SPENT FUEL TRANSPORTATION PACKAGE PERFORMANCE STUDY

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ABSTRACT

The spent fuel transportation Package Performance Study (PPS) investigates the performance of casks and behavior of fuel when subjected to thermal and impact forces that exceed the hypothetical accident conditions specified in 10 CFR Part 71. Issues related to the probability and consequences of severe transport accidents will be examined. The objective of PPS is to verify models, through combinations of detailed analysis and physical testing, used to predict accident risk associated with transportation of spent fuel in NRC certified casks. PPS is a follow-on project to NUREG/CR-6672, "Reexamination of Spent Fuel Shipment Risk Estimates," which was published in March 2000. An enhanced public participatory process has been used in developing the PPS issues for study and the conceptual testing and analysis plans.

INTRODUCTION

The U.S. Nuclear Regulatory Commission’s (NRC's) activities in the transport of spent nuclear fuel include certification of transport packaging designs, approval of transport package Quality Assurance programs, issuance of general licenses to offer material to carriers for transport, and establishment of physical protection requirements for spent nuclear fuel in transit. Pertinent NRC regulations are contained in 10 CFR Part 71, “Packaging and Transportation of Radioactive Material,” and in 10 CFR 73.37, “Requirements for Irradiated Reactor Fuel in Transit.” [1]

The Commission has been studying the safety of spent nuclear fuel transportation in terms of the Agency’s regulations for nearly 25 years. When the Commission adopted a generic environmental impact statement for transportation, it directed that regulatory policy concerning transportation be subject to close and continuing review. Since that time, NRC’s studies have shown that the risk of release of radioactive material from transport is low. Moreover, NRC’s transportation regulations are based on those developed through consensus at the International Atomic Energy Agency (IAEA) and the experience derived from the shipment of spent nuclear fuel by IAEA Member States who have corroborated NRC’s safety results.

Nevertheless, public concern over spent nuclear fuel shipments is high. As an example, when a shipment of less than 10 individual spent fuel rods (less than one assembly) from PECO Energy's Limerick reactor to the General Electric facility in Vallecitos, California, was announced, numerous questions arose from local government and media representatives about shipment safety and security. In October 1999 NRC staff held a public meeting in Alameda County, California, to address concerns about the shipment and facility operations at General Electric. Days before the shipment departure, the State of Ohio Turnpike Authority advised the NRC that it was denying access to the shipment, resulting in a last-minute re-routing of the shipment through Maryland and West Virginia. The State of Illinois also expressed concerns about the shipment route. The Limerick shipment contained 10 spent fuel assembly rods, or a little over 20 kg of 2.8 percent enriched uranium. As large-scale shipment campaigns approach, with much greater quantities of spent nuclear fuel going from NRC-licensed facilities to storage and disposal facilities, public interest is expected to increase substantially.

OVERVIEW OF PAST STUDIES

The NRC first reported an evaluation of the impact on public health and safety that result from regulated transportation activities in NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes" (Vols. I and II, December 1977). [2] Impacts from all licensed material by land, air, and sea transport modes under both incident-free and accident conditions were examined. Spent nuclear fuel was one of 25 radioactive materials that were studied. The report contains an assessment of spent nuclear fuel shipment risk using the 1975 level of shipments, and a projection of risks for 1985, based on the assumption of a reprocessing fuel cycle. Sandia National Laboratories conducted the risk assessment for NRC, and developed the RADTRAN I radioactive material transport risk code, to perform the related dose calculations. NUREG-0170 was issued for public comment; Volume I is the technical report and Volume II contains the comments and responses.

Taking into consideration the information developed and received, and the safety record associated with the transportation of radioactive material, the Commission determined in 1981 that the regulations then in place were adequate to protect the public against unreasonable risk from the transport of radioactive materials, and that no immediate changes in the regulations were needed to improve safety (46 FR 21619). [3] The U.S. Department of Transportation also relied on NUREG-0170 to assess the impact of radioactive material transportation under its "Hazardous Materials Regulations" (49 CFR Subchapter C, Parts 171-180). [4]

In the mid-1980s, several spent nuclear fuel shipment campaigns were initiated to return spent nuclear fuel from the West Valley facility in western New York to the originating utilities. These campaigns drew considerable public interest, and questions focused on the difficulty in comparing NRC's spent nuclear fuel cask accident standards with actual accident conditions. The standards are expressed as a series of hypothetical tests and acceptance criteria that are contained in 10 CFR 71.73. Because the NUREG-0170 spent nuclear fuel accident source terms were not derived from an explicit examination of the response of spent nuclear fuel and spent nuclear fuel casks to severe accident conditions, NRC sponsored an examination of the response of generic steel-lead-steel truck and rail spent nuclear fuel casks to collision and fire accident conditions, using finite element impact and thermal heat transport calculations. Probabilities and forces associated with severe transportation accidents were also assessed. This 1987 Lawrence Livermore National Laboratory effort is frequently referred to as the "Modal Study," ("Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, Volumes I and II, February 1987). [5] Although the Modal Study did not include dose consequence calculations, a 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 nuclear fuel shipment for shipments by both truck and rail were "at least 3 times lower that those documented in NUREG-0170." The NRC staff concluded from the Modal Study that the results from the earlier NUREG-0170 clearly bounded spent nuclear fuel shipment risks, and reaffirmed the Commission's 1981 decision that there was no need to reconsider the transportation regulations to improve safety.

REEXAMINATION OF SPENT NUCLEAR FUEL RISK ESTIMATES

In 1996, NRC decided to reexamine the risks associated with the shipment of spent nuclear fuel by truck and rail. The reexamination was initiated because (1) a significant increase in the number of spent nuclear fuel shipments is likely during the next few decades, (2) these shipments will be made to facilities along routes and in casks not previously examined in risk studies, and (3) the risks associated with these shipments can be estimated using new data and improved methods of analysis. The full report, "Reexamination of Spent Nuclear Fuel Risk Estimates," NUREG/CR-6672, March 2000, [6] documents the results of this study, which was performed by Sandia National Laboratories.

The purpose of the Reexamination was to assess the characteristics of the large-scale spent-fuel shipment campaigns currently anticipated and, using the results of the Modal Study and the most recent version of the RADTRAN risk assessment code (RADTRAN 5), to determine whether the original NUREG-0170 risk estimates bounded those for the anticipated shipment campaigns. Like NUREG-0170, this study calculates the risks for spent nuclear fuel shipments under both incident-free and accident conditions, but unlike that earlier study, takes into account such factors as the enrichment, burn-up, and cooling time of fuel currently anticipated to be shipped in the U.S.; the capacity and designs of newer transport casks; and current population densities along road and rail routes.

In addition, for the first time in an NRC sponsored transportation risk study, the analyses in NUREG/CR-6672 explicitly treats variability of RADTRAN 5 input parameters. For the "more important" input parameters (e.g., route lengths, population densities, accident rates, durations of truck stops, 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). This procedure generated one set of 200 parameter values for spent nuclear 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. Central (best) estimate values were selected for each of the parameters that have less impact on risk calculations or have low variability (e.g., breathing rate).

For source term parameters, review of studies of transportation accidents, in particular the Modal Study, allowed representative sets of truck and train accidents and their impact and fire environments to be defined. The analysis addressed 19 representative truck accidents and 21 representative train accidents. Severity fraction and release fraction values were estimated for each representative accident. Severity fractions specified 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. Because only an 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 U.S. Department of Agriculture data [7] and Geographic Information System (GIS) methods [8].

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 nuclear 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 and then comparing the scaled rod strains to a strain failure criterion [9]. Heating of the cask by a hot long duration fire to rod burst rupture temperatures was assumed to fail all rods (i.e., those not failed by collision impact). Rod-to-cask release fractions were estimated by review of literature data, especially the experimental results of Lorenz [10, 11, 12]. Cask-to-environment release fractions were based on MELCOR [13] fission product transport calculations [14] 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 [15]. 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 for a yielding surface. 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.

The Reexamination attempts to provide a best estimate of accident risk, by extending the Modal Study methodology to examine the response of the cask closure mechanism to mechanical and thermal loads. The Reexamination contains the results of two analyses, one based on Modal Study cask response and release information, and another based on newer cask response and release information developed in the Reexamination study. Results using the Modal Study cask information, coupled with the data representative of anticipated shipments, continue to show that accident risk estimates are less than those in NUREG-0170. The best-estimate spent-fuel shipment risks from the reexamination appear to be less than the Modal Study based estimates, by as much as 2 orders of magnitude. This is also much less than the NUREG-0170 estimates. To support NRC's efforts on improving risk communication and public confidence, a plain English summary of the Reexamination Study is being prepared in addition to Sandia's technical report.

PACKAGE PERFORMANCE STUDY

The most recent NRC initiative in the transportation area is the “Package Performance Study.” This study began in 1999 and should take approximately 5-7 years to complete. The objective of the Package Performance Study is to address spent nuclear fuel transportation issues remaining from the Modal Study and the Reexamination of Spent nuclear fuel Transportation Risk Estimates, using a public-participation approach to solicit public and stakeholder interests in developing the study’s scope and parameters for review. Further, whereas the preceding studies were all analytical in nature, the Package Performance Study will also, where appropriate, use physical testing to address issues. Risk insights obtained using current analysis techniques and physical testing, and through interaction with stakeholders and the public, will support NRC’s ongoing efforts to assure that its regulatory actions are risk-informed and effective.

Sandia has completed the first phase of the Package Performance Study, which was a scoping study. Two sets of roundtable public meetings, in Maryland and Nevada, have already been held on the Package Performance Study. A World Wide Web site, http://ttd.sandia.gov/nrc/modal.htm, has been established to facilitate interactions on the project. Ongoing public interactions throughout this project will help ensure that public concerns are effectively identified and understood, and that the study design considers these issues. The product of this scoping phase of the study was an “Issues and Resolutions Option Report,” (Issues Report) [16] released as a letter report in June 2000. NRC also plans to compile the report and comments received on it for publication as a NUREG-series report.

The Issues Report documented the issues and concerns that were raised at public meetings and by questions and comments submitted to the NRC as a result of those meetings. The report considered five topical areas: (1) package performance during collisions, (2) package performance during fires, (3) spent nuclear fuel behavior during accidents, (4) highway and railway accident conditions and probabilities, and (5) other transportation safety issues. A technical merit score was recommended in the report by the Sandia authors, for each issue and associate resolution options.

With the close of the scoping phase of the Package Performance Study, the confirmatory research phase began in mid-2001. Likely areas on which the study may focus include the following:

- demonstrating the validity of cask finite element package collision damage predictions by comparison to test results,
- demonstrating the validity of thermal analysis predictions of package heating rates in fires by comparison to test results,
- determining response of CRUD, fuel pellets, fuel rods, and fuel assemblies to severe impact environments by experiments and computations, and
- reconstructing the Modal Study truck and train accident event trees and the parameter distributions associated with these trees using recent industry practices and accident data.

Cask damage due to impact onto hard surfaces may be estimated in greater detail than has been done in NUREG/CR-6672 for generic casks, by performing finite element impact calculations based on actual cask designs. In this way the behavior of the closure-seal system, including bolts, can be modeled to better calculate details of leak pathway creation in severe impacts. A test plan will be developed for an extra-regulatory impact test of an actual certified cask design, and a fuel canister, against an essentially unyielding target. It is anticipated that the test specimen will be propelled with sufficient velocity to sustain permanent/plastic deformation that is readily visible and measurable. The test plan will also discuss the feasibility and benefits of performing a regulatory test (impact equivalent to a 30' drop onto an unyielding surface in the most damaging orientation) on the test specimen, before the high-velocity test.

Cask damage due to exposure to fires could be estimated by performing three dimensional heat transport calculations. To demonstrate that these computational methods are able to credibly predict the results of hypothetical severe cask accidents, pretest computational predictions could be compared to the results of crash and fire tests that employ a sub-scale or a full-scale test article.

The behavior of spent nuclear fuel rods, CRUD, and fuel pellets when subjected to impact loads could be examined by performing bench-scale experiments that examine rod failure, fracturing of CRUD and fuel pellets, formation of particle beds due to fracturing of fuel, and filtering of respirable particles by particle beds.

The Modal Study truck and rail accident event trees may be updated by developing new branch point probabilities and new wayside surface hardness frequencies. NRC expects the need for alternative event trees will be determined, with justification, based on the current accident database and carrier practices (e.g., use of dedicated freight service). In addition, NRC expects to construct a barge/inland vessel event tree, with conditional probabilities. Distributions of bridge heights, embankment heights, accident speeds (both initiating speeds and speeds at impact), and fire durations (based on historic data and on inferences derived from quantities of shipped combustibles) will be constructed. NRC staff is also interested in developing a methodology and capability to link any specific route to the representative route characteristics. Finally, NRC expects to develop a method to map selected historically severe, real transportation accidents into cask structural-thermal response regimes.

Stakeholder and Public participation will continue through the confirmatory research phase of the package performance study. As a next step, detailed test and analysis plans will be developed that clearly state the objectives, procedures, success definitions, and limitations of possible research to be performed. These test and analysis plans will be issued for public comment and will include plain-language explanations. In addition NRC expects that these plans will be peer reviewed, possibly by a committee of the National Academy of Sciences. Each of the test plans will describe options for follow-on testing or analysis; however, NRC will not make a decision on specific aspects of the tests until public comments and peer review activities are completed. NRC staff expects to base its decisions to proceed on value-benefit assessments performed in the context of NRC’s four performance goals: (1) maintaining safety, (2) decreasing unnecessary regulatory burden, (3) increasing public confidence, and (4) improving regulatory effectiveness and efficiency.

The shipment of spent nuclear fuel in NRC-certified packages has an excellent safety record. Since spent nuclear fuel transportation occurs in the public domain, shipments have, and will continue, to raise considerable interest, particularly as the series of new large-scale shipments approaches. The

Commission studied public interest issues associated with spent nuclear fuel shipments ("Case Histories of West Valley Spent Fuel Shipments," NUREG/CR-4847, January 1987), [17] as a way to identify effective measures to help address public concerns before commencement of spent nuclear fuel shipment campaigns. That study found that the development and implementation of comprehensive public information (and educational) programs that explain the technical, operational, safety, and physical protection aspects of spent nuclear fuel transport in layman's terms improve public confidence in spent nuclear fuel shipping campaigns. The NRC is implementing this lesson learned in its transportation risk study plans.

CONCLUSION

The transportation risk studies described here provide a technical basis for determining that current regulations are sufficient to prevent releases of radioactive material during transport. The most recent Package Performance Study provides a process for public involvement in the decision making process for further studies.

REFERENCES

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