failure criterion;
(c) cask leak areas, which were estimated from unyielding surface finite element impact calculations;
(d) the yielding surface impact speeds, that produce these leak areas and failure fractions, which were estimated by partitioning the yielding surface impact energy between the impact surface and the cask and increasing the impact speed until the energy into the cask equaled the result of one of the unyielding surface impact calculations;
(e) the cask heating times in fires (calculated by 1-D heat transport methods) needed to reach seal failure, rod burst rupture, and average hydrocarbon fuel fire temperatures; and
(f) a critical review of radionuclide release data for sections of spent fuel rods.

Subsequent papers in this session will describe in greater detail the development of these data, the results of the RADTRAN 5 calculations that were performed to estimate the risks associated with spent fuel shipments, and the conclusions drawn from these results.

## INTRODUCTION

Because spent fuel storage pools at power reactor sites are almost full, shipments of spent fuel to an interim or a permanent repository may begin and then increase substantially in the near future. To prepare for this eventuality, during the summer of 1996, the U.S. Nuclear Regulatory Commission (NRC) asked Sandia National Laboratories (SNL) to reexamine the risks associated with shipping

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spent fuel by truck and rail. NRC stated that this reexamination, wherever possible and appropriate, should use the methods and data, that were developed by Lawrence Livermore National Laboratories for their pioneering study of the response of spent fuel casks to severe accident conditions, and were documented in NUREG/CR-4829 [4], which is usually called the Modal Study. Finally, NRC directed SNL to compare the new spent fuel transportation risk estimates to the risk estimates for spent fuel transportation published in NUREG-0170 [5], NRC's generic EIS titled "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes, which was published in 1977. The results of this reexamination by SNL of spent fuel truck and rail transportation risks were published in NUREG/CR-6672 [1].

This paper and the next five papers [6-10] summarize the methods, results, and conclusions of the NUREG/CR-6672 study. This paper presents the study objectives and outlines the study methodology. The next paper [6] describes the development of specifications for the generic spent fuel casks examined by the study and the response of these casks to fires. The third paper [7] describes the response of these casks and the spent fuel they contain to the severe impacts that might be experienced during collision accidents. Paper four [8] describes the development of accident source terms. The fifth paper [9] describes the construction of cumulative distributions for those RADTRAN 5 input parameters that can take on a wide range of values in the real world (e.g., route parameters and accident rates). Finally, the last paper [10] describes and discusses the results of the RADTRAN 5 [2,3] transportation risk assessment code calculations that were performed for the study, and presents the study's conclusions.

The NUREG/CR-6672 study examined the risks posed by accident-free truck and rail transport of PWR and BWR spent fuel and by the occurrence of accidents that might occur during the transport of this fuel in four generic casks: a steel-lead-steel truck cask, a steel-DU-steel truck cask, a steel-lead steel rail cask, and a monolithic steel rail cask. Because spent fuel will be shipped mainly by rail, because the results for rail are typical, and because most spent fuel is PWR fuel, this set of six papers will present results principally for the shipment of PWR spent fuel by rail in a monolithic steel rail cask.

## OBJECTIVES

The NUREG/CR-6672 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 were bounded by the estimates and projections of spent fuel shipment risks published in 1977
- Examination of any outstanding spent fuel transportation issues or environmental concerns
- 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.

## COMPARISON OF STUDY METHODOLOGIES

Table 1 summarizes and contrasts the methods of analysis used in the NUREG-0170 EIS, the Modal Study, and the NUREG/CR-6672 study.

**Table 1. Comparison of Study Methodologies**

| | EIS NUREG-0170 | Modal Study NUREG/CR-4829 | This Study NUREG/CR-6672 |
|---|---|---|---|
| Severity Fractions | Expert Judgement | Event Trees | Event Trees |
| Response of Cask Closure and Fuel Rods to Severe Accidents | Not Modeled | Inferred from cask shell response | Modeled |
| Fission-product Transport<br>Rod-to-Cask<br>Deposition in cask | <br>Not modeled<br>Not modeled | <br>Lorenz data<br>Neglected | <br>Lorenz data<br>Transport calculation |
| Source Terms | Expert Judgement | Calculated | Calculated |
| Routes | 2 Generic | Not Examined | 200 Generic, 4 real |
| Consequences<br>Incident-Free<br>Accident | RADTRAN 1<br>Population Dose<br>LCFs | Not Calculated | RADTRAN 5<br>Population Dose<br>Population Dose |

Table 1 shows that NUREG-0170 [5]

- used expert judgement to estimate values for the chance of accidents falling into each of eight accident severity ranges;
- did not model the response of the cask or its contents to severe accident conditions or the transport of fission-product species from failed rods through the cask to the cask leak;
- instead postulated a spent fuel accident source term for an especially severe accident; and
- calculated accident consequences and risks with RADTRAN 1 [11] for this source term and for shipments that occur without accidents.

Next, the table shows that the Modal Study [4]

- estimated accident severity fractions, where a severity fraction is the fraction of all accidents that follow a specific accident scenario, principally by constructing event trees;
- inferred the response to severe impacts of spent fuel rods and the cask closure from the severe impact response of the cask body;
- modeled the release of fission-product species from failed rods to the cask interior using the experimental results of Lorenz et al. [12,13,14], but neglected deposition of fission-product species (particles, condensible vapors) onto cask interior surfaces;
- calculated accident source terms as the product of a cask inventory and the rod-to-cask release fraction for each class of fission-product species modeled; and
- did not calculate accident consequences or risks, which meant that shipment routes were not examined.

Finally, the table shows that NUREG/CR-6672

- used the Modal Study event trees, modified to include wayside surface occurrence frequencies which were estimated from the characteristics for several lengthy transportation routes, to calculate accident severity fractions;
- directly modeled the response of fuel rods and the cask closure to severe impacts and fires;
- developed rod-to-cask release fractions by a critical review of the data of Lorenz et al.;
- used the results of a fission-product transport calculation in a TN-12 cask [15] to estimate deposition onto cask interior surfaces of the particles and condensible vapors released from failed rods;
- calculated accident source terms as the product of a cask inventory, the rod-to-cask release fraction for each class of fission-product species modeled, and a cask-to-environment release fraction that reflected deposition of particles and vapors onto cask interior surfaces; and
- calculated accident consequences and risks with RADTRAN 5 [2,3] for these source terms and for shipments that take place without the occurrence of significant accidents.

## DETAILED OVERVIEW OF THE NUREG/CR-6672 METHODOLOGY

Risks were estimated for the NUREG/CR-6672 study (1) for transport that takes place without the occurrence of significant accidents, (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 [16,17,18], RADTRAN 5 input parameters were divided into three groups:

- source term parameters (severity and release fractions);
- parameters that take on a wide range of values in the real world (e.g., cask surface dose rates, accident rates, route wayside population densities), which were represented by distributions; and
- parameters that take on a single value or a narrow range of values in the real world, which could be adequately represented by central estimate values (e.g., breathing rate).

**Central Estimates.** For parameters that do not vary widely in the real world, central estimate values were selected by expert judgement and by review of previous RADTRAN transportation risk assessments.

**Distributions.** For parameters that can take on a wide range of values in the real world (e.g., route lengths, population densities, accident rates, cask surface dose rates), cumulative distributions of parameter values were constructed that reflect the likely real-world range and frequency of occurrence of the value of each parameter. The construction of these distributions is described in the fifth paper in this session [9].

**Source Term Parameters**. Review of studies of transportation accidents, in particular the Modal Study [4], allowed representative sets of truck and train accidents and their impact and fire environments to be defined. This analysis developed 21 representative truck accidents and 21 representative train accidents. Severity fractions and release fractions were estimated for each representative truck or train accident.

**Release Fractions.** 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 [19] and then comparing the scaled rod strains to a strain failure criterion [19]. Heating of the cask by a hot, long duration, fire to rod burst rupture temperatures was assumed to fail all unfailed rods (e.g., those not previously failed by collision impact).

Rod-to-cask release fractions were estimated by a critical review of literature data, especially the experimental results of Lorenz [12,13,14]. Cask-to-environment release fractions were based on MELCOR [20] fission-product transport calculations [15] 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 would occur. The development of rod-to-cask and cask-to-environment release fractions is described in the fourth paper in this session [8].

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 [21]. The response of these generic casks to severe collisions (e.g., seal leak cross-sectional 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. The probability of a real world collision at this speed gives the chance that the damage calculated for the corresponding unyielding surface collision will also be caused by this yielding surface collision. The third paper in this session describes the finite element impact calculations performed for NUREG/CR-6672, their extrapolation to yielding surfaces, and the estimation of rod failure fractions by scaling 30-mph rod impact strains to higher impact speeds [7].

Seal degradation and rod burst rupture temperatures caused by heating during fires were estimated from literature data. The time periods, that co-located, fully engulfing, optically dense, hydrocarbon fuel fires needed to burn in order to cause cask seal leakage or rod burst rupture, were estimated by performing one-dimensional heat transport calculations. The probability of fires with these durations was assumed to equal the probability that accidents involving fires will cause seal failure or rod burst rupture. These heat transport calculations are described in the second paper in this session [6].

**Severity Fractions.** Severity fractions specify the fraction of all possible accidents that is 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 [4]. Because only impact onto a very hard surface can result in the release of radioactive materials during a collision accident, new values for the frequencies of occurrence for route wayside surfaces (e.g., hard rock; concrete, soft rock, and hard soil; soft soil; water) in the Modal Study event trees, were developed from Department of Agriculture data [22] by Geographic Information System (GIS) methods of analysis [23]. The development of accident severity fractions is described in the fourth paper in this session [8].

## RADTRAN CALCULATIONS

A structured Monte Carlo sampling technique, Latin Hypercube Sampling [18, 24], was used to select 200 sets of values for each RADTRAN 5 input parameter, for which a cumulative distribution had been constructed because the parameter could take on a wide range of values in the real world. This procedure generated one set of 200 parameter values for spent fuel transportation by rail and a second set for transportation by truck. 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 (a) the single set of central estimate values, selected for the RADTRAN 5 input parameters that did vary over a wide range in the real world, (b) the 200 sets of values for the parameters that did vary widely in the real world, and (c) the 21 sets of representative rail accident severity and release fraction values, input for 4200 single-pass RADTRAN 5 calculations was developed for each generic rail cask. Similarly, by taking all possible combinations of the truck input data, input for 3800 single-pass RADTRAN calculations was developed for each generic truck cask. Finally, application of standard statistical methods, to the results of these 4200 RADTRAN 5 rail or 3800 RADTRAN 5 truck calculations, allowed 200 Complementary Cumulative Distribution Functions (CCDFs) to be constructed, one for each of the 200 sets of RADTRAN 5 input. Standard statistical techniques then allowed estimates of the expected (i.e., mean) result and the spread of these results (the 5$^{th}$, 50$^{th}$ and 95$^{th}$ percentile values) to be developed.

## IMPROVEMENTS YIELDED BY THE NUREG/CR-6672 METHODOLOGY

The NUREG/CR-6672 methodology fully integrates the development of parameter values for all of the input used in the NUREG/CR-6672 analyses. Thus, severity and release fractions are not developed independently. Instead they are developed for 21 representative sets of accident conditions by hand or code calculations that implement models that are mutually consistent. For example, deposition of particles and vapors onto cask internal surfaces was estimated from the results of a fission-product transport calculation [15]. That calculation showed that deposition decreases as cask blowdown rate increases and that the cask blowdown rate depends on the size of the cask leak, which was estimated from the results of the finite element, unyielding surface, cask impact calculations [7]. Rod failure fractions were estimated by scaling a 30-mph rod strain map to higher impact speeds using the peak accelerations predicted by these finite element calculations and comparing the resulting strains to a rod strain failure criterion.

Conversion of unyielding surface impact speeds to yielding surface impact speeds, that would cause the same damage to the spent fuel cask as had been predicted for the unyielding surface impact, allowed the probability that real accidents would cause this damage to be estimated from the Modal Study cumulative distribution of accident speeds. Similarly, determination by heat transport calculations of the durations of fully engulfing, optically dense, hydrocarbon fueled fires, that would heat a cask and the spent fuel rods carried in the cask to seal failure or rod burst rupture temperatures, allowed the chance that real fires would cause this damage to be estimated from the Modal Study cumulative distribution of accident fire durations. Finally, the principal result of this integrated methodology is that, relative to prior spent fuel transportation risk studies, the chance that a given set of accident conditions occurs is found to decrease, the size of the fission-product release caused by that set of accident conditions is also found to decrease, and consequently the predicted accident risks are predicted to decrease substantially.

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