TESTING TO FAILURE: DESIGN OF FULL-SCALE FIRE AND IMPACT TESTS FOR SPENT FUEL SHIPPING CASKS

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ABSTRACT

Full-scale physical testing of spent nuclear fuel shipping casks continues to be a major public policy issue. The U.S. Nuclear Regulatory Commission (NRC) does not currently require full-scale physical testing of shipping casks as part of its certification process. In March 2003, however, the NRC published a draft proposal (NUREG-1768) for full-scale cask testing as part of the Package Performance Study (PPS) that grew out of the NRC reexamination of the Modal Study. After a careful review of the extra-regulatory, full-scale cask test protocols proposed in NUREG-1768, the authors reject the NRC approach, and propose an alternative approach: regulatory compliance testing of all cask designs, and extra-regulatory testing of selected cask designs.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) does not currently require full-scale physical testing as part of its certification process for sent fuel shipping casks. The State of Nevada, Clark County, other potentially affected state and local governments, Indian tribes, and public interest organizations have long urged NRC to require full-scale testing. (1) In 1999, NRC began developing a proposal for demonstration testing of one or more selected casks as part of the Package Performance Study (PPS). NRC published draft protocols for full-scale demonstration testing, NUREG-1768, in February 2003, and distributed the document for public review in April 2003. (2) The State of Nevada and Clark County were active participants in the NRC PPS process, attending all public meetings, providing issue papers on transportation risk issues, and submitting written comments on NRC documents, including NUREG-1768. (3,4,5,6,7)

NEVADA APPROACH TO FULL-SCALE TESTING

The State of Nevada Agency for Nuclear Projects (NANP), supported by Clark County, has proposed a five-part approach to full-scale cask testing: meaningful stakeholder participation in development of testing protocols and selection of test facilities and personnel; full-scale physical testing (sequential drop, puncture, fire, and immersion) of each cask design prior to NRC certification or DOE procurement; additional testing (casks, components, models) and computer simulations to determine performance in extra-regulatory accidents and to determine failure

thresholds; reevaluation of previous risk study findings, and if appropriate, revision of NRC cask performance standards; and evaluation of costs and benefits of destructive testing of a randomly-selected production model cask. (1)

The authors, who helped develop the Nevada approach, believe that comprehensive full-scale testing would demonstrate compliance with NRC performance standards. It would also improve the overall safety of the cask and vehicle system, and generally enhance confidence in both qualitative and probabilistic risk analysis techniques. It could potentially increase acceptance of shipments by state and local officials and the general public, and could potentially reduce adverse social and economic impacts caused by public perception of transportation risks.

A comprehensive regulatory testing program (drop, puncture, fire, and immersion as proposed for the first truck cask, would likely cost $7.8-8.4 million. Comprehensive regulatory testing for the first large rail cask would cost $9.1-12.0 million. In addition, a one time cost of about $10 million would be incurred upgrading the testing facility to lift and drop rail casks weighing up to 150 tons. Subsequent tests would likely cost considerably less per cask. The authors estimate that it would cost $40-75 million to conduct a comprehensive testing program for the five to eight truck and rail cask designs expected to be used for repository shipments. (1)

NANP originally planned to issue a report in December 2003, offering more specific details regarding extra-regulatory fire and impact testing. NANP has sponsored research that will help define the concept "testing to failure," particularly in regard to extra-regulatory fire testing. An extra-regulatory fire test would involve subjecting a cask to a thermal environment in excess of the hypothetical accident condition specified in NRC regulations [10 CFR 71.73(b)(4)], an engulfing fire at 1475ºF (800ºC) for 30 minutes. Due to budget restrictions and project delays, this report is now planned for December, 2004.

COMMENTS ON NUREG-1768

In April, 2003, the NRC issued NUREG-1768, Package Performance Study Test Protocols Draft Report for Public Comment. (2) NANP and Clark County filed written comments on NUREG-1768 in May 2003. (6,7)

Both NANP and Clark County applauded the public participation process used by NRC during the public meetings in Rockville, MD, Las Vegas, NV, Pahrump, NV, and Chicago, IL, and the timely manner in which transcripts of those meetings were prepared and posted on the PPS website. Clark County specifically recognized and commended the efforts of NRC staff to incorporate stakeholder perspectives and encourage general public input. Both urged NRC to give verbal comments made during the meetings the same consideration as formal written comments.

After careful review, however, both the State of Nevada and Clark County concluded that the proposed testing protocols were unacceptable, and called upon the NRC to reissue new draft test protocols for public comment. NANP stated three primary reasons.

- "NUREG-1768 proposes a testing program for two casks that will cost more than $20 million, but will not determine if the two casks meet the accident performance standards set forth in the NRC regulations." (7)

- "NUREG-1768 proposes a testing program that will cost more than $20 million, but will not determine the failure thresholds of the two casks tested. Based on comments made during the public meetings, it appears that many other affected stakeholders advocate testing to failure." (7)

- "NUREG-1768 states that the primary technical objective of the PPS is to 'further validate the computer models used to evaluate the safety of cask transportation… .' [p.1] Yet the proposed PPS impact tests will result in cask deformations so small that they may not be accurately measurable, and the proposed fire tests are so vague that there is no way of knowing what, if any, useful cask temperature data will result." (7)

The NANP comments specified that "full-scale testing should be conducted to evaluate the performance of the casks themselves, not the performance of the computer models. NRC must go back to the drawing board and develop test protocols that confirm cask compliance with current regulations, and that determine cask failure thresholds. If properly designed, such tests will also provide physical data that can be used to benchmark the computer models used for transportation risk assessments." (7)

NANP and Clark County were not alone in advocating testing to determine cask failure thresholds. The Association of American Railroads (AAR) filed this comment regarding impact testing: "Whatever method is used, the data should be collected to allow the modelers to predict the speed at which the cask will fail, and also allow the report team to compare the forces needed to fail the cask with the forces that occur in real world accidents to determine if there are any potential real world accidents that are capable of breeching the cask. By understanding this relationship, designers and system operators might be able to design the system to prevent these potential forces from occurring." (8)

Regarding fire testing, AAR commented:"[W]e would like to see whatever fire testing that is done to be completed in such a way that the data can be used to determine when a cask could fail, based upon the heat input. That information could be used by emergency responders to assist in determining the amount of time they have to take action to reduce heat input with water, or other means to prevent that occurrence. The data might also be used for cask and cask system design." (8)

AAR also called NRC attention to the potential benefit of back breaker impact test results for understanding accident crush forces, which are not addressed in current NRC regulations: "Trains consist of multiple cars. When trains are involved in derailments, cars can and do pile on top of each other. For that reason, crush loads are a real possibility. While the back breaker test is not a crush load test, data collected from a back breaker test that could be used to determine what happen to [sic] if one cask were to impact upon another cask, thereby subjecting one of them to a crush load. The purpose of such an analysis would be to determine if there are credible railroad accidents that might occur that have the potential to breech the cask." (8)

STAKEHOLDER PARTICIPATION IN PPS TESTING

As of February 2004, NRC plans for future stakeholder participation in the PPS are not clear. NRC has made no formal public announcements about the PPS process since publication of NUREG-1768. NUREG-1768 says the following regarding stakeholder participation: "After receiving and considering all stakeholder comments on the test protocols, the NRC staff will develop detailed test plans and procedures for each of the PPS testing programs, again making use of SNL's [Sandia National Laboratories] expertise. The NRC will make these detailed plans, procedures and tests available to the public before finalizing and conducting the planned tests. Thus, the finalized detailed plans will reflect public comments on these test protocols, constraints imposed by NRC's programmatic priorities, and the available funding to support these tests." [Pp. xiii]

Both the State of Nevada and Clark County, in written comments on NUREG-1768, urged NRC to continue the extensive stakeholder participation process followed up to March 2003. NANP stated: "The NRC plans for future stakeholder involvement are not acceptable, and are almost certainly insufficient to inspire public confidence in spent fuel transportation safety. The NRC must provide a meaningful and substantive role for stakeholders in finalizing the testing protocols, selecting the testing contractors, and overseeing the implementation of the test program. The first step is for NRC to agree to publish revised draft test protocols for public review and comment." (7)

Both the State of Nevada and Clark County recommended the approach used for testing of the TRUPACT shipping container as a model for effective stakeholder involvement. The TRUPACT-II shipping container is used for transporting transuranic waste to the Waste Isolation Pilot Plant (WIPP) in New Mexico. In that case, representatives from affected states, as well as outside consultants identified by the states, were fully involved in the design of the test program and in overseeing its implementation. Such involvement resulted in greater public confidence in container safety and acceptance of the entire WIPP shipping program. It also resulted in the identification of engineering and safety flaws, and corresponding package design changes that likely would not have been found absent the involvement of these "outside" participants.

The authors strongly recommend that NRC commit to full stakeholder participation in any full-scale cask testing program. Our previous analysis estimated that extensive stakeholder involvement in development of test plans, witnessing of the actual tests, and evaluation of test results and peer reviews, would cost about $800,000 for each cask tested. (1) Stakeholder participation is a minor cost factor, but a major credibility factor. Meaningful stakeholder participation in test program planning and implementation is absolutely essential for public acceptance of test program results.

SPECIFC RECOMMENDATIONS ON PPS TEST PROTOCOLS

NUREG-1768 asked stakeholders to advise NRC on eleven specific technical questions related to extra-regulatory testing. Clark County decided not to submit detailed comments on those questions "because to do so would be to accept the flawed premise that the NUREG-1768 tests are an adequate substitute for full-scale regulatory testing." (6) NANP decided to submit

comments integrating recommendations for regulatory testing with recommendations on the selection of casks, design of impact tests, and design of fire tests.

Selection of Casks

NANP advised NRC that one truck cask and four rail casks should be used in regulatory tests. Over the next 40 years, the overwhelming majority of spent nuclear fuel and high-level radioactive waste shipments in the United States are expected be shipments to the proposed Yucca Mountain repository. Each of the truck and rail cask designs used for these shipments should be tested full-scale, to demonstrate compliance with existing regulations. NRC has identified five currently licensed cask designs as "most likely to be used for large shipping campaigns to a disposal facility" – the General Atomics GA-4 truck cask, and four rail casks: the NAC International NAC-STC, the Transnuclear West NUHOMS MP187, the Holtec International HI-STAR 100, and the Transnuclear TN-68. (9)

Additionally, at least one of these truck cask designs, and at least one of these rail cask designs, should be subjected to extra-regulatory test conditions to determine cask failure thresholds, and to determine if finite element analyses can accurately predict the release (or lack of release) of radioactive material from a cask. Based on the information presented in the DOE Final EIS for Yucca Mountain, the General Atomics GA-4 cask, designed to transport 4 PWR assemblies, is the most appropriate choice for extra-regulatory testing. The GA-4 could be used for about two-thirds of all shipments under the DOE "mostly legal-weight truck" national shipping scenario. (10)

Selection of the rail cask for extra-regulatory testing should be deferred until detailed, comparative, finite element analyses are provided in a revised draft test protocol. Selection of the most appropriate rail cask, or casks, for extra-regulatory testing, is crucial to the credibility of the PPS. Although similar in overall dimensions, gross weight (125-141 tons) and payload capacity, the four rail casks exhibit differences in design (such as use of a welded internal canister) that should be fully evaluated before selection of one or more test subjects. This decision is particularly important because of the DOE stated intention to maximize use of rail for shipments to Yucca Mountain, even though DOE has not yet demonstrated the feasibility of the "mostly rail" shipping scenario.

Impact Test Design

NANP recommended that full-scale casks, without impact limiters, should be used for both regulatory and extra-regulatory impact tests. The drop test proposed in NUREG-1768 was a free drop on the impact limiter. Because the impact limiter would absorb most of the impact, little deformation of the cask itself was predicted. The drop test as proposed would fail to achieve the objective of demonstrating that finite element analysis can accurately predict the performance of the cask in an accident situation.

NUREG-1768 states, "But the main concern for the impact test is how well the pretest analysis does in predicting the response of the cask body, not the impact limiter. Because deformations to the cask body will likely be small, accurate measurements (±. 0.0254 mm [±. 0.001 in.]) are

needed to compare with the results of the pretest finite analysis. Measurements to this accuracy on a full-scale cask are difficult because the thermal expansion of cask structures caused by a change of a few degrees in temperature will produce changes in structures of this magnitude, leading to larger inaccuracy in the measured result." [p.10]

NUREG-1768 concludes, regarding the proposed GA-4 impact test, that "finite element analysis results may depend significantly on the response of cask features that are too small to model." [p. 73] The same observation would appear to apply to the rail impact test as well, particularly if the test were performed on a rail cask that did not rely upon a welded MPC for containment. If the objective of the test is to verify the finite analysis, a drop without the impact limiter would result in much more deformation of the cask, reducing the effects of temperature on measurement, and the difficulty of modeling small but important features (such as bolt threads).

It should also be noted that in a severe accident, a cask could be subject to more than one severe impact. Accidents involving multiple rail cars within a train, or multiple rail cars from another train, could result in multiple impacts to a cask. A rail cask involved in an accident could also suffer damaging multiple impacts with man-made structures and/or natural objects. The first impact, if oriented correctly, could either cause significant deformation to the impact limiter, or rip the impact limiter from the cask. Therefore, it is not unrealistic to assume that once the impact limiter's effectiveness is destroyed, a subsequent severe impact could occur.

The performance of impact limiters has been extensively evaluated in scale-model tests for currently licensed casks. Scale-model drop tests have also been performed for several cask designs. (1) The revised draft test protocols should include an evaluation of all previous scale-model package drop tests, and scale-model impact-limiter drop tests, conducted on the TN-8, DOE 125-B, TN-BRP, TN-REG, GA-4, NAC-STC, FN-FSV, NUHOMS MP 187, HI-STAR 100, and TN-68 casks.

NANP recommended that the impact tests should be conducted as drops from a tower. Nevada generally agreed with the NUREG-1768 discussion of the advantages and disadvantages of drop tests versus rocket sled tests. However, the discussion of the "newly constructed target" to be used for drop tests should have included cost data. Further, NUREG-1768 should have identified other potential drop testing facilities in the Untied States and abroad (such as those at Oak Ridge National Laboratories, and at Cheddar Gorge in the United Kingdom), their lift and drop capabilities, and the cost of using and/or upgrading existing facilities other than those at Sandia National Laboratories.

NANP recommended that the drop orientation for the four rail cask regulatory impact tests (drop from 9 meters), should be drop onto the lid end, with center of gravity-over-corner impact, without impact limiters. For the rail cask extra-regulatory impact test or tests, final specification of impact speed and orientation should be deferred until detailed, comparative, finite element analyses are provided in a revised draft test protocol. NRC should evaluate both end-impact and back breaker drop test orientations for rail casks, at impact speeds of 75 mph or greater, without impact limiters.

NUREG-1768 asked stakeholders to respond to this question: Is 26.8 to 40.2 m/s (60 to 90 mph) a reasonable speed range for the rail cask impact test, given that the frequency for a rail cask impacting a hard rock surface within this speed range is 10^{-6} to 10^{-8} per year? NANP responded that the 60 to 90 mph speed range was reasonable, but that train accidents are known to have occurred at speeds in excess of 90 mph. AAR also agreed with the reasonableness of the speed range, but commented: "Freight trains operate up to 70 miles per hour. For that reason, trains on opposite tracks could be operating at a relative speed of 140 miles per hour." (10) NANP criticized the basis of the NRC stated frequency of a rail cask impacting a hard rock surface within this speed range, 10^{-6} to 10^{-8} per year. NANP noted that the actual historical accident rate for U.S. spent fuel shipments by rail is about 4.6 accidents per million cask-miles, or ten times greater than the projected accident rate used by NRC.

For both the rail and truck cask extra-regulatory impact tests, NANP recommended that final specification of impact speed and orientation should be deferred until detailed, comparative, finite element analyses are provided in a revised draft test protocol. Based on preliminary analyses, cask impact speeds of 75 mph or greater, without impact limiters, would likely result in significant cask deformation.

The truck cask back breaker drop test as proposed in NUREG-1768 would not challenge the lid closure to the same extent as an end-first impact. The use of impact limiters in the back breaker test, as proposed in NUREG-1768, would limit the extent of wrap-around cask deformation more than would be the case in a real world accident, where the bridge support column would not be backed up by a flat unyielding surface.

Fire Test Design

NANP recommended for the five cask regulatory fire tests, the fire duration should be 30 minutes at 1475ºF (800ºC). For the truck and rail cask extra-regulatory fire tests, final specification of fire duration and temperature should be deferred until further analyses are provided in a revised draft test protocol. The fire tests should be designed considering both predicted temperature failure thresholds and historical accident fire conditions.

Extra-regulatory fire test design should assess potential temperature failure thresholds for critical cask components (such as lid seals) and fuel cladding, assuming both intact and damaged neutron shields and impact limiters. Since rail cask designs with and without internal welded canisters could perform differently in severe fire environments, both types of rail casks (with and without internal canisters) must be tested.

Based on preliminary analyses of the July 2001 Howard Street Rail Tunnel fire in Baltimore, the minimum extra-regulatory test fire conditions should be 3 hours at 1800ºF (1000ºC), or 6 hours at 1475ºF (800ºC). NANP and NRC are separately sponsoring additional studies of the Baltimore fire.

For the five cask regulatory fire tests, the cask position should be one meter above a fuel pool, one to three meters beyond the side of the cask. For the extra-regulatory fire tests, final specification of cask position should be deferred until further analyses are provided in a revised

draft test protocol. NRC should consider cask placement at the edge of the fuel pool under various wind conditions. NRC should also consider furnace testing as an alternative to fuel pool fire testing.

Since PWR fuel will be the predominate form shipped to the repository, PWR fuel should be in the truck cask and in at least one of the rail casks during the tests. Each cask should contain one real, fresh fuel assembly. The remaining fuel basket cells could be loaded with the correct weight of dummy and/or surrogate fuel and heaters.

CONCLUSION

NRC does not currently require full-scale physical testing of spent fuel shipping casks as part of its certification process. NRC is considering demonstration full-scale cask testing as part of the Package Performance Study. The authors propose an alternative approach: regulatory compliance testing of all cask designs, and extra-regulatory testing of selected cask designs. Many technical details of full-scale cask testing remain to be determined. The authors' primary recommendation is that NRC commit to full stakeholder participation in determining the test details before proceeding with any full-scale cask testing program.

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