THE MODAL STUDY: THE RESPONSE OF SPENT FUEL PACKAGES TO SEVERE TRANSPORTATION ACCIDENTS

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ABSTRACT

The Modal Study was initiated by the U.S. Nuclear Regulatory Commission (NRC) to further evaluate the safety of spent fuel shipments. The Study involves an investigation of the relationship between NRC's spent fuel package performance standards and real transportation accident conditions. The probable response of representative spent fuel packages to the forces generated in actual accidents was determined. The Modal Study results are used to provide several perspectives on the level of safety provided under real accident conditions by spent fuel packages designed to current standards and practices.

BACKGROUND

The transportation of radioactive materials is regulated principally by the Nuclear Regulatory Commission (NRC) and the Department of Transportation. A Memorandum of Understanding (MOU) defines the respective roles of the two agencies. Under the MOU, NRC develops package safety standards for fissile and larger quantities of radioactive materials, while the Department of Transportation (DOT) develops transport safety regulations for all packages and standards for packages of quantities of radioactive materials not covered by NRC. NRC's packaging regulations are found in 10 CFR Part 71.

In the mid-1970's, the NRC conducted a reevaluation of its transportation regulations to assess the adequacy of its regulations to protect public health and safety. In the course of the reevaluation, the NRC published a Final Environmental Statement, designated NUREG-0170, which included an examination of the transportation of radioactive material by all modes of transport. After considering the information developed, the public comments received, and the safety record associated with the transportation of radioactive materials, the NRC determined that its regulations are adequate to protect against unreasonable risk from transport of radioactive materials and that no immediate changes were needed to improve safety. Nevertheless, the NRC continues to study safety aspects of transportation of radioactive materials to determine where improvements might be made.

The accident resistance of packages was identified as a subject for further study in NUREG-0170. It was recognized that for certain types of shipments, such as spent fuel, the nature and quantity of material being transported was such that the consequences of release in an accident could be serious. Packages used for these types of shipments are required to be designed so that there is essentially no increase in radiological hazard when the package is subjected to the Hypothetical Accident Condition tests specified in 10 CFR Part 71. The tests are adequate to assure high integrity packaging and are generally recognized to be rigorous. The extent to which the tests simulate real accidents, however, had not been fully developed. The adequacy of the tests, particularly with respect to spent fuel packages, had also become a subject of public concern. To address these concerns, the NRC initiated a study to evaluate the safety of spent fuel shipments in terms of severe accidents which actually occurred in non-nuclear shipments in surface transport modes. This study became known within NRC as the Modal Study.

The final phase of the Modal Study has recently been completed by the Lawrence Livermore National Laboratory (LLNL), and LLNL has recently presented their findings in a report entitled "Shipping Container Response to Severe Highway and Railway Accident Conditions" (NUREG/CR-4829). Prior to publication, the report was subjected to a peer review by the Denver Research Institute. The descriptions presented in this paper are based on the LLNL final report and its analysis by the NRC staff.

PACKAGE STANDARDS

Safety in transporting radioactive materials is regulated through a combination of packaging requirements and operational and administrative controls. The requirements and controls are based on the radiological hazard posed by the materials to be shipped. For shipments of small quantities of radioactive materials, primary reliance for safety is placed on an administrative control. That is, the regulations limit the package content of radionuclides to an amount which, if released under accident conditions, would not pose a substantial radiological hazard. For shipments of larger quantities of radioactive material, such as spent fuel, primary reliance for safety is placed on the packaging.

To provide safety in transport, a spent fuel package must provide three functions: containment of the spent fuel; shielding from radiation emitted by the spent fuel; and control of the spent fuel configuration so as to prevent a chain-reaction (i.e., maintain nuclear subcriticality). NRC's packaging standards have been developed to assure that spent fuel casks provide these functions under both normal and accident conditions in transport. The standards are performance oriented, that is, the standards basically state how the packaging must perform under normal and accident test conditions. The performance standard approach for spent fuel packagings was developed and accepted internationally, with the requirements expressed in terms that may be reproduced and satisfied by test or analysis.

NRC's performance standards for casks are comprised of two components: (a) package tests, to represent transport conditions; and (b) acceptance criteria, to gauge the package's performance after being subjected to the tests. The tests for hypothetical accident conditions, upon which we will focus, specify a sequential series of severe impact, puncture, fire, and immersion environments as follows (paraphrased):

(1) Free Drop - Thirty-foot drop of the cask onto a flat, horizontal, unyielding surface with the cask positioned so that its weakest point is struck.

(2) Puncture - Forty-inch free drop of the cask onto a 6-inch diameter steel bar at least 8-inches long; the cask must strike the bar at the cask's most vulnerable point.

(3) Thermal - Totally engulf cask in a fire or furnace at 1475°F for 30 minutes. (Other thermal conditions must be met.)

(4) Submersion - Immerse all packaging surfaces under 3 feet of water for 8 hours. An additional test requires immersion of a separate undamaged package in 50 feet of water for 8 hours.

The acceptance criteria used with the tests are expressed in terms related to the three safety functions described earlier: the package may not release more than a small amount of its contents, or exhibit more than a small increase in the external radiation levels, and the package must maintain subcriticality.

As part of the NRC's package design certification process, an applicant must demonstrate that a package design meets the acceptance criteria after being subjected to the test conditions. The demonstration may be accomplished by actual tests, but demonstration by analysis is more commmon. The package design is reviewed by the NRC engineering staff to verify its accident resistance. A certificate is issued by the NRC before a package fabricated from the design can be used to transport material. In addition to other requirements, both manufacturers and users of the packages must follow NRC approved quality assurance programs.

A difficulty with the expression of performance standards is that the severity of the hypothetical accident conditions is not readily understood. This is particularly true for the 30-foot drop test and the half-hour fire test. For example, in the free-drop test, attention is often focused on the 30-foot height of the drop, while the requirement that the package strike an unyielding surface is disregarded. If the drop height alone is (mistakenly) considered to indicate the severity of the test, the test may not appear rigorous when compared to real accidents. There are many instances of trucks falling off highway bridges from heights exceeding 30 feet. But, the height comparison alone is inappropriate because it disregards the hardness of the surfaces being struck. The unyielding surface requirement in the test basically means the package must absorb almost all of the energy of the impact, and therefore, poses a very rigorous test of package integrity. Surfaces under bridges, such as river beds, railroad tracks, etc., and the vehicle itself, all yield under impact, thereby absorbing energy and posing a less severe impact shock to the package. Thus, the impact test is more rigorous than it may appear on first impression.

What has proved a more serious difficulty is illustrating how packages designed in accordance with the standards would perform in severe, real-world transportation accidents. Limited information about this relationship has hampered efforts to explain the level of safety provided by the existing standards. Addressing this issue was the central objective for the Modal Study: investigate the relationship between the package performance standards and real accident conditions, and explain clearly the level of safety provided by packages meeting the standards. The investigation was designed to constitute a generic, systematic evaluation of the standards. In addition to explaining safety, the results of the investigation were also intended to provide a basis for reaffirming the adequacy of the existing standards or indicating where changes are needed.

THE STUDY

A conceptual description of the Modal Study approach and methodology follows. For a precise description of the Modal Study's structure, please consult NUREG/CR-4829.

The approach used in the Modal Study is analytical. Basically, the Study first involves an examination of actual highway and railway accident experiences to determine the conditions encountered in real accidents. Computer models were then used to evaluate how a package designed to NRC standards would respond to the types of forces generated in those accidents.

The Modal Study is not empirical in nature. An empirical approach was not considered feasible since such an approach would rely necessarily on either spent fuel package accident experience or new accident experiments. With respect to accident experience, the scarcity of cask accidents provides an inadequate basis for the evaluation of cask response to severe accidents. During the last 30 years, only a few cask shipments have been involved in vehicle damaging accidents. There was no release of radioactive material in any of the accidents. Also, none of the accidents were considered to be particularly severe from an impact or fire standpoint. Regarding new experiments, the number of full- or semi-scale demonstration (crash) tests required for this study would be large and therefore prohibitively expensive. Further, such an approach would have required the definition of some sort of "reference accident" for the demonstration tests. The approach followed was to determine the response of large packages designed to current standards upon exposure to real accidents. Thus, the Modal Study did not include any specific crash tests.

One of the initial steps in the Modal Study was to determine a generic reference package design. The package design used is important because it serves as a surrogate in evaluating transport safety standards. The contractor developed a representative design for a road and a rail cask which would satisfy the standards. These representative cask designs were not as detailed as those for actual casks, but did include those features judged necessary to evaluate the safety functions described earlier. The representative designs for both road and rail casks employed concentric stainless-steel shells (inner shell providing containment) with lead placed between the shells to provide shielding. This basic design type was selected because it is in common use and because the lead shielding material melts at a lower temperature than does other shielding materials.

The next step included determining how the representative designs would respond to the range of forces encountered in real accidents. The contractor determined that strain on the inner steel shell was the best measure of package response to mechanical forces (impact, crush, puncture, etc.) and that temperature at the mid-line of the lead shielding was the best measure of package response to thermal input. Using computer models, the contractor then determined the degree of package response, i.e., determined the amount of damage caused as mechanical forces or thermal input on the package was increased. This analysis defined "package response states" for the various combinations of strain and temperature. The analyses were performed for both the road and rail packages.

The radiological hazard of each package response state was then estimated, based on the assumption that the packages contained a full load of spent fuel that had been cooled 5 years. That is, the contractor estimated the amount of radioactive material release or increase in external radiation level, if any, for each response state. The contractor could then determine the radiological hazard arising from a given strain or temperature on the representative casks.

The other major steps concerned determining the forces which are experienced in real accidents, and the accident probabilities for various levels of severity. This involved a review of the historical record for road and rail accidents, including the severe accidents. This review yielded distributions of accident scenarios showing the occurrence rates for collisions over a widerange of target hardness, from soft objects, such as traffic cones, signs, etc., to hard objects, such as large concrete columns or abutments. An estimate of the forces involved in severe accidents were derived from reported accident conditions, vehicle speed in particular.

In the final steps of the evaluation, the contractor combined the package response and accident force analyses to estimate, given an accident has occurred, the probability of a representative cask reaching the various response states. Since the cask reflects the package standards and the cask response states can be related to radiological hazard, it is possible to determine the relationship between the standards and radiological safety provided under real accident conditions in transport.

THE RESULTS

The Modal Study approach, assumptions, and analyses have been reviewed by an independent peer review group, the Denver Research Institute. The Institute received analytical assistance from the Los Alamos National Laboratory. The group examined the appropriateness of the Study approach, the conservativeness of assumptions, and the accuracy of calculations. The peer review group did not identify any technical issues that would substantially alter the Study's results. For further detailed information, including a discussion of the impact of uncertainty in determining parameter values, refer to NUREG/CR-4829.

The Modal Study's objective was to investigate the performance of spent fuel packages under transport accident conditions and explain the level of safety provided by spent fuel package standards. The results, as summarized here, provide three perspectives on spent fuel transport safety: (1) the probability of an accident in which the package acceptance criteria are exceeded; (2) the total annual risk to the public from a large number of shipments; and (3) the probable response of the representative package to specific, severe accidents on record.

With respect to severe accident probabilities, results from the Study indicate that if the representative truck casks were involved in 1,000 accidents, the forces involved in 994 would not exceed either the strain or thermal responses corresponding to the Hypothetical Accident Conditions. For this 99.4 percent of accidents involving casks, damage would be superficial, and any release of radioactive material or increase in radiation exposure levels would be well within NRC acceptance criteria.

Of the six remaining accidents, four would cause minor functional damage to cask; however, the analyses indicates that the radiological hazard of these accidents would be small, still well within NRC's acceptance criteria.

In 2 of the 1,000 accidents, cask structural damage could be significant, although rupture of the cask's containment shield would not be expected. Thermal damage could include some lead shield melting. The analysis predicts that the radiological hazard of those accidents would only slightly exceed the regulatory acceptance values.

Finally, if the number of cask accidents were to approach 10,000, 1 of these accidents might be expected to lead to cask damage in the higher response states. The associated radiological hazard is estimated to be 10 times that of the acceptance criteria. It should be noted, however, that the contractor could not identify a historical accident of sufficient severity that would cause this degree of cask damage. Results for the representative rail cask are similar to those for the truck cask.

The preceding discussion summarizes the likelihood of real accidents resulting in various levels of cask damage and how the associated radiological hazard compares with the acceptance criteria for releases of radioactive material and increases in radiation exposure. With regard to the acceptance criterion for criticality, the results indicated that the probability of a cask reaching conditions necessary for a criticality event, i.e., significant package damage and package immersion, is less than 0.000001 percent, given an accident has occurred.

Another way to view the level of safety is to evaluate the risk to the public if packages designed to NRC standards were used over time in a large series of shipments. This type of risk evaluation for spent fuel shipments was included in NUREG-0170.

The NUREG-0170 evaluation assumed an annual shipment scenario of 1,530 truck spent fuel shipments of 1,570 miles each and 650 rail shipments of 750 miles each. The annual radiological risk from accidents, which was based on conservatively assumed package releases in NUREG-0170, was estimated to be 0.0004 latent cancer fatalities per year. In the Modal Study risk evaluation, the assumed shipment scenario from NUREG-0170 was left essentially the same. The Modal Study, which is based on analysis of package releases, indicates the annual risk from accidents to be less than one third of the NUREG-0170 values. It may be recalled that NRC's finding that transport risk is small and transport regulations are adequate was based, in part, on the NUREG-0170 values.

In addition to the level of safety and risk summaries, the Modal Study provides a third perspective on cask performance. Since the Modal Study analysis is based on subjecting the representative package designs to real accident conditions, it is possible to evaluate how the representative package would have performed had it been involved in specific, historically severe accidents. Part of the Modal Study analysis included a review of the 400 most severe accidents on record at the Department of Transportation. From these, the contractor selected several particularly severe accidents to illustrate the probable cask response. Two of these evaluations are described below:

In March 1981, a tractor-trailer was struck by a pickup while on an overpass on Interstate-80 near San Francisco, California. The tractor-trailer broke through the bridge railing and fell 64 feet to the soil surface below. The probable response of the representative truck cask was estimated, assuming the truck struck the ground at an impact angle between 20 and 70 degrees. From the height of the fall, the cask impact velocity would be approximately 44 mph, which would cause 0.2 percent strain on the cask. The accident would fall between the superficial and minor cask structural damage response regions, still within NRC acceptance criteria.

On September 28, 1982, 43 railroad cars derailed near Livingston, Louisiana. Following derailment, a fire started to burn various cargoes, including plastic pellets, vinyl chloride, and petroleum products. The fire was allowed to burn for several days because of the toxic chemicals involved. A rail tankcar carrying motor fuel anti-knock compound exploded about 19 hours after the derailment. On October 1, 82 hours after the derailment, a car carrying vinyl chloride exploded, rocketing 400 feet north of the derailment. The fire cooled down sufficiently on the fifth day to permit fire fighting operations.

The contractor estimated the probable response of the representative rail cask to the Livingston train accident. Assuming that the vinyl chloride fire continued until the fifth day and that the cask was located adjacent to the fire, the accident would fall in the significant thermal damage region. The radiological hazard, however, was estimated to only slightly exceed those permitted in the standards.

By relating NRC's package tests and acceptance criteria to real accident conditions, the Modal Study provides new insight to the protection provided by the standards against severe accident conditions. One of the key objectives of the Modal Study was to explain this relationship in an easily comprehendible manner. The Modal Study report, however, is of necessity a very technical document of analyses with appendices numbering several hundred pages. NRC staff is preparing a 40-page brochure which summarizes the Modal Study's approach and results. It is hoped this brochure will make the information contained in the Modal Study more understandable to the public at large.

In this discussion of package performance and accident conditions, attention has been focused on the role of hypothetical accident conditions and large packages in protecting public safety. It should be noted that many other requirements and guides apply to the package certification process, including guidance on suitable and well-known material properties, quality assurance programs in fabrication and use, etc., all of which embody a quality product principle. The results of the Modal Study should not be applied to packagings with significant differences in overall quality.

In conclusion, the Modal Study clarifies the level of safety provided under real accident conditions by spent fuel packages designed to current standards and practices.