2 TESTING AND ANALYSIS

2.1 NRC PRESENTATION

2.1.1 Overview of Research Program Objectives, E. William Brach, Director, Spent Fuel Project Office, NRC

Mr. Brach opened by stating that NRC staff believes, unequivocally, that shipments of spent fuel in the United States are safe using the regulations and programs currently in place. This belief is based on NRC's confidence in NRC-certified shipping containers and ongoing research on the issue of transportation safety. This confidence is also based on the industry's strict compliance with the safety regulations and the conditions of the certificate and conditions of use that have resulted in a strong transportation safety record.

The NRC ensures that shipping containers are robust. Safety assurance is obtained in many ways by regulating the design and construction of the shipping containers. During the certification process, NRC staff reviews the design and independently confirms the ability of the package to meet the regulations (e.g., ability to withstand hypothetical accident conditions) through modeling, analysis, and verification of the applicant's analysis and testing. The NRC provides oversight of entities, licensed in accordance with 10 CFR Part 71, to assure that packages are fabricated and maintained in strict compliance with the NRC-issued certificate for the package.

The NRC also follows an aggressive program to investigate and assess the continued safety of spent fuel shipments. This is accomplished through a number of avenues. For example, spent fuel transportation experience data are analyzed to evaluate new transportation issues such as the potential for increased spent fuel shipments, increased and changing radioactive material contents of spent fuel packages, and population density and density changes along the routes. Other factors, such as modeling and analytical capabilities, are used to estimate current and future potential risks to the public as a result of spent fuel transportation.

The NRC has found that the likelihood of a release from an accident involving a spent fuel transportation package, and the associated risks to the public, is extremely low. Notwithstanding, NRC continues to maintain vigilance over spent fuel transportation in fulfillment of its primary mission to ensure public health and safety.

Clearly, the interest in spent fuel transportation has increased with the prospect of a national repository being built at Yucca Mountain, Nevada. With regard to transportation as it relates to the National Geological Repository at Yucca Mountain, NRC's role and responsibilities are guided by the Nuclear Waste Policy Act (NWPA). The NRC's primary role in the transportation of spent fuel to a repository would be to certify the packages used for transport.

Section 180(a) of the NWPA prohibits the Secretary of Energy from transporting spent nuclear fuel or high-level waste except in packages that have been certified by the Commission. The NRC has reviewed and certified a number of spent fuel package designs which could be used for the transport of spent fuel to a repository. Additional designs and design amendments are under review as well. The NRC anticipates that additional designs will likely be submitted in the not too distant future.

Certain provisions of the NWPA apply to the actual transportation of spent fuel. The U. S. Department of Energy (DOE) is required to follow NRC's advance notification requirements. These requirements pertain to notification of and coordination with State governments in terms of plans for spent fuel transportation. DOE is required to fund state and local governments and Indian tribes with regard to response and preparedness activities.

Past transportation shipments have included the return of reactor fuel to utilities from the closed West Valley Processing Plant in the early 1980s, as well as shipments currently taking place between power plants and shipments of research reactor fuel. Over 1300 spent fuel shipments in NRC-certified packages have taken place over the last 20 years; currently, approximately 10 to 20 shipments continue to take place each year.

The proposed Private Fuel Storage (PFS) facility located approximately 100 miles west of Salt Lake, City, Utah, and Yucca Mountain, and approximately 100 miles northwest of Las Vegas, may receive a significant number of spent fuel shipments. Neither of the facilities has yet obtained an NRC license for construction or operation. The PFS has applied for a license to store spent fuel in accordance with 10 CFR Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor Related Greater than Class C Waste." Issuance of the license is currently being considered in hearings before the Atomic Safety Licensing Board. The PFS facility is planning to use the Holtec HI-STAR 100[1], dual purpose[2] cask system at its facility.

The Yucca Mountain facility is roughly twice the capacity of the PFS facility. The NWPA limits the amount of high-level waste that can be stored at Yucca Mountain to approximately 73,000 metric tons of commercial sector spent fuel. The PFS facility plans to operate for a 20-year period and is forecasted to receive approximately 50 shipments per year. The preliminary information NRC has received from DOE is that approximately 175 shipments, 130 by rail and approximately 45 by truck, would be received annually at the Yucca Mountain facility.

The NRC routinely conducts studies to review the adequacy of its regulations. For transportation regulations, NRC has completed three major studies since the 1970s, with the most recent having been completed in 2000. In addition, a current major effort is the Package Performance Study (PPS).

After completing the final environment impact statement on the transportation of radioactive material by air and other modes, commonly referred to as NUREG-0170 (Ref. 1), the Commission concluded in 1981 that its transportation regulations are adequate to protect the public against unreasonable risk in the transport of radioactive materials, including spent nuclear fuel. Spent fuel was only 1 of approximately 25 radioactive materials addressed in NUREG-0170. At that time, the Commission also concluded that regulatory policies concerning radioactive materials be subject to close and continuing review. In the ensuing years, NRC has conducted additional transportation risk assessments that confirm earlier findings on spent fuel transportation safety.

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[1] The structural integrity of the Holtec High Star Cask System is discussed in Section 1.4.1 of this NUREG-series report.

[2] A dual purpose cask may be used for both storage and transportation of spent nuclear fuel and high-level radioactive waste.

To better assess response of spent fuel and spent fuel casks to severe accident conditions, in the mid- to late-1980s, NRC sponsored an examination of collision and fire accident condition conducted by Lawrence Livermore National Laboratory (LLNL). The study was documented in NUREG/CR-4829 and is frequently referred as the Modal Study[3] (Ref. 2). From the Modal Study, NRC staff has concluded that NUREG-0170 clearly bounded spent fuel shipment accidents by a factor of approximately 3.

In March 2000, NRC published NUREG/CR-6672 (Ref. 3). This study focused on the risks of a modern spent fuel transportation campaign from reactor sites to a possible interim storage facility, such as the PFS facility, or to a permanent geological repository, such as the Yucca Mountain facility. NUREG/CR-6672 was initiated in 1996. The NRC recognized that the number of spent fuel transportation activities would increase significantly over the coming decades. NUREG/CR-6672 reviewed contemporary spent fuel package designs that are larger in size and have larger radioactive material contents than some of the packages that had been examined in previous studies. NUREG/CR-6672 concluded that the accident risks were much lower than estimated in NUREG-0170.

In 1999, NRC initiated the PPS. This study is expected to take 5 to 6 years to complete. The staff is developing the study to confirm the reliance on analytical techniques to predict cask performance, and to consider public concerns and input. The study is also being developed to demonstrate the robustness of NRC-certified transportation casks.

The PPS is using what the staff refers to as a public-enhanced, public participatory process, an approach to solicit and obtain public input and comments on the study's testing approach and concept. Current plans for the PPS include full-scale physical testing to confirm cask performance and safety during transportation accident conditions.

Some additional transportation studies are currently in progress. In July of 2001, a train derailed in Baltimore. The NRC is continuing to review this accident closely with the U. S. Department of Transportation (DOT) and the National Transportation Safety Board (NTSB) to assess what might have happened if a spent fuel cask had been on the train. The NRC's preliminary analyses are very positive and suggest that the transportation cask would not have failed had it been in the Baltimore Tunnel railroad fire.[4]

Other activities are underway as well. The NRC and other Federal agencies are currently jointly funding a project at the National Academy of Sciences (NAS). The NAS Board of Radioactive Waste Management is assembling an expert panel that will review the societal and health risks of transportation of spent fuel.[5]

There have been other spent fuel transportation studies, tests, and demonstrations not sponsored by NRC, including the Sandia National Laboratories (Sandia) and the British crash tests in the 1970s and 1980s, that received significant attention. The tests did not have an NRC regulatory purpose and, therefore, are not a part of the basis for NRC's regulatory

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[3]The Modal Study is further discussed in Section 2.2.3 of this NUREG report.

[4]The Baltimore Tunnel railroad fire is further discussed in Section 2.5.1 of this NUREG report.

[5]The NAS study is further discussed in Appendix D of this NUREG report.

program. However, those tests demonstrated that the casks are very robust in the specific accident conditions in which they were tested.

One important conclusion demonstrated by the Sandia and British studies is that the crash surfaces actually absorb much of the energy upon impact. The NRC transportation regulations test criteria require that drop tests take place on an unyielding surface so that all of the energy of impact is transmitted back into the transport package.

This was a brief overview of a number of the research and study programs and activities that have occurred over the past 20 years, as well as some that are ongoing right now to address spent fuel transportation. The United States domestic standards and requirements were developed using an expert consensus approach, both domestically and through participating with fellow international transportation regulators at the International Atomic Energy Agency (IAEA). These regulations have resulted in an exemplary level of safety and have demonstrated a long, favorable history of use, both here in the United States as well as internationally.

Risk insights or risk studies have not traditionally been used to establish these regulations but have mostly been confirmatory in nature. They have supported the conclusions regarding the adequacy of our current regulatory standards. As technologies have changed and analysis capabilities have improved, NRC will continue to review the research and findings and conclusions consistent with the Commission's 1981 direction that regulatory policy concerning radioactive materials be subjected to close and continuing review.

It should be noted that, to date, none of the NRC-sponsored transportation risk studies have included physical testing. The studies have been primarily based on computer modeling and analysis and, therefore, the staff is looking forward to the PPS which does include aspects of physical testing. The basic methodology that was developed for NUREG-0170 and its supporting works, including, for example, the development of the RADTRAN computer code to estimate radiological releases from transportation accidents, has reasonably withstood the test of time and has recently been used in major environmental impact statements.

2.1.2 TWG Questions Regarding NRC Research Programs

Dr. Garrick stated that he was struggling with NRC's position that the Sandia tests were not part of the NRC research program. He noted that generating the steam tables was not a part of any NRC program either; however, the staff uses them all the time in thermal-hydraulic work. It seems that the results of those tests inevitably have to be a part of the analyses and the investigations that are performed regarding transportation safety. Mr. Brach noted that the point he was trying to make is that the conduct of those tests were not the part of the regulatory basis relied on by NRC in the development and confirmation of existing regulatory standards and bases.

Dr. Garrick stated that NRC has been focusing on the transportation packages and questioned whether any route-specific analysis was planned to understand how risk is affected by the choice of the transportation route. Mr. Brach responded that the selection of routes to be used for the PFS facility or potentially to Yucca Mountain is not an NRC decision. Those routes are selected by other regulatory agencies. For example, DOT will select routes to the PFS facility and DOE, in consultation with the States, will select routes to Yucca Mountain. However, NUREG-6672 did study some selected, representative routes that span the country in various parts of the United States. In selecting the routes, the study analyzed what might be some of the most challenging or limiting types of conditions of transport with regard to accident conditions and resulting consequences.

Dr. Wymer noted that, in connection with the PPS to be completed in about 2005, there will be enhanced public participation. The NRC has appeared to have had substantial public participation in the past. Dr. Wymer questioned what enhanced public participation meant. In response, Mr. Brach stated that, over the past few years, the staff has conducted a series of public outreach meetings with regard to the PPS. The staff started the process with a series of meetings in the Washington, DC, area, as well as in Las Vegas, Nevada. During the first round of public meetings, the staff asked stakeholders for input with regard to what type of spent fuel package physical testing and test conditions should be included in the study. From that series of meetings, the staff developed an issues paper which summarized the various stakeholder suggestions and comments. A second series of public meetings followed, again in the Washington, DC, and Las Vegas areas, to ascertain whether NRC appropriately characterized and summarized the issues. In addition, the staff assessed what various test conditions and activities would provide the most information. From that process, the staff developed what is referred to as the test protocol. The staff also established an interactive Web page for submitting comments during the entire PPS process.

Mr. Brach further explained that the staff has drafted the PPS test protocol which describes the type of testing and analysis that could be conducted in the PPS. Next, the staff will hold another round of public meetings to discuss the test plan with the stakeholders and to ask for views and comments before the tests are finalized and performed. Mr. Brach summarized by stating that an "enhanced public participatory process" means that the staff is providing the public a significant opportunity to provide input on the PPS and to make sure that the staff understood what the stakeholders stated during development of the PPS.

Dr. Hornberger questioned whether the staff anticipated any changes in the regulations resulting from the package performance test. Mr. Brach stated that the staff believes, from the standpoint of the staff's understanding of the package designs, testing, and modeling, the PPS to be confirmatory in nature. The tests are to confirm predictions and expectations. However, the staff must be alert to the implications that the results might have on regulations and other practices.

Mr. Levenson commented that he was glad Mr. Brach referred to the other tests (Sandia, etc.) because some misunderstandings have occurred in the past in terms of whether full-scale testing had been performed. In discussing technical issues, the staff needs to include all of the available literature and information, not just NRC literature.

Overview of Research Program Objectives

E. William Brach, Director

Spent Fuel Project Office
U.S. Nuclear Regulatory Commission

1

Overview

- Spent Fuel Transport Safety
- Scope of Spent Fuel Transportation
- Role of Research - Risk Assessments and Transport Studies

2

Key Messages

- NRC ensures that casks are robust
  - *Regulates design and construction*
  - *Reviews designs and independently checks ability to meet accident conditions*
  - *Ensures containers are built, maintained, and used properly*
- Exemplary industry compliance with safety regulations, resulting in strong transport safety record
- Supported by confirmatory research

3

NRC Yucca Mt Transport Role

- Nuclear Waste Policy Act Section 180
  - *DOE must use NRC certified cask*
  - *DOE must apply NRC advance notifications*
  - *DOE must provide training and funds to local and Tribal governments along routes*

4

Scope of Spent Fuel Transportation

- Historical/Current:
  - ~1300 shipments in NRC certified casks in 20 yrs; 4 accidents but no releases
  - Currently about 10 SNF shipments/yr
- Private Fuel Storage (40,000 MTHM)
  - **~50 rail shipments/yr @ 4 casks each** for 20 yrs
- Yucca Mountain (63,000 comm. MTHM)
  - Mostly rail scenario (FEIS): **~130 rail shipments/yr @ 3 casks each + 45 truck shipments/yr for 24 yrs**

5

Transportation Studies

- NUREG-0170 (Final Environmental Statement, 1977)
  - All radioactive materials by all modes
  - NEPA basis for Part 71 & 49 CFR
  - Resulted in 1981 Commission Policy Finding: Transport regulations adequate, subject to close and continuing review
- Modal Study (NUREG/CR-4829, 1987)
  - First incorporation of cask finite element analyses & detailed thermal/impact response

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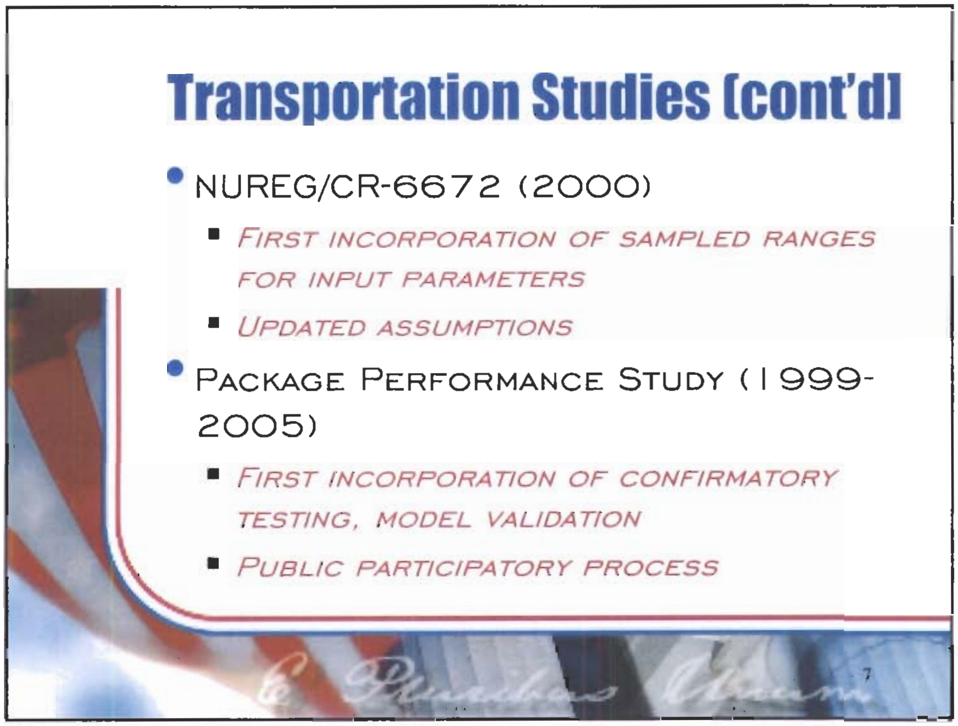
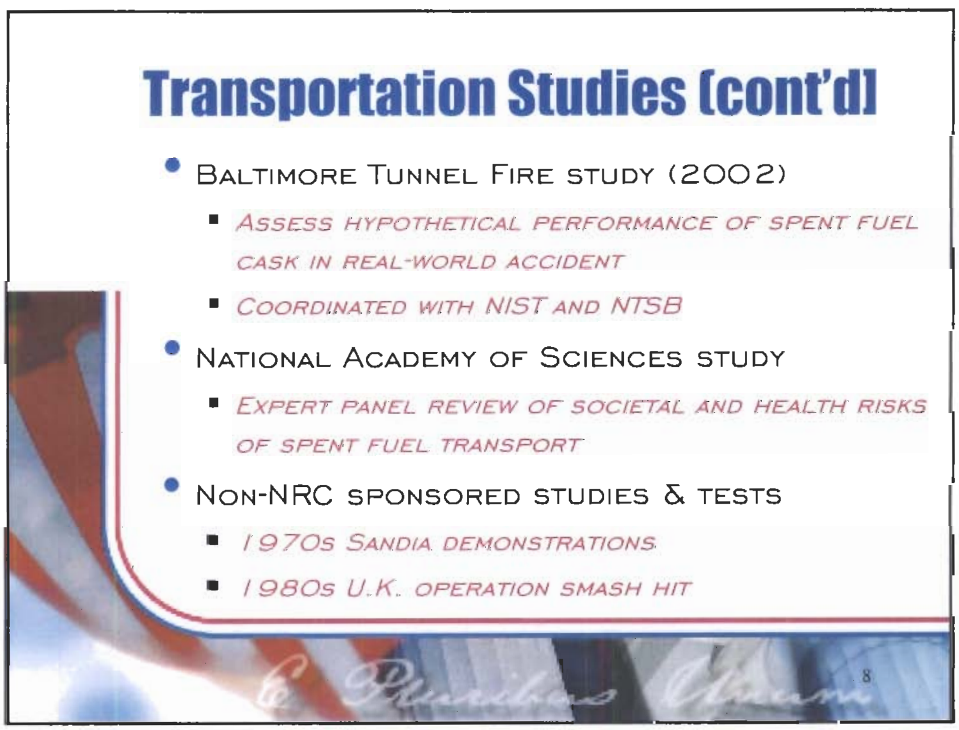

Transportation Studies (cont'd)
NUREG/CR-6672 (2000)
First incorporation of sampled ranges for input parameters
Updated assumptions
Package Performance Study (1999-2005)
First incorporation of confirmatory testing, model validation
Public participatory process
7


Transportation Studies (cont'd)
Baltimore Tunnel Fire study (2002)
Assess hypothetical performance of spent fuel cask in real-world accident
Coordinated with NIST and NTSB
National Academy of Sciences study
Expert panel review of societal and health risks of spent fuel transport
Non-NRC sponsored studies & tests
1970s Sandia demonstrations
1980s U.K. operation Smash Hit
8

Conclusion

- High confidence in safety provided by transportation regulations
- Transportation research programs
  - *Confirmatory in nature*
  - *Consistent with Commission direction*
  - *Valuable insights into cask performance & release estimates*
  - *Developed the approaches used for key Environmental Reviews for licensing*
  - *Support Public Confidence*

9

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2.2 National Laboratories Presentations

2.2.1 Summary of Sandia National Laboratories Research, Doug Ammerman

Mr. Ammerman stated that Sandia is a DOE facility that has been involved in areas of national interest since its inception in 1948. Sandia has primarily been involved in nuclear weapons, but that expertise has led to other areas of system level testing.

The presentation in this section reviewed past significant test programs at Sandia, starting with the 1970s Crash Test Program discussed in Section 2.1 of this NUREG, some certification testing that Sandia performed for DOE on defense high-level waste, and the certification testing that Sandia performed for DOE on the TRUPACT-II (used for transporting transuranic waste). The certification tests for the TRUPACT-II were full-scale tests. Discussions in this presentation also reviewed Sandia's analysis methodology. Finally, the discussion focused on linking analysis that Sandia has performed to testing, both code verification and validation, and side-by-side comparisons of analysis results with test results. The presentation concluded with a discussion of "Where are the gaps? What do we need to know more than what we currently know?"

Sandia has, since its beginning, been involved in systems level testing. As stated earlier, initially those systems were nuclear weapons, but systems level testing expertise applies to many different fields, and it has been used in the area of transportation package testing for approximately 30 years. Of course, different programs have different goals and different purposes. These goals and purposes define the way the tests were carried out. Some of the tests were engineering tests to improve the state of knowledge; others were certification tests performed to determine whether packages meet NRC requirements. Some of the tests are tests to demonstrate that a package will survive in an environment that was not a regulatory environment, but was a severe environment.

The 1970s Crash Test Program was perhaps one of the most visible testing activities carried out on spent nuclear fuel packages. The purpose of this program was to assess and demonstrate the validity of analytical tools and scale model techniques for predicting the response of packages to accident environments by comparing the predicted results with full-scale actual test results. The tests were also performed to gain quantitative knowledge regarding extreme accident conditions by measuring the response of full-scale packages under actual crash conditions.

One of the purposes of this program was to show that the hypothetical accident conditions of the NRC regulations do indeed provide adequate safety in actual accident conditions. In this program, mathematical models were developed, including some very crude computer scale model testing and a combination of full-scale tests.

This test program included some instrumentation on the scale and full-scale hardware to measure accelerations of package and transport systems, including the conveyance that was being used. In addition, for a couple of tests, Sandia also placed strain gauges on the targets to measure strains on various cask and transport system components.

While it is not part of the NRC regulations, the certification processes imply that package designers try to limit the amount of plastic deformation to packages. Strain gauges are a way of measuring plastic deformation. In addition, high-speed photography was used to record cask and transport system response.

The most spectacular test simulated a railroad grade crossing accident. A truck transporting a spent fuel cask was stopped while crossing a railroad track and was slammed into by a locomotive. It was an actual truck in transport trailer that was used at that time for transporting it. One of the criticisms of this particular test has been that the center line of the cask was higher than the frame rails or was not equal to the frame rails of the locomotive, causing the cask to ride up over the train and be thrown up into the air. Recently, however, the Association of American Railroads (AAR) Test Facility at Pueblo, Colorado, performed some tests that collided passenger trains into each other and the same kind of behavior was observed. The locomotive essentially plows underneath what it strikes.

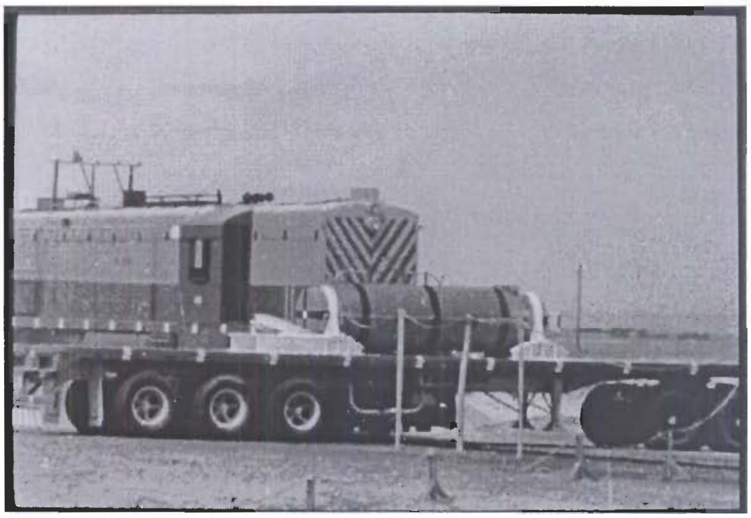

Figure 1 Train Impacting Truck Cask

This was a spectacular test that provided an 80-mile per hour (mph) impact and demonstrated that the regulatory impact, which is 30 mph into a rigid target, provides a large margin of safety for these packages. A train is something that most people consider very rigid. Few structures in the transportation world are viewed to be more rigid than the front end of a train. However, the test showed that the train absorbed a significant amount of the energy of the impact, resulting in considerable deformation of the train.

The results of that test are documented in SAND79-2291 (Ref. 4). Eighteen high-speed cameras, seven strain gauges on the cask body, four accelerometers on the cask, and one accelerometer on the locomotive were used. A telemetry system to a remote recording site was used to acquire the data, and the data. Therefore, no cables ran off of the cask, as is typical in most transportation package testing. An umbilical line of cables was used to translate the data from the test to a recording system.

In two tests, a truck carrying a 22-ton spent fuel cask impacted a 690-ton concrete block at 60 mph and 84 mph. The results of those tests are documented in SAND77-0270 (Ref. 5). The tests were monitored with approximately 14 high-speed cameras (between 400 frames per second and 3,000 frames per second), five accelerometers on the cask body, strain gauges on the cask head and pressure transducers placed inside the cask cavity. The results of the 60 mph test had such little deformation to the cask that Sandia staff said, "You know what? That was no big deal. Let's go out and do a faster test." So a second test was performed at 84 mph. Even that test showed very little deformation to the cask and the package remained essentially tight.

The next test was performed on a rail transport cask. In this particular instance, Sandia used only the rail car that was used to transport the cask and not the whole train for the impact.

Typically during an accident, a mitigating structure of cars would be in front of the car being tested to absorb energy as well, but in this particular test, the car was slammed into the same structure used in the truck tests. The 74-ton shipping cask, carried by a cask rail car, crashed into the concrete block at 81 mph.

The rail car was extensively deformed. However, the cask did not actually come completely out of its carriage, and again, no significant leakage from the cask resulted. Documentation of that test is available in SAND78-0458 (Ref. 6). Staff monitored the test using numerous high-speed cameras (up to 3,000 frames per second), placed above, on the sides, and at various angles. Staff also placed accelerometers on the rail car frame, the rail car cage cover, which was extremely damaged in the test, on the cask, and on the target.

In addition to these impact-type tests, the test program also involved a thermal test. The same rail car that impacted the concrete barrier was placed into a fully engulfing fire and burned for a period of 90 minutes. After 90 minutes, three times the duration of current qualification test criteria, surface temperatures exceeded 1400 °F. Inside the cask, where the spent fuel rods would be contained, temperatures were below 300 °F, not enough to melt the spent fuel rods. The cask in the fire was instrumented with numerous thermocouples, both inside and outside, to measure the thermal response of the cask.

The results of the Crash Test Program indicated that, during the 1970s, analytical and scale modeling techniques could predict vehicular and cask damage in extremely severe accident environments with reasonably good accuracy. In addition to the full-scale tests, Sandia also conducted scale model tests of some of those casks. The similarity in response was remarkable. The scale models do not have the same degree of complexity as the full-scale ones. However, the response was so similar, the staff had difficulty distinguishing which data came from the scale model test and which data came from the full-scale test.

The data collected on responsive transport systems and accident environments were valuable. They demonstrated that the casks are extremely rugged and capable of surviving very severe accidents with much higher velocities than the regulatory 30 mph impact velocity.

Additional information can be gleaned from these tests. The analytical computer software available today is much more robust and capable than it was in the 1970s when 2D final analysis and lump parameter models were used. Today, detailed 3D final element models are available that can model many of the components of the packages as well as the global response.

Some of the data from these tests could be used to benchmark present day codes. For example, the locomotive cask grade crossing test is a good candidate for such an effort. One of the difficulties though, is that in order to develop the detailed finite element models that are used today, the analyst needs detailed information, including the geometry, about the packages that were tested, or are being tested, and the target, or in this case the locomotive. Since those tests were done so long ago, Sandia cannot provide the material properties of the different materials that were involved in the impact test or the exact geometry of the cask. Analysts could use the drawings of the cask, which may still be on file at NRC since they were certified casks to obtain some of this information.

Even more problematic is identifying the properties of the locomotive. The quality assurance (QA) on locomotive design is probably not as stringent as the QA on cask design. Information about the exact geometry of the particular locomotive used in these tests may be very difficult to find. In addition, since the 1970s, data collection, instrumentation, and sensors have been tremendously improved. Tests performed today yield much more information than was possible in the 1970s.

In 1986, Sandia conducted, another extensive test program known as the defense high-level waste (DHLW) cask tests. This test program was designed primarily as a certification impact and puncture test sequence to provide test data on accelerations and strains which could then be compared to analytical data. Mr. Ammerman pointed out that this is the same kind of thing that Sandia is looking at today. Sandia did not conduct a fire test to define the damage state of the cask as input into the hypothetical fire analysis because it was a half-scale model. Half-scale fire tests do not work very well and so this package was to be certified in a fire environment by analyses only. Therefore, to perform that analysis, Sandia needed data on what the deformed shape of the package would be. The test sequence also included five 30-foot drops and two puncture spike tests.

Sandia staff used a substantial amount of instrumentation for the DHLW tests. Accelerometers on the cask varied from 6 to 15, depending on cask orientation. Strain gauges varied from 4 to 24. Staff replaced some of the closure bolts with bolts that had strain gauges mounted on the inside of them so that the bolts could act like load cells and measure the loads on the particular bolts. The side impact test did not have any strain gauge bolts and the end impact and corner impact tests had up to eight. In addition, staff used linear variable differential transducers to measure the displacement between the cask lid and the cask body to assess the accuracy of the analysis that predicted that there would be no deformation of closure.

Tests on the DHLW package were performed at -31 °C. This package is somewhat different than a spent fuel cask. The purpose of the DHLW package is to transport vitrified high-level waste logs. Therefore, the package is essentially a stainless steel canister filled with glass that contains high-level waste. Its unique design does not use an impact limiter around the end.

The results of the test sequence indicated that the package was leaktight after each test; closure deformations were very small. The closure deformation measured 0.004 inches. This measurement was a peak dynamic measurement taken during the test, the final closure measurement was smaller. At the end of the test, all the closure measurements were essentially a zero strain or zero deformation. The peak strain measured 0.0033 inches. Yield strain levels for stainless steel are about 0.0015 inches, so this value is barely above yield. Strains in the impact limiter are considerably higher than that. Peak acceleration measured 2200g on a half-scale, which equates to 1000g on a full-scale. The DHLW package is very stiff resulting in acceleration levels much higher than are typically seen in spent fuel casks.

This test series was very thorough and is a good example of the types of instrumentation information that can be obtained from a drop test. Recall that strain gauge data, accelerometer data, load cell data, and deformation data were acquired dynamically during the test. Any future testing, such as that proposed in the PPS, should include these types of instrumentation.

Mr. Ammerman stated that resurrecting any of the digital data that were obtained from the tests would be difficult since the tests were performed in 1986. Therefore, comparing these test results to new analysis results would not have the same fidelity as a comparison made using data from a test done today. However, analysis could compare the test results to modern analysis results with slightly lower fidelity than current test results.

Dr. Hornberger questioned why would it be difficult to resurrect the data. Mr. Ammerman stated that the data are archived on 9-track tape and that few 9-track tape readers are still available. Although an analyst could still retrieve the data, it would be difficult.

Another test sequence performed at Sandia was a full-scale test in the TRUPACT-II. Most of these tests were carried out in 1989, although some earlier ones were conducted in 1988. The TRUPACT-II package was certified by full-scale testing, therefore, the staff performed very little analysis in conjunction with the certification process. Multiple tests of each type were performed because the regulations require that packages be tested in the most damaging orientation. However, the most damaging orientation to one component of the package may not be the most damaging orientation to some other component. Thus, the staff conducted quite a few tests in this test sequence.

The test sequence used very little dynamic instrumentation because there was no need to compare test results to analysis results. Staff performed post-test leak checks and the package remained leaktight. The tests also used photometric coverage.

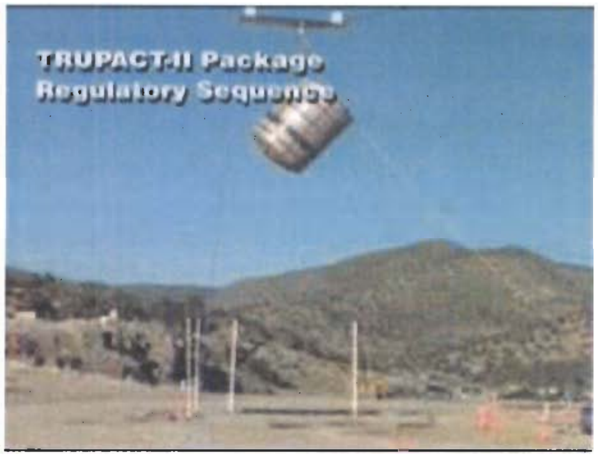

Figure 2 TRUPACT II Drop Test

Elevated temperatures were used for some of the tests on the TRUPACT-II. The package uses polyurethane foam as an impact-absorbing material which has significant temperature-dependent material properties. Sandia staff performed some of the package tests with the package hot and some with it cold. The TRUPACT-II package remained leaktight following all tests but the relatively flexible package experienced some visible deformations in impact limiter areas. The lack of instrumentation during the test sequence makes it difficult for analysts to compare test results to analyses. One can compare deformed shape but that information is not easily archived.

Staff performed a total of 14 drop tests on the TRUPACT-II using two different test units. The tests demonstrated the expense associated with relying on testing for certification. This is one of the main reasons why the package vendors typically use a combination of testing and analysis when seeking certification of a package design.

Cask vendors rely on analysis to some extent to demonstrate package response to the hypothetical accident tests. Even for the TRUPACT-II, which was certified primarily by tests, the vendor performed analyses to demonstrate compliance with some of the requirements of the 10 CFR Part 71. Other packages are certified without any testing.

Conservatisms introduced into analysis methods, or assumptions within those analysis methods for design certification, are not always applicable for test predictions. Typically, the design of a transportation package uses minimum material properties. The actual package tested will have material properties closer to the nominal material properties. Therefore, the behavior of the package will be different. When performing a test prediction, the analyst must know exactly the material properties of the test unit. Using standards, such as American Society of Mechanical Engineers (ASME) code properties, is not adequate for performing a pre-test prediction of the behavior of the package. The actual stress/strain curve of that particular package material must be known. Therefore, any detailed program, such as the PPS, should require actual coupon testing of the real material as used in the package, including the stress/strain curve.

Mr. Levenson questioned why all that detailed information is required if the purpose of the test is to demonstrate to the public that nothing happens to the cask. Mr. Ammerman responded that the risk analyses performed by Sandia, for example NUREG-6672, use computer analyses that demonstrate the response to the package to environments that have never been tested. In order to have confidence in those computer analyses, a pre-test prediction of the response of the package to an actual test is performed. In order to do a pre-test prediction, even to the regulatory test where there is very little plastic deformation, the material properties must be accurately known. If minimal properties are used in lieu of the actual material properties, the analysis will predict a different result than shown in the test. If the results are different, the public may not have confidence in the ability of the analysis to predict the actual test results.

Mr. Levenson noted that this would only make sense if the analysis had zero conservatism in it. If it does not have zero conservatism, the test is only going to confirm that it is conservative, but is not going to demonstrate how conservative. Mr. Levenson expressed concern whether this was acceptable for regulatory purposes. Mr. Ammerman stated that the certification process requires conservative analysis, however, when predicting test results, the analyst attempts to get the most accurate answer as opposed to a conservative answer. The PPS tests are not going to be used to certify a package. The tests will be used to demonstrate that the certification process is sufficient to demonstrate safety. The package vendors are responsible for demonstrating that the package used for the PPS meets regulatory requirements. The analyses that Sandia will perform as part of the PPS are not for package certification.

To develop structural models, Sandia uses transient dynamic finite element codes with explicit integration of the equations of motion. Such codes are called shock dynamic codes. The first code of this type was HONDO, which was developed at Sandia. The LLNL developed a follow-on code with more capability called DYNA. That particular code has been commercialized and is available to anybody in the commercial sector. PRONTO is another code developed at Sandia. Staff used this code to do the analyses found in NUREG-6672. The PRONTO code is export controlled and is not available commercially because of the very tight distribution requirements on it. The same analysts who developed PRONTO also developed ABAQUS/Explicit, which is commercially available. Just recently, Sandia developed a code called PRESTO which is the newest code in this family. PRESTO, unlike the previous codes, was written from the start for parallel analysis using parallel computers and is therefore more robust in that environment.

For thermal modeling analysis, Sandia uses both computation fluid dynamics codes and finite element codes to solve the fire dynamics and the heat transfer problems. CAFÉ, which stands for cast analysis in fire environments, was developed at Sandia to model large fires engulfing a package. CAFÉ is coupled to P/Thermal so that the CAFÉ part of the code models the fire environment. P/Thermal models the heat transfer within the cask. P/Thermal is a fine element code which is commercially available.

Sandia One-Dimensional Direct and Inverse Heat Transfer (SODDIT) is a code that is used when performing fire tests. Analysts cannot measure the incipient heat onto the package, that is, the number of kilowatts per square meter imparted to the package. No gauge measures that type of information. Therefore, the surface temperatures on the package are measured and a code like SODDIT is used to calculate the heat transfer rate to the surface of the package. As a one-dimensional code, SODDIT essentially assumes that the test unit has a spherical geometry. Consequently, this code has some limitations when applied to a cylindrical geometry.

Sandia developed COYOTE, a fine element code, to solve heat transfer problems.
It is a very robust code that can be used to solve a large class of problems. However, it is being phased out in favor of CALORE, which is the newest Sandia fine element heat transfer code. One of the advantages of CALORE is that it was developed in the same architecture as the impact code, PRESTO. These two codes talk to each other completely so an analysts can build a model in PRESTO, subject it to impact, take the deformed shape resulting from the impact calculations, and use CALORE to apply a fire environment to it.

How does Sandia confirm that these analysis codes are yielding the correct results? One method is code verification validation. Verification validation provides high confidence to the computational accuracy of simulations, demonstrating the predictive capability of the codes and their underlying models.

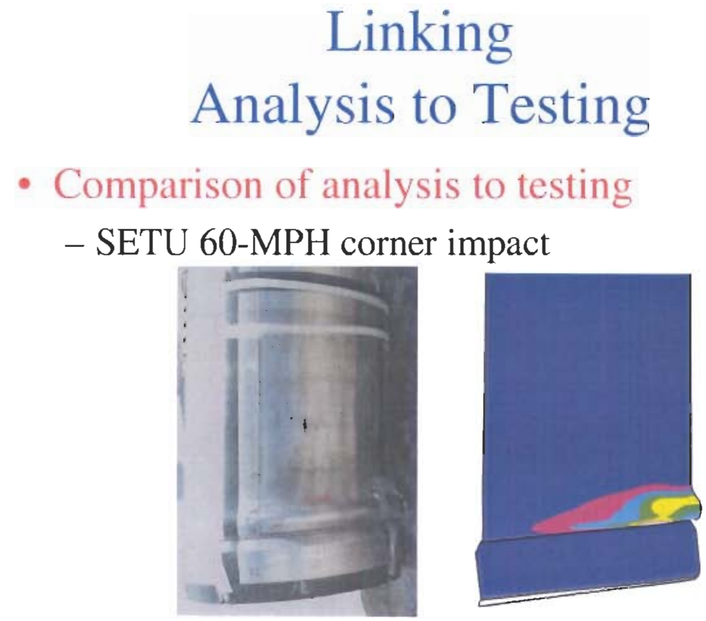

Figure 3

Verification is the process of determining that the code is correctly implementing the mathematical models that are used to describe the physical process. In other words, "Does the code solve 2+2 and get 4?"

Validation is the process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model applications. Validation makes use of physical data and results from previously validated computer models. The validation process tells the analyst that 2+2 is what he/she wants to solve, not 2x2. The combination of verification and validation tells the analyst that 2+2 and 2x2 yield the right answer which is 4. An analyst needs to do this over a broad range because 1x3 is not the same as 1+3. Validation not only makes use of physical data (e.g., comparing tests to analyses) but also makes code-to-code comparisons—does this code get the same answer as another code? The DHLW package tests are an example of where the analysis results and the test results agreed fairly well.

In conclusion, gaps in the information that Sandia has obtained in the testing and analysis of transportation packages still exist. Certification tests, for example, DHLW and TRUPACT-II, do not involve significant plastic deformation in the closure region. That was by design. Packages should not exhibit plastic deformation in their closure region during regulatory testing and analysis.

The SETU tests were not full-scale tests and did not involve the complete cask system. The test package had a bolted closure and a lead steel wall, but it did not have some of the other components that packages have. It did not have test parts, drain valves, or neutron shielding. The impact limiters were designed only for end impacts or nearly end impacts; the package did not didn't have a complete impact limiter system. That was done to aid the comparison of test and analysis results.

The Crash Test Program in the 1970s had little instrumentation to compare analysis results with test results and it also used cask designs that were obsolete at the time that they were tested, almost 30 years ago. Therefore, the tests do not accurately portray the packages being used today to transport spent fuel.

No data are available on surface heat flux incipient onto a rail cask-like object in a fully engulfing open pool fire. Tests have been performed with a calorimeter. A rail cask has a lot of mass and a high thermal capacity. Thermal mass affects the fire dynamics. Sandia does not have any data on how well an interaction between a massive, large cask and an engulfing fire can be modeled.

In addition, no data are available on the response of spent fuel to severe transportation environments, particularly on how a package would fail in accident environments. In its certification process, NRC usually assumes that under the hypothetical accident conditions 100 percent of the fuel has failed. This is why vendors typically design transportation packages to be leaktight to demonstrate that the package will not have a release of greater than A_2[6] per week.

There is also no demonstrated comparison between the analysis used in risk assessments (e.g., NUREG-6672) and full-scale, high-speed impact and fire tests. The PPS is aimed at addressing this information gap.

[6]See 10 CFR Part 71 for more information on A_2 quantities of radioactive materials.

2.2.2 TWG Questions Regarding Sandia Research

Dr. Wymer noted that no data existed on surface heat flux incipient on the rail cask-like object in an open pool fire. However, earlier in the presentation, Mr. Ammerman stated that a 1400 °F fire had resulted in a temperature of 300 °F inside the waste package. Mr. Ammerman further explained that Sandia collected temperature data during that particular test, but relating temperature to heat flux is not easy. That particular test package was tested with its rail car included, which severely affected the heat flux onto the package. In a real accident, the package would likely be in such a configuration. For most fires, the cask would remain on its conveyance. The conveyance provides thermal shielding and protects part of the package from the fire environment. In that particular case, a cage placed all the way around the package provided a great deal of protection to the cask. However, a test done using this configuration is not conservative, thus NRC does not do such a test in the certification process. Therefore, the plan for the PPS is to test the package without its conveyance so the impact involves only the package and not the package plus tractor trailer or the package plus rail car. The fire test will also involve a bare package sitting in the fire environment thereby simulating the scenario that the tie-downs had failed causing the package to come off of its conveyance mode.

Mr. Ammerman added that the same is true with the impact tests, such as the truck crash. The tractor absorbed some energy, and the front part of the trailer also absorbed some of the impact energy. By the time the cask actually hit the impacting surface, which was not a rigid surface, the cask was no longer traveling at its initial velocity of 60 mph for the first test or 84 mph for the second test; it had slowed down before impact. Those environments may or may not have been extra-regulatory.

Dr. Garrick questioned how the information obtained through the PPS will be used. He observed the crash tests performed at Sandia in the 1970s were very impressive as a demonstration of the safety of the transportation cask. Comparing those tests with other engineering issues that exist, and the gaps between demonstration tests and other engineering designs, [it appears that much less testing was done, and much less data were collected than has been analyzed for the analysis of transportation package safety]. Dr. Garrick thought the use of accelerometers, strain gauges, high-speed photography, and target instrumentation during the 1970s tests had been downplayed. He asked if these previous tests had been included in the models and risk studies that have been performed. Mr. Ammerman stated that the data have been used very little.

Dr. Garrick commented that it was remarkable that the past test results had not been used more and that he did not have a lot of confidence that a great deal of benefit would come from the PPS. He thought there must be a way of showing the separation between what is for the good of science and what is necessary to give the public high confidence in the safety of the cask. The PPS did not take any credit for energy absorption in anything except the cask itself. If meaningful analysis of energy absorption based on the 1970s tests were performed, additional information would be obtained on how the energy absorption is allocated in these kinds of events.

Dr. Garrick further stated that the TWG has many questions regarding the lack of use of historical information between the tests and the risk analyses. The risk analyses contained very little information on the uncertainties that are involved and do not really give an accountability of the issues that should be of concern to NRC. The risk is in the uncertainties, and yet, those assessments do not present the results with any kind of uncertainties associated with the critical parameters, except in the sampling process that was performed in the course of doing the analysis. A great deal needs to be done in terms of getting the right message out to the public, while allowing the science to move forward as necessary. Dr. Garrick noted his concern that the test data generated in the past have been buried and are not being used in the kinds of analyses that are presently being performed, particularly if the staff is committed to risk-informed decisionmaking.

Mr. Ammerman noted that the Sandia and NRC staff have struggled with the dual purposes of the PPS. On the one hand, it is a scientific study intended to address shortcomings in current understanding; on the other hand, it is also a program to demonstrate transportation safety. To what degree these two purposes can be joined together to come up with a single program that addresses both issues is a difficult struggle because, as Mr. Ammerman pointed out, sometimes what one side wants is counter to what the other side wants. He admitted that he was not certain if the currently proposed program achieves the correct balance which is one reason Sandia will conduct public meetings to discuss the test protocols.

Some members of the public will be more swayed by the safety demonstration issue than the science issue which might push the compromise more toward the safety side of the fence. However, Sandia is the organization who wrote the test protocols and has primarily a scientific interest and so the current plan is more focused on scientific analysis and answering the scientific questions.

Mr. Ammerman went on to say that if the scientific community as a whole is convinced that this program was conducted in a rigorous manner and, therefore, the results of it are correct, then these results could be applied to a risk study. This would provide credence to the fact that the risk study is also correct and would therefore remove one of the stages of doubt on the risk study.

Dr. Garrick noted that major breakthroughs were made in understanding reactor safety when the industry started looking at things like the likelihood of containment failure as a function of the capacity of the containment. Some very important discoveries were made that gave high assurance that at least some of these containments were over designed and conservative. He stated that NRC wants to regulate conservatively, but staff also wants to know what constitutes the baseline for conservatism. In the case of the containments, especially on the large, dry containments, the analysis and testing convincingly demonstrated that the capacities of the containments were anywhere from 1½ to 4 times their design basis. This is a reassuring piece of information that came out of a combination of tests and analysis and risk analysis.

Therefore, information regarding the likelihood of release as a function of impact force or energy absorption would provide important insights as to the containment capability of these packages. Dr. Garrick believes that, from a safety and risk perspective, these are the kinds of things upon which new analysis should focus.

Mr. Ammerman noted that one of the big differences between NUREG-6672 and prior risk studies was that the previous studies contained zero design margin. NUREG-6672 did not make that assumption.

Dr. Garrick noted that he would like to see a much stronger relationship between the tests and the analyses, and the nature of the analyses with risk and safety. Nothing makes the final connection to allow the analyst to determine whether one of these packages is going to break open and release large quantities of radioactive waste material

Mr. Levenson stated that he was having a problem separating out the certification testing and demonstration testing to assure the public and questioned why the staff proposed impact velocities up to 175 mph. Mr. Ammerman responded that there is definitely no need to go to impact velocities that are higher than the accident record. Sandia developed the initial plan for the PPS before the staff had reviewed the accident record. In developing this plan, the staff relied on the accident record as portrayed by the Modal Study which only had impact velocities of up to 150 mph. However, freight trains do not travel at 150 mph. Accidents may have occurred at this velocity but they would have involved passenger trains and not freight trains. The accident record does include impacts up to 90 mph for both truck and train collisions so it is difficult to draw the line for demonstration and safety purposes—perhaps a value somewhat less than that would be appropriate. The ability to determine whether our analytical capabilities are adequate to predict failure of various components may drive the test velocity to a higher value to demonstrate that the test confirms failure of a particular component and that its failure was correctly predicted. Mr. Levenson stated that he is more interested in the codes accurately predicting package response under realistic conditions than package failure under accident conditions that are beyond reality.

Mr. Levenson questioned whether it was significantly cheaper to extract the test data from the old tapes than to conduct a new series of tests. Mr. Ammerman stated that it would be significantly cheaper, however, Sandia could achieve a much higher level of confidence if it predicted a test result rather than match a test result. Mr. Levenson noted that, in this case, Sandia does not have the data yet, it can predict the outcome and then confirm it. In Sandia's DHLW test, the analytical results were generally conservative. Mr. Levenson questioned how much conservatism was used (a factor of 50 percent or 2 orders of magnitude).
Mr. Ammerman noted that the DHLW analysis results were conservative because the analysis results were not pre-test predictions. Minimum material properties were used in the analysis and the test unit had real material properties. Conservatism ranged from a factor of 1.2 up to perhaps a factor as high as 4.

Mr. Kobetz questioned the types of design margins and design characteristics (e.g., a stainless steel shell or a carbon steel shell, a bolted closure or a welded closure, and more than one sealed boundary). He asked how did the packages tested in the 1970s compared to today's packages. Mr. Ammerman stated that the packages were stainless steel casks with bolted closures, very similar in concept to the packages today. They were all designed for wet transport of fuel, in other words, fuel with cooling water in the cask cavity. In contrast, today's packages are designed to transport fuel dry with inert gas in the cavity. This is probably one of the biggest differences. In addition, the closures were not as robust as modern closures. Older cask designs typically had fewer closure bolts than the newer cask designs. The packages were tested with water, and the closures were not as robust as current package designs. Further, the design requirements were not as stringent as current requirements. The requirement was A_2 per week and in some of those tests there was actually some leakage of that water. There was a burp of the closure and a relatively small amount of cooling water was released. After the dynamic event was over, the closure returned to its initial position and the leakage stopped. This would probably not be acceptable today. Today's package closures are designed so that the dynamic impact on the lid does not completely relieve the pre-load that is in the closure bolts and, therefore, the package will not "burp."

Summary of Sandia National Laboratories Research

Presented at:

Advisory Committee on Nuclear Waste
Transportation Working Group Workshop

Doug Ammerman
Sandia National Laboratories
November 19, 2002

Outline

- Review Past Significant Test Programs at Sandia
  - 1970s Crash Test Program
  - Defense High Level Waste (DHLW) 1/2-Scale Cask Testing
  - TRUPACT-II Full-Scale Tests
- Analysis Methodology
  - Structural Modeling/Analysis Codes
  - Thermal Modeling/Analysis Codes
- Linking Analysis to Testing
  - Code Verification and Validation
  - Examples of Analysis vs. Testing
- Conclusions - Where are the Gaps?

Past Test Programs at Sandia

- Sandia has, since its beginning, been involved in systems level testing.
- Transportation package testing has been going on for over 30 years.
- Different test programs had different purposes and goals.
- The goals define the way the tests are conducted.

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1970s Crash Test Program

- Purpose
  - Assess and demonstrate the validity of analytical tools and scale modeling techniques for predicting damage in accident environments by comparing predicted results with actual test results
  - To gain quantitative knowledge regarding extreme accident environments by measuring the response of full scale hardware under actual crash conditions
- Approach
  - Mathematical analyses, scale model testing and full scale tests

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1970s Crash Test Program

- Extent of instrumentation on scale model and full scale hardware
  - Accelerometers – measure accelerations of the package and transport system
  - Strain gages – measure strains on various cask and transport system components
  - High-speed photography – record cask and transport system response

1970s Crash Test Program

- Truck cask impacted by a locomotive

1970s Crash Test Program

- 80 mph grade crossing impact
  - Truck cask impacted by a locomotive (SAND79-2291)
  - Utilized 18 high-speed (400-2500 fps) cameras
  - Seven strain gages on cask body
  - Four piezoresistive accelerometers
  - An accelerometer on the locomotive
  - Data was acquired via a telemetry system

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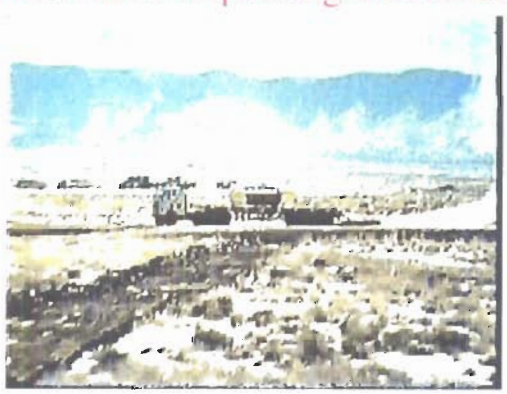
1970s Crash Test Program

- Truck with cask impacting a concrete barrier



Slide 8

1970s Crash Test Program

- 60 and 84 mph truck cask impact tests
  - Truck with cask impacting a concrete barrier (SAND77-0270)
  - Test was monitored with about 14 high speed cameras (framing rates between 400 and 3000 fps)
  - Five active accelerometers were placed on the cask body
  - Strain gages were placed on the cask head
  - Pressure transducers were placed inside the cask cavity

1970s Crash Test Program

- Rail car with cask impacting a concrete barrier

1970s Crash Test Program

- 80 mph impact of special railcar
  - Rail car with cask impacting a concrete barrier (SAND78-0458)
  - Monitored with numerous high-speed cameras (up to 3000 fps) placed above, on the sides, and at various angles
  - Active accelerometers were placed on the rail car frame, rail car cage cover, and on the cask, as well as on the target
  - Strain gages were installed on the railcar frame, the cask body, and on two fuel rods inside the cask

1970s Crash Test Program

- Rail car with cask in a fully engulfing fire

1970s Crash Test Program

- Rail car with cask in a fully engulfing fire
  - Instrumented with numerous thermocouples to measure thermal response of cask exterior and interior

1970s Crash Test Program

- Results
  - Indicated that current (at the time of the tests) analytical and scale modeling techniques could predict vehicular and cask damage in extremely severe accident environments with reasonably good accuracy
  - Much data was collected on response of transport systems in accident environments
  - Tests indicated that spent fuel casks are extremely rugged containers capable of surviving very severe accidents

1970s Crash Test Program

- Is there any additional information that can be gleaned from these tests?
  - The 3D finite analysis computer codes and computational hardware available today provide more detailed information about the response of packages and transport systems than the lumped parameter and 2D finite element models of the late 1970s. Some of this data could be used in benchmarking present day codes, for example, locomotive-cask impact test.
  - There have been tremendous improvements in data collection instrumentation and sensors since these tests were performed. Future full-scale tests would be better documented.

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DHLW Cask Tests (1986)

- Purpose
  - Certification impact and puncture test sequence
  - Provide test data on accelerations and strains to compare with analysis results
  - Define the damage state to use as an initial condition for the hypothetical fire analysis
  - Test sequence included 5 drops and 2 punctures

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DHLW Cask Tests

- Extent of instrumentation
  - Accelerometers - varied from 6 to 15, depending on test orientation
  - Strain gages - varied from 4 to 24, depending on test orientation
  - Strain gage bolts - varied from 0 to 8, depending on test orientation
  - LVDTs - varied from 0 to 6, depending on test orientation

DHLW Cask Tests

- End drop test at -31°C

DHLW Cask Tests

- Results
  - Package was leak-tight after each test
  - Closure deformations were very small (< 0.004 in)
  - Peak strain measured was 0.0033
  - Peak acceleration measured was 2200 Gs
  - Analysis results were generally conservative

DHLW Cask Tests

Is there any additional information that can be gleaned from these tests?

- This test series was very thorough and can be used as a demonstration of the types of information that can be obtained from a drop test.
- The tests were performed in 1986, and it would be difficult to resurrect any of the digital data from the tests.
- The test results could be compared to modern analysis results.

TRUPACT-II Full-Scale Tests (1989)

- Purpose
  - Certification test sequence - drop, puncture, fire
  - Multiple tests of each type performed
  - Package certified by full-scale testing

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TRUPACT-II Full-Scale Tests

- Extent of instrumentation
  - Very little dynamic data taken
  - Post-test leak checks were performed
  - Photometric coverage

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TRUPACT-II Full-Scale Tests

Regulatory test sequence was performed

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TRUPACT-II Full-Scale Tests

- Results
  - Package remained leak-tight following all tests
  - The relatively flexible package experienced visible deformations

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TRUPACT-II Full-Scale Tests

- Is there any additional information that can be gleaned from these tests?
  - The lack of instrumentation during this test sequence makes it difficult to compare the test results to analyses.
  - Extent of test sequence demonstrates the expense of relying on testing to demonstrate regulatory compliance.

Analysis Methodology

- Cask vendors rely on analyses to some extent to demonstrate package response to the hypothetical accident tests.
- Conservatisms introduced into analysis methods (or assumptions) for design certification are not always applicable for test predictions.

Structural Modeling/Analysis Codes

- Sandia uses transient dynamic finite element codes with explicit integration of the equations of motion.
  - **HONDO** - 1st code of this type, developed at Sandia
  - **DYNA** - developed at LLNL, available commercially
  - **PRONTO** - developed at Sandia
  - **ABAQUS/Explicit** - commercially available
  - **PRESTO** - Newest Sandia code in this family

Thermal Modeling/Analysis Codes

- Sandia uses CFD and finite element codes to solve fire dynamics and heat transfer problems.
  - **CAFE** - developed at Sandia; designed to model large fires engulfing a package, coupled to P/Thermal
  - **MSC P/Thermal** - commercially available, FE code used to solve heat transfer problems
  - **SODDIT** – a Sandia developed one-dimensional direct and inverse heat transfer code
  - **Vulcan** - CFD code developed at Sandia used to solve a broad range of fire problems
  - **COYOTE** - FE code developed at Sandia used to solve a broad range of heat transfer problems
  - **CALORE** - Newest Sandia FE heat transfer code

Linking Analysis to Testing

- Code verification and validation
  - Verification and validation provide high confidence in the computational accuracy of simulations, demonstrating the predictive capability of the codes and their underlying models.
  - Verification is the process of determining that a computational software implementation correctly represents a model of a physical process.
  - Validation is the process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model applications. Validation makes use of physical data and results from previously validated computer codes.

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Linking Analysis to Testing

- Comparison of analysis to testing
  - DHLW notched impact limiter

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Linking Analysis to Testing

- Comparison of analysis to testing
  - SETU 60-MPH corner impact

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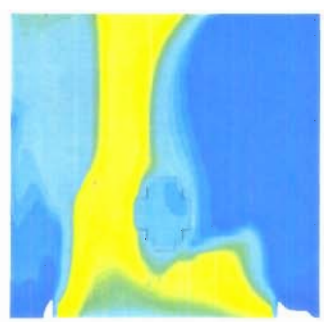
Linking Analysis to Testing

- Comparison of analysis to testing
  - Truck-Cask-Size Calorimeter



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Conclusions - Where are the Gaps?

- Certification tests (e.g. DHLW,TRUPACT-II) do not involve significant plastic deformation in the closure region.
- SETU tests were not full-scale and did not involve a complete cask system.
- Crash Test Program had little instrumentation to compare to analysis results and used casks that were obsolete in the 1970s.
- There is no data on surface heat flux incipient onto a rail-cask like object in an open pool fire.
- There is no data available on the response of spent fuel to severe transportation environments.
- There is no demonstrated comparison between the analyses used in risk assessments and full-scale high-speed-impact and fire tests.

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2.2.3 Summary of Lawrence Livermore National Laboratory Research on Transportation, Larry Fischer

In describing his work experience, Mr. Fischer noted that he worked for General Electric in 1979 as the manager responsible for the IF-300 transportation cask and helped to develop the consolidation report on the IF-300. He has been with LLNL for approximately the past 20 years, working primarily on NRC and DOE safety programs.

Mr. Fischer related that while working for LLNL, nuclear bomb testing was suspended in 1991. This meant that no more ground/underground testing would be performed. However, weapons still needed to be certified that they would work when required and not work at all other times.

The analysis had to be highly reliable. LLNL staff had to understand how the weapons worked and some of the physical basis. The staff relied on a science-based type technology in trying to understand the weapons in lieu of an actual test. Only component tests and subcritical tests could be performed.

In addition, aging problems with the weapons stockpile were occurring. LLNL developed a stockpile stewardship program which it used to certify that the weapons were operable. One of the cornerstones of this program was the development of high-speed computing, greatly expanded memory, and multi-scale, multi-physics computer modeling (Figure 4).

This is just one example of where LLNL is today. The LLNL ASCI White computer is a 14 TeraFlop computer. LLNL is in the process of building a 100 TeraFlop machine to perform full simulations of nuclear explosives and other types of things. LLNL can perform multi-scale, multi-physics analysis down to the nano-level. In fact, some analysis can be performed at the atomic level.

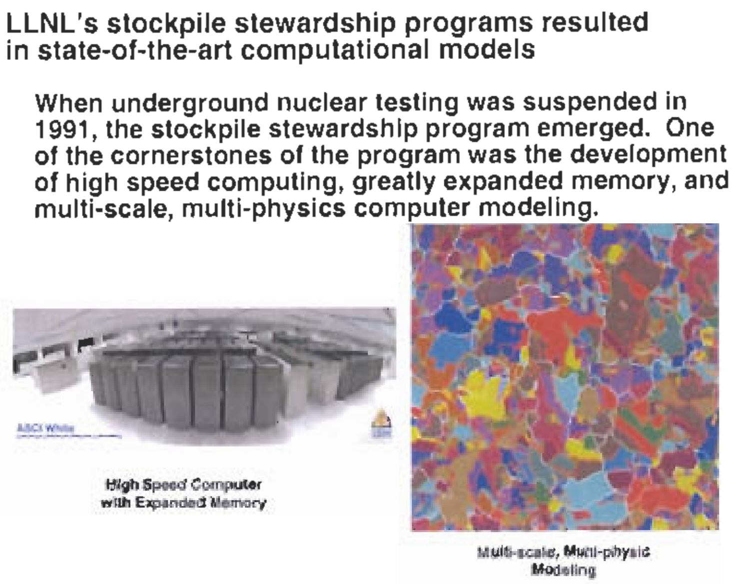


Figure 4

LLNL was involved in several transportation studies. First, there was the Modal Study in 1986/1987. The Shippingport reactor shipment followed in 1988 which was a DOE project. LLNL performed both testing and analysis for the plutonium air transport certification which involved very high velocity impacts. Lastly, on the other extreme, LLNL performed low-velocity impact testing and solid billets onto concrete pads for the spent fuel dry cask storage program.

LLNL came into existence 50 years ago and since then has been combining testing and analysis to evaluate and understand physical phenomena. In the late 1960s or early 1970s, LLNL developed computer codes for structural, thermal, and nuclear transport analysis. This was very similar to what Sandia did, although LLNL focused more on the nuclear transport analysis because of the weapons program. LLNL learned earlier that it had to combine tests and analysis to benchmark computer codes to evaluate system performance under postulated accidents, natural phenomena, and sabotage; if analysis was not performed, thousands of tests would have to be conducted for every situation. LLNL would benchmark its codes to find out how well they work and then apply them to a whole variety of situations and environments to determine how the codes would respond.

Massive parallel processing has been developed and LLNL has exploited it. In addition, the multi-physics modeling has further developed over the past 10 years which allows a number of things to be done now that could not be done in the past. This reduces the need for large-scale modeling and multiple tests.

1980s: Exploration of massively parallel processing has led to unprecedented simulation capabilities

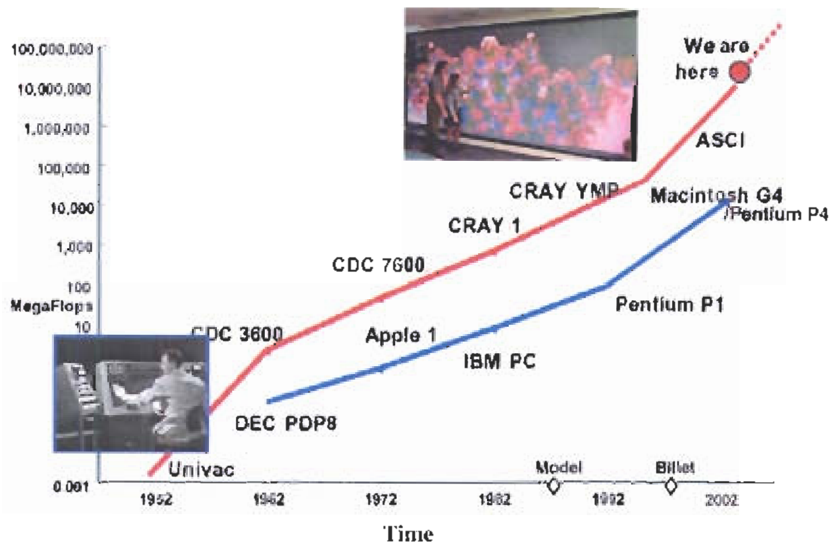


Figure 5

The computing world has exploded since 1952 when LLNL had a Univac which operated at 1000 Flops per second. This is an old tube-type machine. The CDC 3600 accounted for a great jump in speed between 1952 and 1972. Suddenly, speeds were now in the MegaFlops. Computers progressed to the point that they are now able to do multi-processing and massively parallel processing. Speeds are currently up around 14 TeraFlops with ASCI White which has been online for about 2 years. LLNL's 100 TeraFlop machine is currently under construction (Figure 5).

Also very important is the fact that desktop computers and workstations have greatly increased in speed. The Macintosh G4 and Pentium 4 processors are equivalent to the CRAY YMP of just a few years ago. Another jump will take place now that extreme ultraviolet light-lithography is coming online; this could result in a jump in speed by another factor of 3 to 10—maybe even a factor of 100.

While it is great to have all that capability, if no codes exist to use it then nothing happens. Therefore, LLNL has to improve its codes. LLNL started out with simple things like a paper-scaler type of setting using cards. LLNL then advanced into paper and teletype, and finally into microfiche. By this time, LLNL is getting into 2/3D type of codes. The codes were next used to produce graphics and then more improvements were made in the 2/3D code capabilities.

Finally, LLNL is now performing massive parallel 3D renderings and simulations. These codes have made great improvements in the materials modeling associated with the multi-physics, auto contact, and auto meshing.

The Modal Study was the first transportation study that LLNL performed for NRC. It was the first time that LLNL used quantitative computational modeling to analyze and evaluate responses of representative casks to severe accident conditions and to estimate the radiological releases. As discussed in Section 2.1 of this NUREG report, the overall objective of the Modal Study was to reexamine NUREG-0170. Stakeholders expressed concerns that NUREG-0170 did not look closely enough at spent fuel transportation. NUREG-0170 was not a quantitative analysis that tied the specific cask design to the estimated radiological release.

The Modal Study evaluated the safety of the cask provided under severe accident conditions. This included conditions that far exceeded the regulatory test conditions to demonstrate that a significant safety margin is built into the cask. Under regulatory conditions, the cask remains essentially in elastic mode.

LLNL staff understood that the cask had the capability for deformation under very high loadings, especially if using ductile materials such as 304 stainless or high-grade, small-grain steels. The cask could actually deform, store up a lot of energy, and not fracture or break. The cask had a "graceful failure" versus a catastrophic failure.

The CRAY 1 (1 GigaFlop) was used to perform the analysis. It was primarily a 1D and 2D analysis because the costs were very high and the time was limited. About 25 to 30 percent of the budget was spent just on computer time which was very expensive for those days.

One single 3D analysis was performed to demonstrate that the results of a 2D analysis were comparable and conservative. A problem that arose at that time was the lack of benchmark data for the code for a transportation cask. The code had been benchmarked for weapons components and closed form solutions, but a gap existed for cask performance.

When modeling a 90 mph impact of a lead-shielded cask onto an unyielding surface, the analysis identified lead slump. LLNL performed a 3D analysis of a truck cask, with an impact limiter installed, impacting at 90 mph to determine how the impact limiter interacted with the cask. The results for most of the deformation compared favorably with the results from the 2D model.

LLNL used the CRAY YMP for the Shippingport reactor vessel analysis in 1988. LLNL used computational analysis with scaled modeling to obtain certification for the Shippingport reactor package for shipment. This package was certified by DOE, not NRC. The Shippingport reactor had no fuel in it.

LLNL proceeded to incorporate the important features in a 1/10 scale model. The reactor vessel weighed 1000 tons. Using a larger scale model would have been advantageous, but it was not practical for a 1000-ton drop test. The analysis and scale testing were in fairly close agreement (30 percent), given that the size of the package and the instrumentation was state-of-the-art at that time.

Using the benchmarked DYNA code, which used the 1/10 scale data, the full reactor package was then analyzed in three different orientations, a bottom drop, a side drop, and a corner drop. The analysis confirmed that the package met the regulatory drop requirements with good safety margins (a factor of 1.5), thereby demonstrating that the package would not fail even when accounting for a 30 percent difference in the benchmarking.

The reactor vessel was over 40 feet long and about 18 feet in diameter. For shipping, a new lifting beam was fastened on top. Some of the insulation and vessel internals were filled with grout. All of these modifications were included in the finite element model.

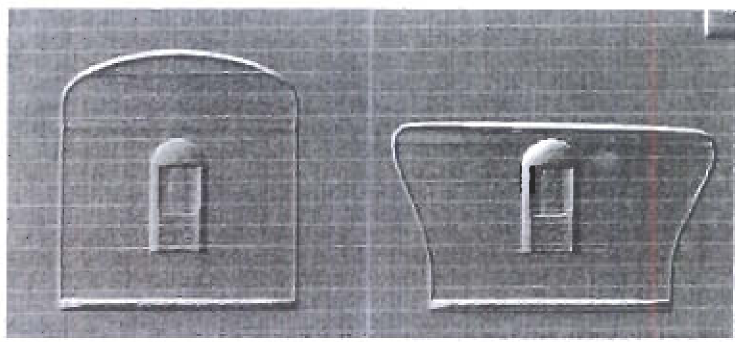
LLNL is having problems in retrieving these old data files. Unfortunately, the analysis was run on the YMP computer which is a classified computer. Currently, it is difficult to get unclassified data off of classified computers. LLNL is attempting to make some unclassified information available in the future.

LLNL also performed testing and analysis of the plutonium air transport certification. This analysis was performed on a Silicon Graphics workstation and, therefore, did not have the high cost or time constraints associated with running the analysis on a CRAY YMP. It did take longer to run the analysis on this machine, but it was a 200 MegaFlop-type machine with double precision. LLNL was able to complete all other computational analysis with this machine. The analysis used very high impact velocities of up to over 600 mph, or about 950 feet per second (ft/s).

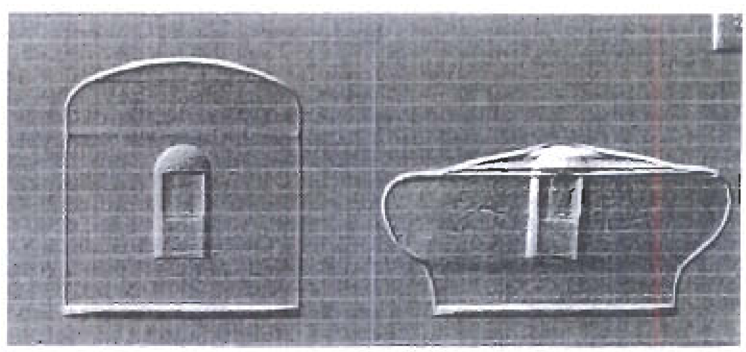
LLNL fabricated a 1/6 scale model to benchmark the code. Grout was used for the impact limiter because of the experience gained in the Shippingport package analysis. The grout was well characterized so LLNL felt comfortable using it as an impact limiter, rather than crushing it. The grout basically deforms and moves mass to the side. This is how the energy is absorbed.

Little aluminum balls were placed inside the package to obtain information on the peak g-force to which the package would be subjected. The tests were performed with impact velocities from about 17 to 157 meters per second (m/s) on an unyielding steel surface. Tests were also performed using a concrete surface at up to 208 m/s. (The 288 m/s value included on the presentation slide was an error.)

Figure 6 shows close agreement was obtained between the scale modeling and the computational analysis for impact limiter deformation. However, there always seemed to be a minor problem with correlating accelerometer test data with the analysis results; however, this problem has since been resolved.



Radiograph of test model after impact on steel plate at 167 m/s (516 ft/s)



Radiograph of test model after impact on grout block at 288 m/s (945 ft/s)

Figure 6

The scale model was shot out of a 6-inch Howitzer gun at the targets. LLNL had this Navy gun in its bunker.

The tests showed that at a velocity of 167 m/s onto an unyielding surface, the package contents got close to the end. The tests tried to determine what the equivalent velocity was for an unyielding surface versus a soft rock type surface such as grout. This test was performed at 288 m/s and the package did not quite hit the target straight on. One of the problems with shooting the model out of a gun is that it is difficult to get exact straight-on hits. The test radiographs showed good correlation of deformation with the computer analysis.

LLNL also performed billet testing for NRC. Again, this was performed on a Silicon Graphics workstation because of the cost consideration and the fact that it was conveniently available. This analysis primarily looked at dry storage cask tip-over accidents onto a concrete pad. The analysis showed that, when the accident occurs on an unyielding surface, an impact limiter should be used on top of the cask. This raises two problems; impact limiters are expensive and they are difficult to put on which could result in additional dose to workers.

For testing, a 1/3 scale model of the storage cask was used. It was just a steel billet and concrete pad reinforced with rebar. The pad, rocks, and sand were also all 1/3 scale to obtain a valid test.

Very precise, well-calibrated, accelerometers were used for the tests. It was also important to develop a methodology for determining the cutoff frequency. If the frequency were cut off too high, the g-forces would appear too high because not that much energy is really in the cask system. If the frequency were cut off too low, then deformation, or energy, would deposit into the cask and the decelerations would register too low. LLNL developed a methodology for determining the cutoff frequency by looking at the different modes. Based on this, LLNL determined that 450 Hertz was the correct frequency for the billet. This resulted in between a 1 to 15 percent agreement with the analysis.

This is significant with respect to the spent fuel basket because these forces, when transferred to the spent fuel basket, could buckle or bend the basket components, thereby affecting the spent fuel. Therefore, it was very important to know the exact g-forces that are being translated not only to the cask, but also to the spent fuel basket and to the fuel. A computational analysis was performed to benchmark the DYNA 3D code. LLNL achieved good to excellent agreement with the scale model testing.

Once the benchmarking was complete, a typical full-size cask tip over was analyzed without an impact limiter installed. The analysis determined that an impact limiter was not required to protect the cask from a tip-over accident.

Using similar analysis techniques, LLNL has performed a seismic analysis of Morrow Point Dam located about 250 miles southwest of Denver, Colorado. The analysis involved a 6.5 to 7.0 magnitude earthquake that may occur in Colorado approximately every 1000 years. The dam was constructed in segments. Its columns were poured and connected with interlocking pins. Similar to corrugated steel interlocked together. The dam was constructed in this manner for expansion and contraction between the summer and winter. On the back side of the dam, a very tough rubber sealer was installed to prevent water leakage during expansion and contraction.

The computer model used in this analysis included ground motion in the bottom of the dam, rather than to the ground, which caused the top of the dam to move much more than it should. This makes it a little more exciting and demonstrates the capabilities of these types of tools which can include the friction between the segments and slide lines as things move. The model even simulated the water sloshing.

Using models, LLNL can zero in on the high stress points and other places of concern for particular structures. Simulations of this type were used by the weapons program to identify potential problems. These models can be run on small clusters of desktop computers. Machines with TeraFlop speed do not have to be used for this type of analysis.

Dr. Garrick noted that one of the issues for the Yucca Mountain waste package is the heat treatment of the welds for the lids on the inner and outer waste package in terms of the possibility for stress corrosion cracking that could create a pathway to the fuel. He asked Mr. Fischer if this tool could better quantify the realism of such a potential pathway. Mr. Fischer responded that this type of analysis could be used and is being performed today.

In closing, Mr. Fischer made the following recommendations and conclusions. Finite element codes should be benchmarked against the test for recordings using at least 1/3 scale model, otherwise, too much detail is lost. However, a full-scale cask does not need to be used.

Impact and thermal simulations should be performed for full-size casks in all different orientations. This can be achieved using a scale model test and a high-speed computer with appropriate physics codes. Once sufficient data are obtained for all of the variables, package designers can benchmark their own finite element codes and perform analysis for their own packages. All of these simulations should be made available to the public for evaluation.

2.2.4 TWG Questions Regarding LLNL Transportation Research

Dr. Garrick noted that one of the most convincing pieces of evidence regarding the safety of nuclear materials shipments is nuclear weapon transportation experience. He questioned how much of that experience has been declassified. Mr. Fischer explained that the unclassified data on this subject could be obtained but they were not readily available.

Dr. Garrick remarked that the original test protocols for the PPS included some tests on the behavior of fuel elements to better understand the source term should the cask actually fail. He asked whether this type of testing could simulate the conditions inside the waste package, as well as the conditions having to do with deformation and penetration of the waste package. Mr. Fischer stated that it was possible. He explained that the capability now exists to model the cladding of the fuel and its response to corrosion, pinholes, etc. The physics and chemistry of stress corrosion cracking can be modeled at the nano-level. LLNL has a very large program reviewing stress corrosion cracking at Yucca Mountain under different conditions.

Dr. Hornberger commented that the presentation showed very impressive computational results. It appears that if full computation of a thermonuclear explosion can be performed, it would seem that a cask tip over should be able to be analyzed. Dr. Hornberger questioned if it would it be safe to infer from the presentation that the purpose for a test on a full-scale cask is simply demonstration and not necessarily technical. That is, can we learn everything we need from a 1/3 scale testing? Mr. Fischer responded yes.

Mr. Levenson questioned if it would be relatively easy to identify the appropriate loads to which the fuel would actually be subjected inside casks undergoing other kinds of tests. Mr. Fischer stated that it could be done. Through simulation, the analyst could determine what the loads were and then determine what would happen to the fuel rod given its condition.

Dr. Ryan questioned whether a sensitivity analysis and uncertainty analysis are routinely performed and Mr. Fischer responded yes.

Mr. Yaksh, NAC International (NAC), stated that the tip-over test was extremely important to the dry cask storage vendors. It prevented the vendors from having to perform very expensive soil testing, the results of which, he believes, really provide no additional assurance that the calculations were accurate or that the designs were robust.

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FESSP

Fission Energy and Systems Safety Program

Summary of Lawrence Livermore National Laboratory Research on Transportation

Presented to:
Advisory Committee on Nuclear Waste
Transportation Working Group

Larry Fischer
November 19, 2002

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48

Lawrence Livermore National Laboratory

Making History
Making a Difference

1952-2002

LLNL's stockpile stewardship programs resulted in state-of-the-art computational models

When underground nuclear testing was suspended in 1991, the stockpile stewardship program emerged. One of the cornerstones of the program was the development of high speed computing, greatly expanded memory, and multi-scale, multi-physics computer modeling.

High Speed Computer
with Expanded Memory

Multi-scale, Multi-physic
Modeling

2

Outline

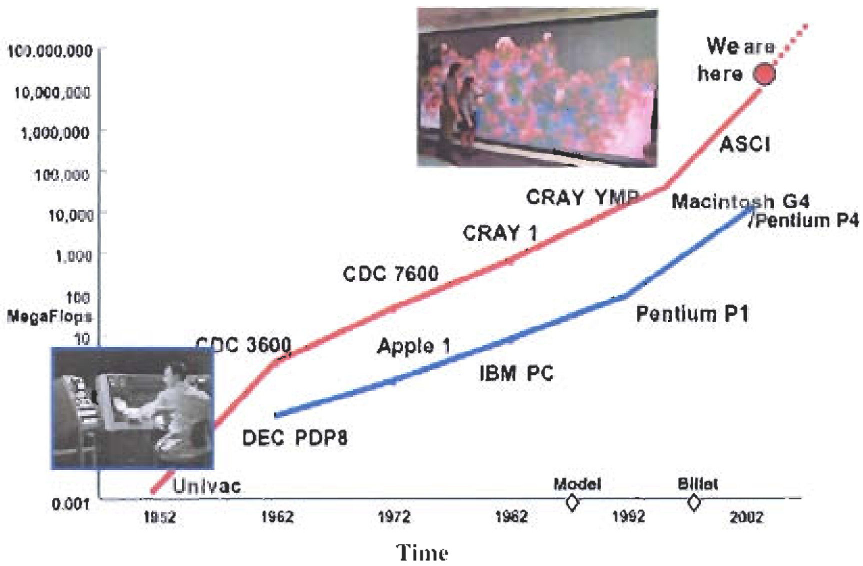
- Background
- Shipping container response to severe highway and railway accident conditions – (Modal Study) – 1986/1987
- Shippingport reactor shipment – 1988
- Plutonium Air Transport Certification (PATC) – 1992
- Low velocity impact tests of solid steel billet onto concrete pads – 1998
- Summary and conclusions

Background

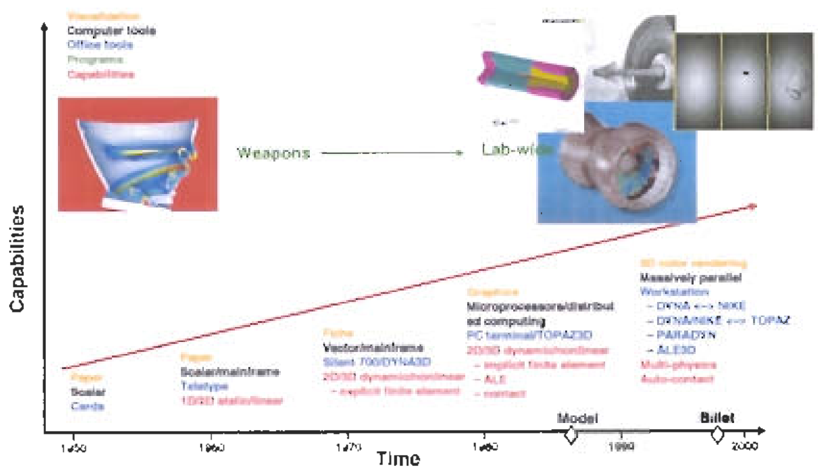
LLNL has used computational analysis combined with testing for over fifty years to evaluate and understand physical phenomena

- Developed in the late 1960's and early 1970's computer codes for structural, thermal, and nuclear transport analyses
- Combined test and analysis to benchmark computer codes in order to use to evaluate system performance, postulated accidents, natural phenomena, and sabotage
- Recent exploration of massively parallel processing and multi-scale, multi-physics modeling has led to unprecedented computer simulation capabilities and has reduced the need for large scale expensive testing

1980s: Exploration of massively parallel processing has led to unprecedented simulation capabilities



Computer code modeling and graphics capabilities also increased dramatically

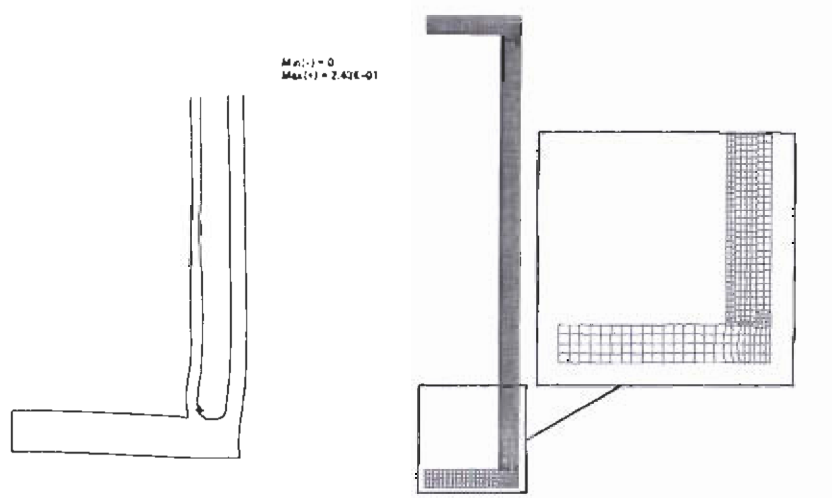


Modal study was performed in 1986 using the Cray 1

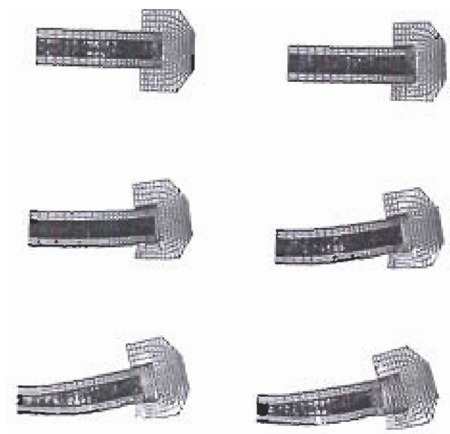
The Modal Study was performed for the NRC to evaluate the level of safety provided under severe accident conditions for spent fuel casks

- Used quantitative computational modeling and analysis to evaluate responses of representative casks to severe accident condition to estimate radiological releases
- Used Cray 1 machine (1 Gigaflop) to perform primarily 1D and 2D analyses and a single 3-D analysis to reduce computational time and costs. Most analysis were performed for unyielding surfaces (consistent with 10 CFR 71 requirements).
- Benchmark of computer codes were limited primarily to weapons components and closed form solutions

Rail cask finite element 2D model and strain results for cask impact at 90 mph



Truck cask finite element 3D model and deformation results for cask impact at 60 mph

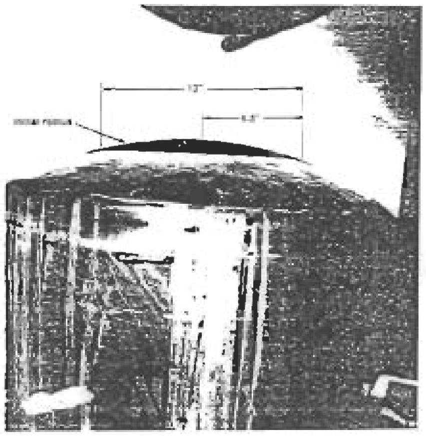


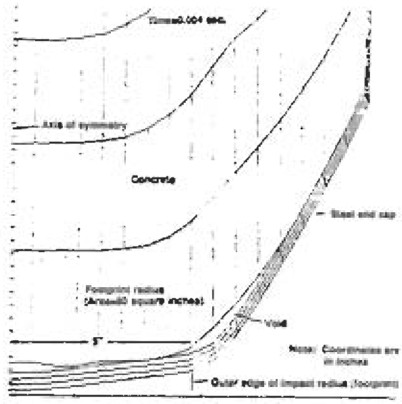
Shippingport analyses were performed with the Cray-YMP in 1988

Computational analysis with scale model testing was used to obtain certification of the Shippingport reactor package for shipment

- Important package features were included in 1/10 scale model for drop and puncture bar tests
- Fair agreement (~30%) was demonstrated between scale model testing and computational analysis
- Using the benchmarked Dyna 3D code, the reactor vessel package was shown to meet regulatory drop requirements with good safety margins

Shippingport forty-five foot drop test and analysis of 1/10 scale model





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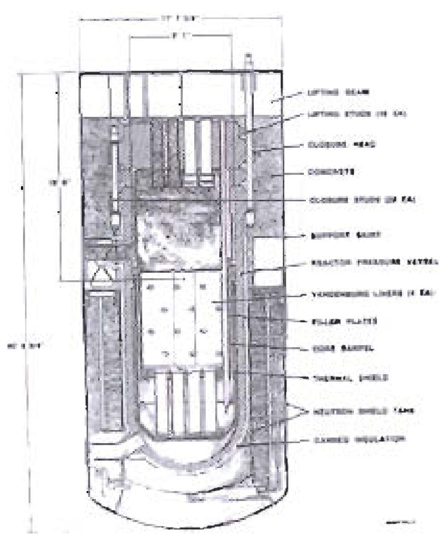
Shippingport reactor package



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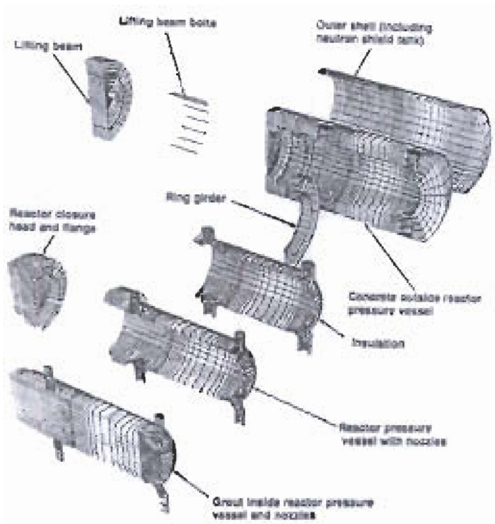
Shippingport Dyna 3D finite element model

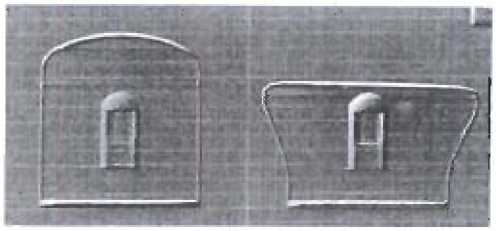


PATC tests – 1992 SGI workstation

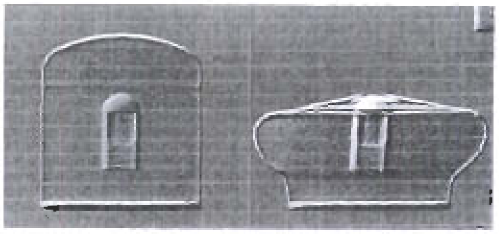
High velocity impact tests of a 1/6 scale air transport package were performed to benchmark a computer code to be used to evaluate impacts on real surfaces

- Package used grout as impact limiter material and a high strength containment system. An aluminum ball was used to measure peak g forces.
- The test impact velocities varied from 17 to 157 m/s on steel surface and 206-208 m/s on concrete surface
- Good agreement with impact limiter deformation was demonstrated between scale model testing and computational analysis

High velocity impact tests

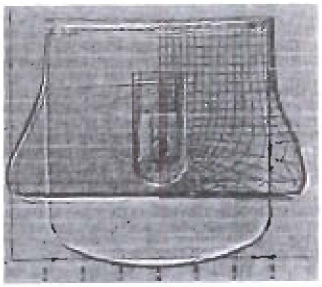


Radiograph of test model after impact on steel plate at 167 m/s (516 ft/s)

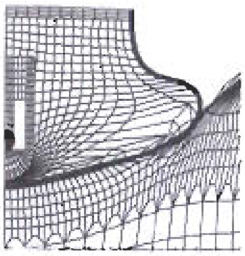


Radiograph of test model after impact on grout block at 288 m/s (945 ft/s)

High velocity impact tests (cont.)



Overlay of computer simulation on radiograph results of test package, impact on unyielding surface at 143.6 m/s



Simulated test package deformed shape with grout damage curve invoked, 288 m/s impact on soft rock

Billet testing performed in 1998 on an SGI workstation

Low velocity impact tests of a solid steel billet were performed to develop a method to use finite element analysis of storage cask drop and tipover onto a concrete pad.

- Impact onto an unyielding surface required the use of impact limiter on top of storage cask. Concrete can absorb energy and may eliminate need for impact limiter.
- Used 1/3 scale model of storage cask (steel billet) and reinforced-concrete pad.
- Used precision accelerometers and developed method for determining cut off frequency for them. Computational analysis was used to benchmark the Dyna 3D code.
- Good to excellent agreement was demonstrated between scale model testing and computational analysis.
- Using the benchmarked Dyna 3D code, a typical storage cask impacting concrete did not need an impact limiter to meet drop and tipover structural integrity requirements.

Billet testing

Maximum Billet End Drop Deceleration Test vs. Simulation

Test # / Channel #	Test data, filtered at 450 Hz	Finite element analysis simulation, filtered at 450 Hz
Test #1 / Channel A1	70.8 g	
Test #2 / Channel A1	78.7 g	
Test #1 / Channel A5	103.8 g	99.5g
Test #2 / Channel A5	88.0 g	

Maximum Billet Side Drop Deceleration Test vs. Simulation

Billet drop height / (Test #)	Test data from channel A3, filtered at 450 Hz	Finite element analysis simulation, filtered at 450 Hz
45.7 cm (18 inches) (Test #3)	108.2 g	
45.7 cm (18 inches) (Test #5)	86.0 g	135.0 g
45.7 cm (18 inches) (Test #10)	125.5 g	
91.4 cm (36 inches) (Test #4)	110.0 g	
91.4 cm (36 inches) (Test #7)	not available	142.7 g
91.4 cm (36 inches) (Test #9)	125.2 g	
1.83 m (72 inches) (Test #6)	206.7	
1.83 m (72 inches) (Test #8)	197.0	[illegible] g

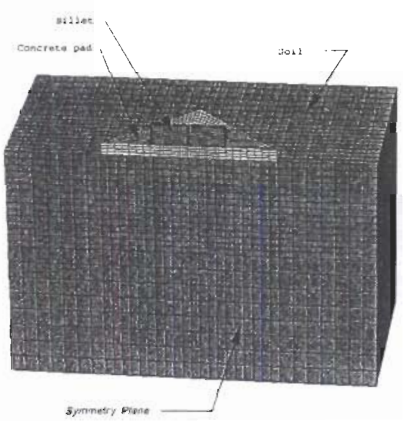
Billet testing (cont.)

Maximum Billet Tipover Deceleration Test vs. Simulation

Test # / Channel #	Test data, filtered at 450 Hz	Finite element analysis simulation, filtered at 450 Hz
Test #11/ Channel A1	237.5 g	244.7 g
Test #12 / Channel A1	213.6 g	
Test #11 / Channel A5	231.5 g	
Test #12 / Channel A5	213.0 g	

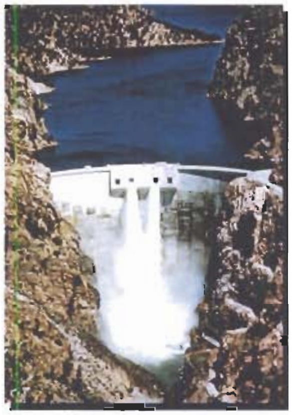
Billet tipover test and finite element model of test

Billet Tipover Test



Finite Element Model

Seismic analysis of Morrow Point Dam



Charles R. Noble

QuickTime™ and a Cinepak decompressor are needed to see this picture.

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Today's analytical capabilities allow more comprehensive analyses of shipping packages

To understand the package design margin, additional analyses are needed

- Residual stresses are created during cask fabrication
  - Metal bending
  - Machining
  - Welding
  - Lead/depleted uranium pouring
  - Annealing
- Detailed analysis of bolted closures requires large, complex computer models
- Contemporary high speed computers allow many analyses of a shipping package
- State of the art visualization tools allow engineers and members of the public to understand computer simulations

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Recommendations

- Perform drop and thermal tests on a typical transportation cask per 10 CFR 71 hypothetical accident requirements
- Use state of the art instrumentation to record cask response, particularly in the closure and weld regions
- Benchmark at least one finite element code against the tests recordings
- Drop and thermal testing can use scaled cask models of at least 1/3 scale
- Perform drop and thermal testing simulations for full size cask
- Use high speed advanced computer system and physics codes for analyses
- Provide methodology and data such that applicants can benchmark their own finite element codes and perform analyses for their casks

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2.3 Public Comments on Transportation Research

Mr. Resnikoff questioned whether fuel cladding that had been irradiated to the levels to which fuel is going to be irradiated, about 45,000 megawatt days per metric ton, has been tested to determine its various physical properties. Mr. Fischer responded that quite a number of tests had been performed for the certification of the IF-300 spent fuel transportation package which are documented in its safety analysis report.

Mr. Resnikoff noted that he was involved with the advisory panel of the 1980 TRUE study regarding the transportation of radionuclides through urban environments. He questioned whether a similar advisory panel would be used for the proposed PPS test protocols. Mr. Brach responded that the staff has used a public participatory process from the very outset of the study. Moving into the next phase, the staff will be providing stakeholders the draft test plan for review and comment. Following that, the staff plans to allow public observation of the tests. Once the test results have been obtained, the staff will make the test results available to all stakeholders and solicit feedback. Mr. Resnikoff stated that while this process was good, he did not think it was as good as an advisory panel.

Ms. Gue from Public Citizen commented that the Sandia full-scale tests in the 1970s did not fully acknowledge an element of the public concern. Using an analogy, if a member of the auto industry were to present a new car design for certification based only on analytical models of crash testing, confirmed through physical tests on obsolete models 3 decades ago, the design would certainly not meet with regulatory approval, much less be worthy of public confidence. Ms. Gue believes it is critical to have those tests from the 1970s updated through the PPS and hopes that NRC will make it clear in its presentation of the PPS that it has limitations—that it is simply a one-time confirmatory test.

Ms. Gue made a second point. If the PPS is limited to being a one-time confirmatory test, Public Citizen would be happy if the TWG would recommend that the PPS consider a test to destruction. For example, while the 90-minute fire test at the regulatory temperature is three times longer than the regulatory requirements, it is still much shorter than some actual fires that have already occurred in the transit of materials on the roads. She did not believe that this situation was highly improbable because unlikely accidents do happen on the roads and rails. Ms. Gue pointed out that if that unlikely accident were to happen and result in a catastrophe in her neighborhood, she would not find it comforting to know that it was unlikely to have happened. Given the large and unprecedented scale of transportation of waste spent fuel and high-level waste that is being contemplated to Yucca Mountain, the test to destruction is, more than ever, necessary.

Finally, Ms. Gue noted the amount of discussion held about the need for extra regulatory tests to determine the performance of casks beyond the requirements in the regulations. Widespread acknowledgment seems to exist that the regulatory parameters drastically underestimate the accident conditions on today's roads and rails. Once again, Public Citizen would be happy if the TWG would go beyond simply acknowledging this in the context of one-time extra regulatory tests, and recommend a rulemaking to update the routine requirements for cask certification to more realistically take into account accident conditions by requiring hotter and longer fire conditions and a more realistic submersion test.

Mr. Fischer responded that Ms. Gue raised some good questions. Certainly, some tests should be performed on newer cask designs. If a cask has a unique feature, different from the one that is actually tested (e.g., a new impact limiter design), the applicant should run some tests. However, complete testing of the entire package is not required.

With regard to testing to destruction, Mr. Fischer commented that the Modal study found that, due to the use of ductile materials, catastrophic failures are not expected to occur. Packages are designed under regulation to fail gracefully. The current regulation essentially requires zero release, which is very simple to measure. Mr. Fischer believes that it is better to concentrate on the fact that 99.9 percent of the accidents all fall within zero release and that the risk studies have shown that other accidents result in releases that are quite small.

Ms. Gue stated that graceful or not graceful, information about the failure points of these canisters is going to be critically important for public safety, not to mention public confidence.

Mr. Brach commented that Public Citizen has been involved in just about all of the staff's meetings on the PPS. Based on all of the modeling and analysis and scale model testing to date, the staff is confident that the test standards that are currently in 10 CFR Part 71 provide for an adequate level of safety and protection of material in transport. The confirmatory nature of these tests is to provide information with respect to the predictability of much of the modeling and simulation used by the staff. The staff's eyes are, and must be, wide open, so that based on the results of the tests NRC will be in a position to respond to whatever information is developed. With regard to carrying out these extra regulatory tests, NRC is trying to develop a concept to allow the confirmation and the information learned from the tests to be used to determine whether the modeling and the computer simulation techniques that are broadly used, not just used on one individual cask design, but are broadly used, are applicable to almost all cask designs.

Lastly, the staff has worked with DOT and the NTSB, as well as the National Institute of Standards and Technology (NIST), with regard to the review and analysis of the Baltimore Tunnel fire (discussed in Section 2.5.1, of this NUREG-series report).

Mr. Resnikoff requested that NRC release the report that NIST has prepared regarding the Baltimore Tunnel fire and that the ACNW review it. It is Mr. Resnikoff's understanding that NIST produced a report of which NRC was critical, and NRC, in turn, contracted with Southwest Research Institute to perform another study on the temperature of the Baltimore Tunnel fire. Mr. Brach stated that the results of the staff's review will be made public. NRC has engaged NIST, as well as the Center for Nuclear Waste Regulatory Analyses in San Antonio, Texas, to assist the staff in the review. Currently, NRC is not in a position to discuss the preliminary information referenced.

2.4 Transportation Package Vendor Presentations

2.4.1 Design Attributes and Structural Characteristics of the HI-STAR Transportation Package, Mr. Kris Singh, President, Holtec International

Mr. Singh, President, Holtec International, stated that Holtec's transportation package is designated the HI-STAR. HI-STAR is a dual purpose cask certified for storage and transport which consists of six components. The cask has two impact limiters, one at each extremity, designed to limit the maximum g-load (deceleration) that the package will sustain if it is dropped from a height of 9 meters in accordance with 10 CFR Part 71. When transported, the HI-STAR requires a transport cradle, rail car, and personnel barrier, which is strictly a non-structural barrier, to prevent people, insects, and animals from getting too close to the cask.

The design mission of the cask is to provide a virtually impregnable physical barrier to protect the multi-purpose canister (MPC). It is also designed to be transported on a rail car at temperatures as low as -40 °F. It can be used as a dry cask storage system and can be anchored to a pad in high seismic areas, although its most common deployment is free-standing.

The weight of the cask must be kept under 125 tons. The weight is directly related to shielding capability, as well as to how much material is required to build the structural rigidity in this structure. Therefore weight, although it sounds like an innocuous number, provides a great challenge to a designer.

The most vulnerable region of the cask is the central region. This region, contains layered shells to keep any fracture from propagating. The cask essentially is protected from the wide variety of loads that can be envisioned after the September 11th terrorist attacks. It will not only withstand a fall, but it will also withstand localized impact loads.

The impact limiter is made of aluminum so it will be resistant to fire, and it will not change its property depending on humidity and temperature. If it were made of wood, there would be a concern about humidity dependence for properties. The impact limiter shell is made of stainless steel; inside is aluminum compressible material. It is a honeycomb material that is made to deform easily at low loads and will actually provide a plastic kind of response under a contact load.

The cradle retains the cask to the rail car to keep the center of gravity of the cask as low as possible and to provide for very high axial load bearing capability. The cradle is extremely energy absorbent.

Holtec analyzed a General Electric engine from a Boeing 767, weighing 13,000 pounds, impacting the center of the cask, which is the most vulnerable region, with a force of 500 mph (Figure 7). The object of the study was to determine whether the cask would separate from the cradle. This model is limited in the sense that the cask can separate

Figure 7

from the rail car, but there was no deformation to the cask. The package remains with the vehicle during rollover for a specified impact angle, which in this case was 30 degrees from the horizontal.

Holtec has performed a 3D analysis of the package, with the impact limiter; the cask, represented by thousands of finite elements, as is the impact limiter, and the MPC inside it, to characterize the deflection response of the cask and the actual deformation of the cask under the impact load. The analysis found that if the same engine were to impact the package at 500 mph, the MPC would not not be affected at all; the cask would withstand the entire impact.

In closing, Holtec believes it is important that vendors interact with the laboratories because of their larger computing capabilities.

DESIGN ATTRIBUTES AND STRUCTURAL CHARACTERISTICS OF THE HI-STAR TRANSPORT PACKAGE

by
Dr. K.P. Singh
President and CEO
Holtec International
555 Lincoln Drive West
Marlton, NJ 08053

HOLTEC INTERNATIONAL

A presentation to Advisory Council on Nuclear Waste
White Flint, MD
November 19, 2002

Components of the Transport Package

1. The HI-STAR dual purpose overpack
2. The Multi-purpose canister (MPC)
3. A set of two impact limiters
4. Transport cradle
5. Rail car
6. Personnel barrier (non-structural)

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2

The HI-STAR Dual Purpose Overpack

- Storage (10 CFR 72) docket No.: 72-1008
- Transport (10 CFR 71) docket No.: 71-9261

Performance Mission:

- Provide a virtually impregnable physical barrier to protect the stored MPC.
- Ready to transport on railcar at as low as -40°F ambient temperature.
- Capable of being stored on an ISFSI pad free-standing or anchored.
- Gross Weight ≤ 125 tons.

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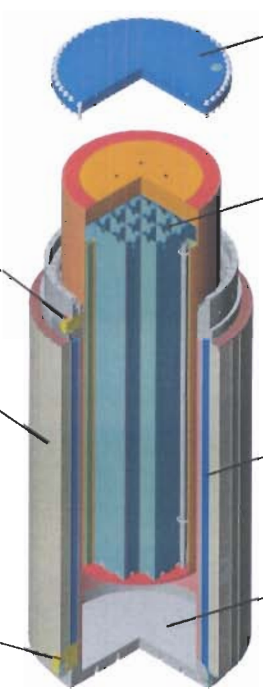
3

HI-STAR 100 Overpack with MPC Partially Inserted



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HI-STAR Design Features

Diameter:

- Bottom (footprint) - 83 1/4 inches
- Top (top lid) - 77 3/8 inches
- Mid-height - 96 inches

Weight:

- Empty - 154,000 lbs
- loaded w/MPC-32 - 243,000 lbs

Height: - 203 1/4 inches

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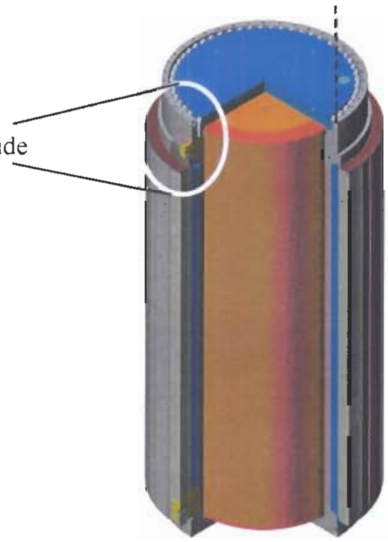
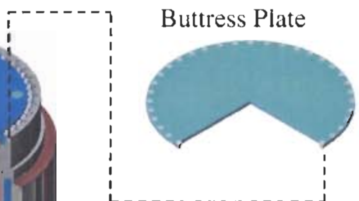
Design Features to Protect Against Accidents





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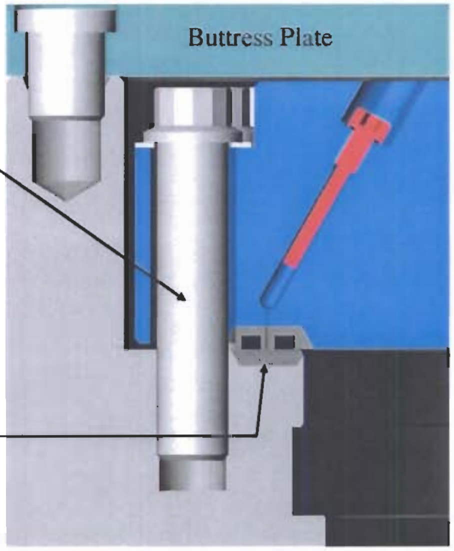
6

Design Features to Protect Against Accidents

- Lid bolts are protected against lateral impact
- Dual gasket closure



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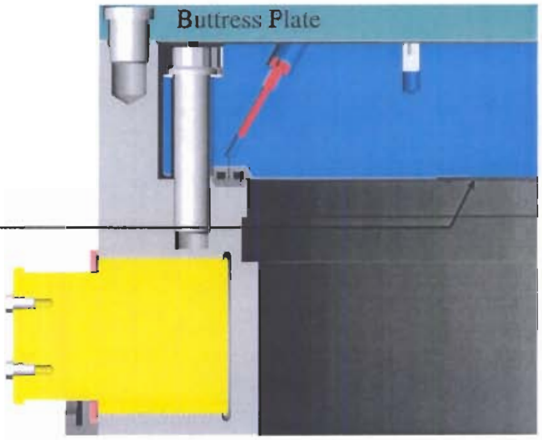
Design Features to Protect Against Accidents

- Top Lid Recessed to mitigate effect of a massive impact.



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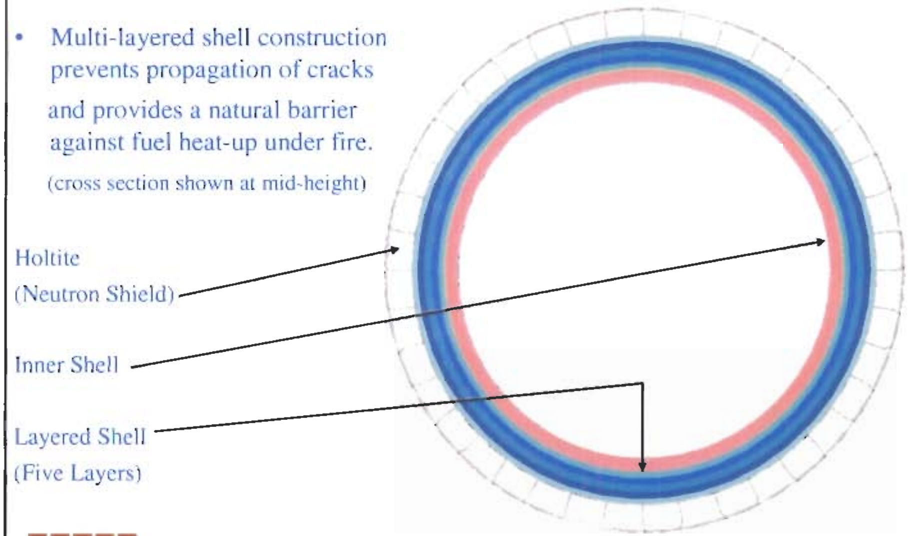
Design Features to Protect Against Accidents

- Multi-layered shell construction prevents propagation of cracks and provides a natural barrier against fuel heat-up under fire.

(cross section shown at mid-height)



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HI-STAR Materials

Part	Material	Thickness
Bottom forging	Ni - steel	6 inches
Top lid	Ni - steel	6 inches
Containment (inner-most shell)	Ni - steel	2.5 inches
Gamma shells (4 total)	Carbon steel	1 1/4 inches each
Outer shell	Carbon steel	1 inch

All HI-STAR load bearing materials qualified to remain fracture resistant @ < 40°F

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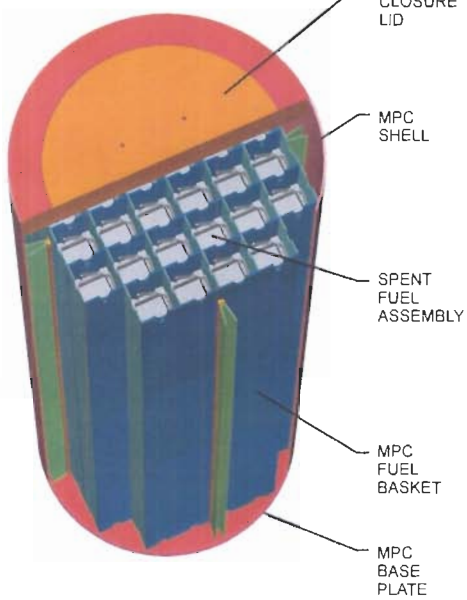
10

MPC-32 with SNF

• The fuel is protected by the MPC enclosure vessel; the MPC is protected by the HI-STAR overpack.

• The MPC Enclosure Vessel is an all-welded, stainless steel pressure vessel.



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MPC-32 Basket

•The fuel basket, an egg-crate of stainless steel plates, orthogonally arrayed and full-length welds at all plate-to-plate intersections.

•The fuel basket is engineered to withstand impact freefall without exceeding ASME code stress limits.

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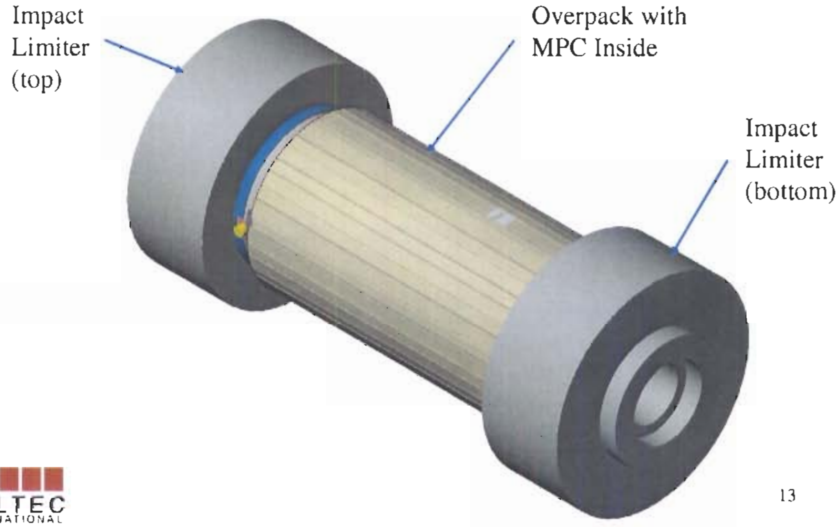
HOLTEC Patent Nos. 5,898,747 and 6,064,710

HI-STAR Package with Impact Limiters Installed



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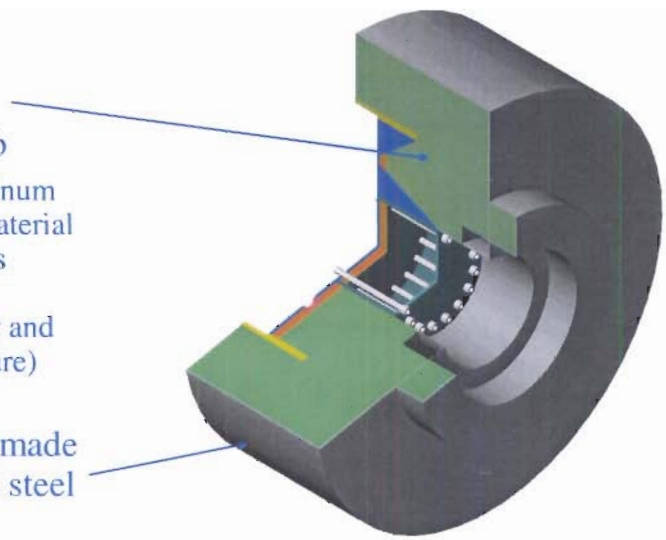
Impact Limiter Design Features

- Made of aluminum honeycomb
  - All-aluminum impact material eliminates weather (humidity and temperature) concerns
- Outer skin made of stainless steel



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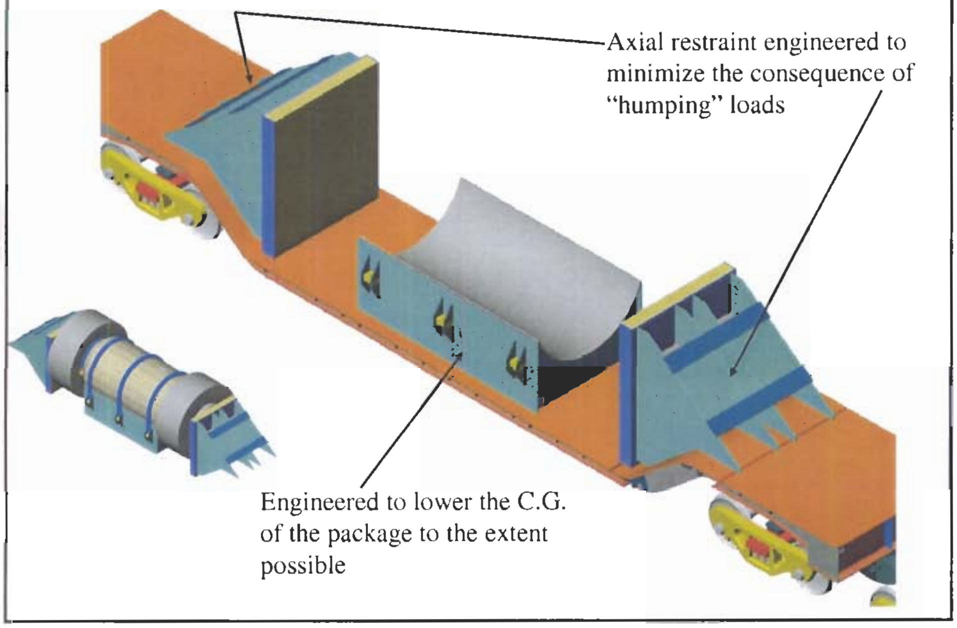
HI-STAR 100 Transport Cradle



The HI-STAR Transport Package (shown without Personnel Barrier)

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Availability & Use

Thus far, eight HI-STARs have been manufactured.

- 4 HI-STAR 100 casks are in use to store MPC-68 (BWR) fuel at Exelon's Dresden Station.
- 3 HI-STAR 100 casks are in similar use at Southern Nuclear's Plant Hatch.
- 1 HI-STAR 100 overpack was built as a full size prototype; similar in all respects to its production unit, available from Exelon for testing purposes.

Exelon Executive responsible for the sale of HI-STAR is V.P. Kevin Yessian (630-657-3650, kevin.yessian@exeloncorp.com)

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GLOBAL DYNAMIC MODEL OF IMPACT

- TRANSPORT PACKAGE, SUPPORTS, RAIL CAR, IMPACTOR SIMULATED FOR DYNAMIC ANALYSIS.
- IMPACTOR - 767 ENGINE AT 500 OR 250 MPH AT 30 DEGREE ANGLE WITH HORIZONTAL; ENGINE WEIGHT = 13,000 LB.
- TARGET – TOTAL ROLLING WEIGHT ON RAILS ~ 475,500 LB.
- ASSUMPTIONS:
  - PACKAGE; RR CAR (with package support saddles,trucks); ENGINE SIMULATED AS 3 RIGID BODIES
  - DAMAGE AT IMPACT LOCATION SIMULATED BY "COEFFICIENT OF RESTITUTION" (COR) – KINETIC ENERGY TRANSFERRED TO PACKAGE (COR = 0.25 OR 0.0).
  - COEFFICIENT OF FRICTION =0.5 SPECIFIED AT WHEEL/GROUND OR WHEEL/RAIL INTERFACE
  - PACKAGE HELD TO RR CAR SUPPORTS ONLY BY FRICTION FORCES; PACKAGE TIE-DOWNS CONSERVATIVELY NEGLECTED.
- OBJECTIVE: DOES THE PACKAGE REMAIN WITH THE RAIL CAR??
- NEXT SLIDES SHOW MODEL AND TWO "MOVIES" CONSTRUCTED DIRECTLY FROM RESULTS OF SLIGHTLY DIFFERENT DYNAMIC SIMULATIONS.

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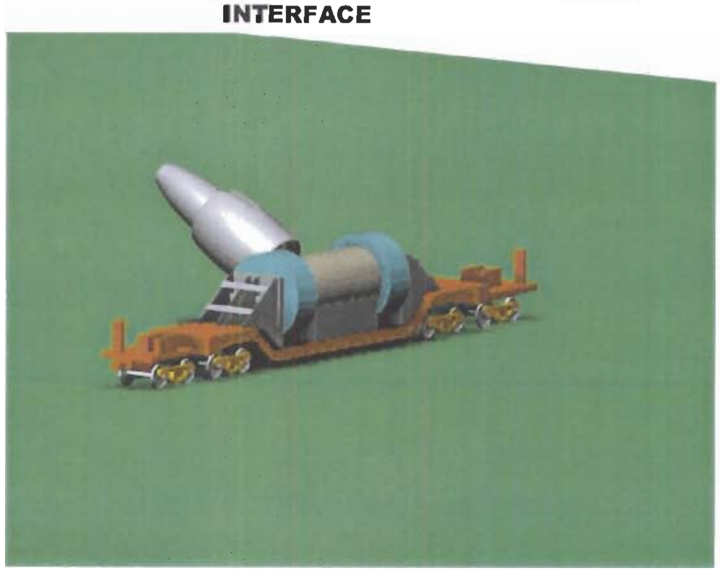
RAIL NOT INCLUDED - IMPACT SPEED 500 MPH; COR=0.25 AT IMPACT LOCATION; COF =0.5 AT WHEEL/GROUND INTERFACE



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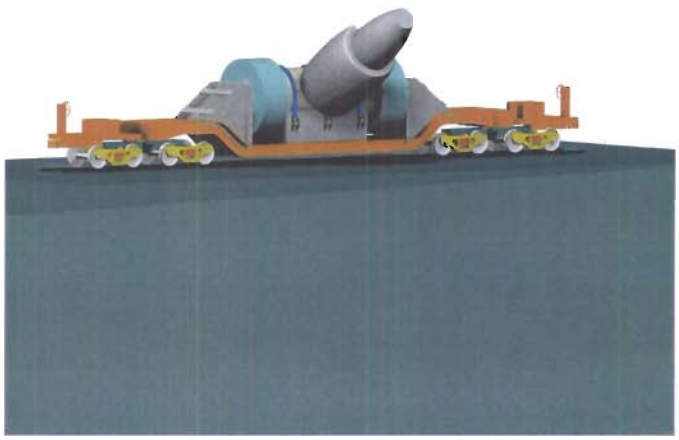
20

RAIL INCLUDED, 250 MPH SPEED; COR=0.0 AT IMPACT LOCATION; COF=0.5 AT WHEEL/RAIL INTERFACE -TIE DOWNS INCLUDED BUT DEACTIVATED



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Post Impact Responses

- Package remains with vehicle during rollover for specified engine impact angle, speeds, and "cor" values.
- Adding different contact algorithms, adding interfaces (Engine/Package, Car Body/Trucks, Wheel/Rail, Rail/Ground), and separating connected rigid bodies, would permit simulation of local energy absorption without significantly adding to simulation times.
- Companion LS-DYNA3D model of complete system(engine is approximated) has been developed to include local deformation.

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2.4.2 Analysis and Testing Associated with Spent Fuel Transportation Casks, Peter Shih, Transnuclear, Inc.

Mr. Shih noted that his presentation would cover the U.S. design criteria for spent fuel transportation casks based on 10 CFR Part 71. In addition, the presentation would cover the European design criteria based on International Atomic Energy Agency (IAEA) standards because some of the casks designed by Transnuclear and certified in the United States, are also designed to meet the IAEA requirements. Transnuclear has over 30 years experience in design, analysis, testing, fabrication, certification, and operation of packages, for both storage and shipping of spent fuel, radioactive waste, and other radioactive material.

In the United States, the design basis of the transportation package is based on 10 CFR Part 71 which specifies all of the design requirements, including the normal conditions for transport and the hypothetical accident conditions. Regulatory Guide (RG) 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels," describes the structure design criteria for the transport cask containment boundary. RG 7.8, "Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material," summarizes the required load combinations. ASME code, Section III, Subsection NB and Subsection WB, are used for design, fabrication, inspection, and testing of the transportation package containment boundary. Subsection NG is used for the design, fabrication, testing, and inspection of the basket that holds the spent fuel assemblies inside the package.

In Europe, most countries use the guideline specified by the IAEA for the design of transportation packages. The ASME code is also used, as applicable, for inspection and fabrication. In addition, when designing a transportation package for use in Europe, special attention must be given to the outside diameter cask.

Transnuclear uses the ANSYS finite element model for both structural and thermal analysis. In addition, some calculations are performed in accordance with the guidelines in NUREG-6007, "Stress Analysis of Closure Bolts for Shipping Casks," for lid bolt analysis; COCASE N-284 is used for the buckling analysis. Transnuclear uses KENO-Va within Scale 4.4 for criticality analysis, American National Standards Institute (ANSI) 14.5 for containment analysis, and MCMP for gamma and neutron dose rate calculations

Transnuclear performs scale model tests of a package with impact limiters to validate the g-force from a 30-foot drop test as predicted by computer analysis. At the same time, Transnuclear uses this testing to validate the crush distance predicted by the computer and to demonstrate the adequacy of the impact limiter design. Impact limiters are chilled to -20 °F for 24 hours prior to testing. They are then attached to the test model and dropped 30 feet onto an unyielding surface.

Another test program performed by Transnuclear in January 2001 was on the 1/3 scale NUMOS-MP197 transfer cask (Figure 8). Testing was performed in three orientations a side drop, a 20-degree slap-down, and a 90-degree

Figure 8 - MP-197 Drop Test

end drop. Figure 8 shows a side drop. The distance from the bottom of the impact limiter to the test target is 30 ft. +1 - 0 inches.

After each drop, the g-load was recorded and an inspection was performed to measure the deformation on the impact limiter and the attachment bolts, as well as on the torque of the bolt. The maximum g-load for the side drop of the 1/3 scale model was approximately 180g; this translates to 60g for a full-scale cask.

Figure 9 - CEGB Operation Smash HT

During the structure analysis for the package, an additional safety factor greater than between 15 and 20 percent of the measured g-load is used.

The Central Electricity Generating Board (CEGB) in the United Kingdom performed a full-scale test of a 240-ton train traveling at 100 mph impacting a package (Figure 9). The cask survived the train crash without any leakage. The impact force on the package from the train crash was found to be much less than the 30-foot drop test.

Transnuclear has also performed tests to simulate F-16 and F-18 fighter jets impacting a dual-purpose cask (Figure 10). The tests were performed on 1/3 scale models of the TN24D and TN24G casks with the missile representing the real hardness and impact condition of a jet engine. The impact velocities were between 336 and 481 mph. The cask components modeled were the external steel shell, neutron shielding, forged steel shell, weld at the bottom, and the bolted lid with metallic seals.

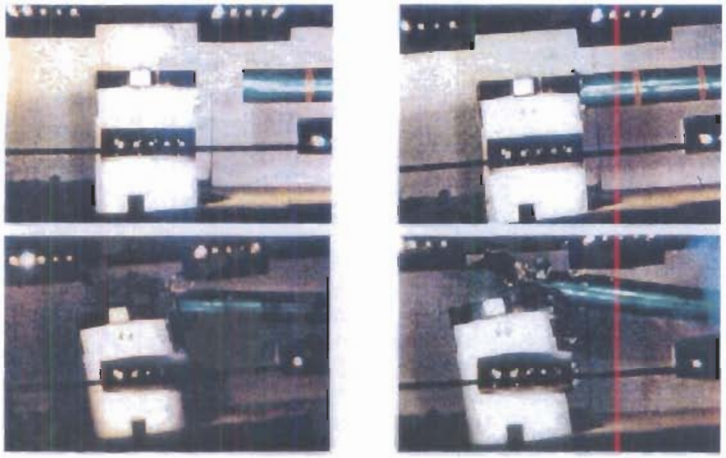

Figure 10

The tests resulted in only local deformation of the outer shell and no deformation of the containment vessel or the closure lid. Measurements showed that the lid tightness was unchanged

Based on all the tests, Transnuclear concluded that its dual purpose metal casks can survive, very severe impacts.

In conclusion, Transnuclear's past experience in cask design, analysis, and testing, combined with today's advanced technology, especially high-speed computing can predict test behavior. Scale model test results provide valuable benchmarking of analytical data. Reduced scale tests are fully justified; full-size package testing is not required.

Mr. Levenson asked for clarification on whether casks built to the IAEA standards are usable for shipments from anywhere in the world into the United States. Mr. Brach answered that DOT was responsible for countries, or companies, that are importing radioactive material into the United States shippers must apply for approval through DOT for authorization to use a non-NRC certified package.

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ADVISORY COMMITTEE ON NUCLEAR WASTE
TRANSPORTATION WORKING GROUP
WORKSHOP
NOVEMBER 19 & 20, 2002

Analysis and Testing Associated with Spent Fuel Transportation Casks

Peter Shih
Structural Analysis Manager

COGEMA GROUP

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OVERVIEW

- Introduction
- Transport Cask Design Compliance
  - US Design Criteria Based on Part 71, NUREG, and ASME Code
  - European Design Criteria Based on IAEA and ASME Code
  - Analysis
    - Methodology
    - Analysis Codes
  - Testing
    - Acceptance Testing
    - Scale Model Impact Testing
    - Full Scale Tests
- Transnuclear Transport Cask Design & Licensing Experience
- Conclusions

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INTRODUCTION

Over Thirty Years Experience in:

Design, Licensing, Fabrication and Operation of Packaging for Both Storage and Shipping of Spent Fuel, Radioactive Waste and Other Radioactive Material.

Experience Includes:

- **Design**
- **Analysis**
- **Testing**
- **Fabrication**
- **Certification**
- **Operation**

US Transport Cask Design Criteria

Design Basis:

- **10CFR Part 71**
- **Regulatory Guide 7.6**
- **Regulatory Guide 7.8**
- **ASME Section III, Subsections NB and NG**
- **ASME Section III, Subsection WB**
- **NUREG/CR-6007, Stress Analysis of Closure Bolts for Shipping Casks**

European Transport Cask Design Criteria

Design Basis:

- IAEA Regulations as Adopted into Law by Specific Countries
- ASME Section III, Subsection NB and NG (as Applicable)
- European Transportation Constraints

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US Transport Cask Design Criteria

Acceptance Criteria:

- Normal Conditions
  - Meet ASME Section III, Service Level A Allowables
  - Maintain Containment
- Accident Conditions
  - Meet ASME Section III, Service Level D Allowables
  - Maintain Containment

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US Transport Cask Analysis Methods

- Structure and Thermal
  - Finite Element Analysis Using ANSYS
  - Accepted Analytical Methods
- Criticality
  - Evaluated Using KENO-Va Within Scale 4.4 System
- Containment
  - Leakage Calculations in Accordance with ANSI 14.5
- Shielding
  - Gamma Dose Rate (MCMP)
  - Neutron Dose Rate (MCMP)

Acceptance Testing (Fabrication)

- Pressure and Structural Tests
  - ASME Code Hydrostatic Test (1.5 Times MNOP)
  - Trunnion Load Test (ANSI N14.6)
- Containment Test
  - ANSI N14.5 Leakage Test
  - Helium Mass Spectrometer (for leak tight or near leak tight requirements)
- Shielding Test (Optional)
  - Neutron Shield Test
  - Gamma Shield Test
- Neutron Absorber Test
  - Thermal Conductivity Testing
  - B10 Areal Density Testing
- Functional Test

Scale Model Testing

- Validate the G Value Predicted by Computer Analysis
- Demonstrate That Crush Depths are Acceptable
- Demonstrate Confinement of the Energy Absorption Material After Drop
- Demonstrate Adequacy of the Impact Limiter Attachment Design
- Evaluate the Effect of Low Temperature on the Crush Strength and Dynamic Performance of the Impact Limiter
- Evaluate the Effect of a 40 inch Drop onto a Scaled Six inch Diameter Puncture Bar on a Previously Crushed Impact Limiter

Scaling Relationships

Length	$L_{scale} = (1/\lambda)\ L_{full}$
Weight	$W_{scale} = (1/\lambda^3)\ W_{full}$
Energy Absorbed During Drop	$E_{scale} = (1/\lambda^3)\ E_{full}$
Velocity at Beginning of Impact	$V_{scale} = V_{full}$
Force During Impact	$F_{scale} = (1/\lambda^2)\ F_{full}$
Deformation	$D_{scale} = (1/\lambda)\ D_{full}$
Impact Duration (Time)	$T_{scale} = (1/\lambda)\ T_{full}$
Impact Deceleration	$G_{scale} = (\lambda)\ G_{full}$

Scale Model Drop Tests

> **Justification**

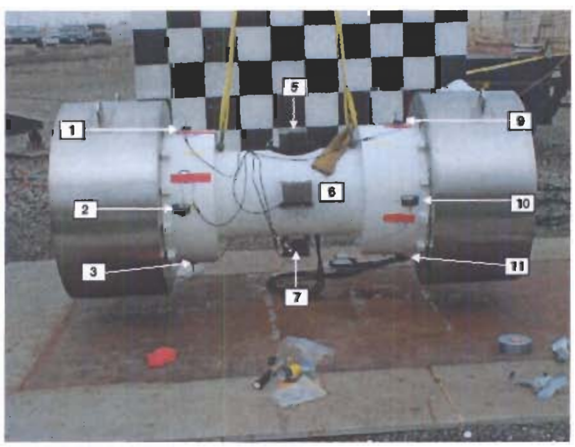
- **The Validity of the Scale Model Test and the Scaling Relationships Have been Studied Extensively by Several Experts**
  - "Drop Testing of Package Using Scale Model" (LLNL)
  - "Design and Testing of Scale Model Transport System" (Sandia)
  - "Study of Mechanical Strength of Cask with Scale Model" (Ecole Polytechnique)
- **Scale Model Testing is Authorized by IAEA and Historically Accepted by USNRC**
- **Scale Model Testing is Widely used for the Qualification of Type B Packages Throughout the World (USA, France, Germany, UK, and Japan....)**

> **Advantages**

- Reduce Fabrication Cost
- Reduce Cost and Potential Difficulties on Schedule due to Availability of the Target
- Reduce the Potential Difficulties of Performing the Test

1/3 Scale Model and Accelerometer Locations

(NUHOMS - MP197 Transport Cask)



Impact Limiter Testing Orientation

(NUHOMS - MP197 Transport Cask)

Test Number	Drop Orientation	Drop Height	Remark
1	0° Side Drop	30 Feet	
2	20° Slap Down	30 Feet	Bottom Impact Limiter Chilled to –20°F
3	90° End Drop	30 Feet	
4	90° End Drop	40 Inches	Drop Onto a Scaled Six Inch Diameter Punch Bar

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0° Side Drop Test Set Up

(NUHOMS - MP197 Transport Cask)

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NUHOMS-MP197 Scale Model and Impact Limiter After 0° Side Drop

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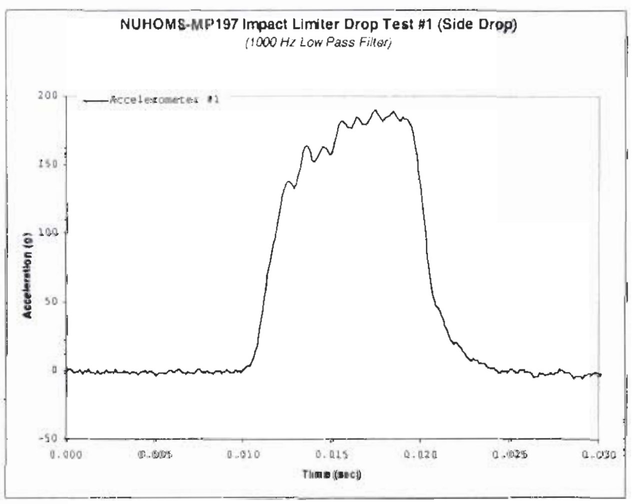
NUHOMS-MP197 1/3 Scale Model and Impact Limiter After 0° Side Drop Acceleration Time History



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20^{o} Slap Down Test Set Up

(NUHOMS - MP197 Transport Cask)

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NUHOMS-MP197 Scale Model and Impact Limiter After 20° Slap Down Drop

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90° End Drop Test Set Up

(NUHOMS - MP197 Transport Cask)

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NUHOMS-MP197 Scale Model and Impact Limiter After 90° End Drop

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NUHOMS-MP197 Scale Model and Impact Limiter After 40 inch Puncture Drop

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Comparison of Measured vs. Calculated g Loads

(NUHOMS - MP197 Transport Cask)

Drop Orientation	G Loads Measured by Drop Test	Input Loading Used in Structural Analysis
0° Side Drop	61G Normal	75G
20° Slap Down	32G Normal 53G Rotational	60G 196G
90° End Drop	65G Axial	75G
90° End Drop (Puncture Test)	N/A	N/A

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Full Size Package Testing

- Scale One Testing Has been Performed on Spent Fuel Casks
- These Tests were Primarily Used for Public Acceptance
- Sandia Test

Sandia Train Crash test

- CEGB Test

CEGB Full Scale Test

- Test on a 50T MAGNOX Spent Fuel Cask in 1984
- Test Program Used a Production Cask and Included 30 ft Drop (Identical to Regulatory Conditions)
- Regulatory 30 ft Drop Confirmed the SAR Results which were Based on Scale Model Tests
- A 240T Locomotive Traveling at 100 mph was Crashed into a Full Scale Cask Placed on Railtracks
- The Cask Survived the Train Crash Without Leakage
- Impact Forces From the Train Crash were Less Than the 30 ft Drop Test
- Full Scale Testing Gave Public Confidence and Confirmed That Regulatory Tests are Realistic when Compared to Real Accidents

MAGNOX Spent Fuel Transport Cask
(Operation Smash Hit)

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MAGNOX Spent Fuel Transport Cask
(Operation Smash Hit)

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MAGNOX Spent Fuel Transport Cask

(Operation Smash Hit)

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Transnuclear Experience in High Speed Impact Testing

> Aircraft Crash Tests Performed on TN Dual Purpose Casks

- Impact of F16 Fighter Jet
- Impact of an F18 Fighter Jet
- The Tests were Performed on Models with Missiles Representing the Real Hardness of a Jet Engine Under Impact Conditions
- Impact Velocities were Between 336 & 481 mph

> Tests were Performed Using 1/3 Scale Models of a TN24D & a TN24G Cask

- External Steel Shell
- Neutron Shielding
- Containment Vessel: Forged Steel Shell & Welded Bottom, Bolted Lid with Metallic Seals

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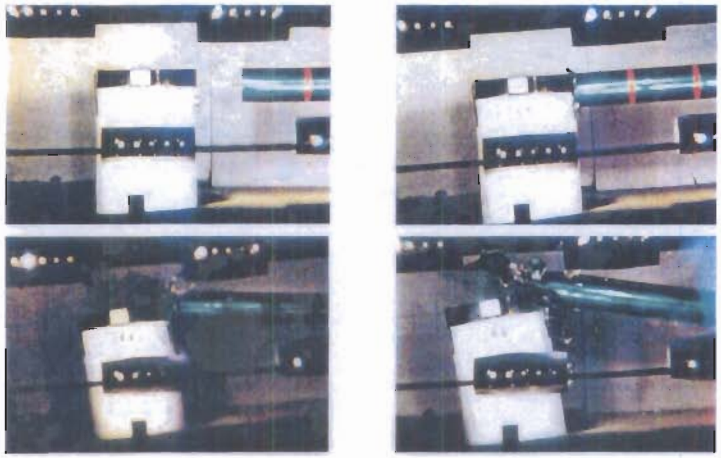
Transnuclear Experience in High Speed Impact Testing (TN 24D Aircraft Crash Test)



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Transnuclear Experience in High Speed Impact Testing (Aircraft Crash Test Results)

> **Test Results**

- The Part of the Cask Outer Shell Struck by the Missile was Locally Deformed but There was no Significant Loss of Shielding
- No Deformation of the Forged Containment Vessel or the Closure lid
- Leak Tightness was Unchanged After the Impact

> **Conclusion**

- Dual Purpose Casks can Survive Very Severe Impacts

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Summary of Transnuclear Cask Licensing Experience (US)

Package	Testing Scale	Transport Mode
TN-8, 8L	1/2	Truck
TN-9	1/2	Truck
TN-BRP	1/3	Rail
TN-RAM	Use results from TN-BRP Testing	Truck
TN-REG	1/3	Rail
TN-FSV	1/2	Truck
TN-68 (Dual Purpose Cask)	1/3	Truck /Rail
NUHOMS-MP187	1/4	Truck /Rail
NUHOMS-MP197 (Part 71 & IAEA)	1/3	Truck /Rail

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Summary of Transnuclear Cask Licensing Experience (European)

Package	Testing Scale	Transport Mode
TN 9	1/4	Truck/Rail
TN 12/1	1/3	Truck/Rail
TN 17T	1/3	Truck/Rail
TN 17/2	1/3	Truck/Rail
TN 24D	1/3	Truck/Rail
TN 24G	1/3	Truck/Rail
TN 24P	1/3	Truck/Rail
TN 24GET	1/2	Truck/Rail
TN 28	1/3	Truck/Rail
TN 97L	1/3	Truck/Rail
TN 1300	1	Truck/Rail
MTR	1/2	Truck/Rail

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Conclusion

Transnuclear's World-Wide Experience in Cask Licensing Including Regulation Scale Model Testing and High Speed Impact Testing Has Shown That :

- **Analytical Method can Accurately Predict Cask Behavior**
- **Scale Model Test Results Provide Valuable Benchmarking Data**
- **Reduced Scale Model Testing is Fully Justified, Scale One Test on Large Package is Unnecessary**
- **Full Size Cask Public Demonstration Tests Prove That the Current Regulations Give Adequate Safety Margins Under Real Accident Conditions**

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2.4.3 NAC International Transport Cask Analysis and Testing Experience, Dr. Michael C. Yaksh, NAC International

Dr. Yaksh, NAC, stated that NAC has received seven Certificates of Compliance (COCs) from NRC for radioactive transportation packages. The NLI-1/2 NAC-1, and NAC-LWT are legal weight truck casks. The unique feature about the NLI -1/2, an older cask that NAC purchased back in the late 1970s, is that it uses uranium for shielding. The other packages use lead. The NAC-STC, the NAC-MPC, and the NAC-UMS are high-capacity casks containing 24 or more pressurized water reactor (PWR) fuel assemblies and 56 or more boiling water reactor (BWR) fuel assemblies.

The number of revisions to the NLI-1/2 and the NAC-LWT package COCs are rather high. The revisions were made primarily to include additional contents reflecting the wide variety of types of fuel and radioactive materials that are transported in these casks.

There are eight NAC-LWTs being used throughout the world and five NLI-1/2s which have been used in over 3300 shipments covering approximately 6.5 million miles. NAC ships spent fuel by truck and ship. NAC shipped weapons grade fuel out of Iraq after Desert Storm in a Soviet aircraft. These casks have been used worldwide and the only accident of which NAC is aware is a truck that jackknifed carrying an empty NLI-1/2. The cask fell off the truck, damaging the bolts and impact limiter. It was repaired and put back into service. No major accidents to these casks have occurred in over the 6.5 million miles that they have been shipped.

An application for an NRC COC is supported by a combination of testing and analysis. The testing is used to confirm the analysis and both are used to demonstrate that the cask design meets the requirements of 10 CFR Part 71. Testing confirms the structural response of impact limiter materials, such as wood, and the impact limiter fasteners. Once benchmarked by testing, the analysis makes it easier to predict response material variations such as temperature, density, and variations in manufacturing processes.

The containment of the spent fuel involves a number of systems. The impact limiters limit the deceleration to which the fuel clad, the basket structure, the cask shell (including shielding), and other components and hardware (e.g., the lid and bolts) will be subjected. This is also important in maintaining cask geometry for criticality control of the fuel within the basket.

The NAC high-capacity casks contain 24 PWR spent fuel assemblies and 56 BWR fuel assemblies, respectively, for a total design weight of 260,000 pounds (the fuel weighs approximately 40,000 pounds). An impact limiter is attached to both ends and is made of a stainless steel shell containing redwood and balsa wood. NAC finds these materials to be very economical and very stable.

The analysis and testing for the NAC-UMS involving dynamic testing of the redwood and the balsa wood was performed at the Naval Surface Warfare Center. The 1/4-scale model used for the tests was modeled down to the impact limiter bolts. The 1/4-scale impact tests were performed at Oak Ridge National Laboratories and at Sandia.

The CY-STC package contains 26 fuel assemblies per canister of spent fuel from the Connecticut Yankee nuclear plant. NAC used the same material testing that was performed for the NAC-UMS and applied it to the CY-STC design. A 1/4-scale model test was performed to verify that NAC could cut 30 to 40 percent of the weight of the impact limiter and convert it to fuel weight, making the CY-STC a much more efficient design. Quite a number of things were learned from the NAC-UMS tests. NAC performed in the early 1990s. NAC wanted to employ this knowledge in the CY-STC design. For that reason, additional confirmatory drop testing was performed at Sandia.

Two NAC-STC casks are being fabricated in Spain for use in China to transport fuel from Diambay to a processing plant and back to Diambay for reuse.

System	Design Weight (lb)	Impact Limiters	Test Type *	Test Location
NAC-UMS	260,000	Redwood/balsa	1, 2	Naval Surface Warfare Center; Oak Ridge National Lab; Sandia National Lab
CY-STC	260,000	Redwood/balsa	1, 2	Naval Surface Warfare Center; Oak Ridge National Lab; Sandia National Lab
NAC-STC	250,000	Redwood/balsa	1, 2, 3	NAC International; AEA, Winfrith, UK
NAC LWT	52,000	Honey comb	1, 2, 3	Hexcell; Oak Ridge National Lab
NLI 1 / 2	52,000	Balsa	None	None
Californium	52,000	Foam	1 (NS-4-FR)	NAC International

(*) 1. Materials testing.
2. Scaled cask body and impact limiters.
3. Scaled basket within scaled cask body.

Table 1

The legal weight truck cask, NAC-LWT, uses honeycomb material for the impact limiter. However, from an economic standpoint, NAC switched from honeycomb to wood for the CY-STC design because a legal weight truck cask is a much smaller cask. The internal diameter of a legal weight truck cask is about 13.375 inches compared to the internal diameter of the larger casks which are in excess of 67 inches. For the NAC-LWT, NAC used dynamic data from the manufacturer of the honeycomb material. The impact limiter skin was fabricated out of aluminum. Table 1 summarizes this information.

NAC was very meticulous in creating a 1/4-scale impact limiter model that would simulate a full-scale impact limiter from the manufacturing standpoint. The cask body was also created at 1/4 scale. Lead was poured for the gamma shielding using the same methods that would be used for a full-scale cask.

The NLI-1/2 is a cask that NAC purchased from another vendor. It uses a balsa wood impact limiter. Casks of this type are still in service.

The Californium cask was a specialty package developed for shipping californium. Californium is a very fissionable and very highly radioactive material. Most of the cask volume is comprised of the neutron shielding material, NS-4. Because the structural integrity of NS-4 was not well known, additional testing had to be performed

Material testing determines a stress-strain curve and is the basis of an analysis. The testing demonstrated that the stress-strain data based on a literature search for the wooden impact limiter material had some gaps in it. Therefore, NAC contracted with the Naval Surface Warfare Center to perform an array of tests. These tests included low-strain weights (quasi-static) all the way up to very high-strain rates of 375 strains per second. The very high-strain rates were used to determine what would happen to the material in impacts up to 80 mph and 100 mph; both velocities exceed the regulatory requirements.

The test temperatures were varied from -40 °F (based on the regulations) up to 200 °F which is the normal operational condition. Because wood is orthotopic, just like honeycomb, an array of tests were performed in both directions to ascertain the weakest, as well as the strongest, direction. Next, as with any natural material, the variability of the properties must be determined. The criteria that were used in performing these specimen tests were the same criteria that were used to build the 1/4 scale impact limiter. In total, NAC has tested the material properties of redwood, balsa wood, honeycomb, NS-4, and a type of foam as impact limiter materials. All accurate analytical predictions start with good material testing.

In performing analyses of the cask design, NAC proceeds in parallel paths. One engineering group will perform stress analysis of the basket and the cask body and the other engineering group will design the impact limiter. Different drop orientations are assessed including the end drop, the corner drop, the side drop, and in some cases, the slap-down.

The slap-down test is an interesting topic. A great deal of studies have been made regarding the slap-down shallow angle. Large casks, which have very small length versus radius of gyration, do not have much of a slap-down effect.

NAC uses the commercially available LS-DYNA code. It is a five element code, but that is where the similarities between LS-DYNA and other codes like NSSS and COSMOS ends. It is an explicit code, that accommodates large strain, finite rotations and finite displacements. Not all codes do that well. The LS-DYNA code was evolved from the DYNA code developed by LLNL (which is described in Section 2.2.2 of this NUREG-series report).

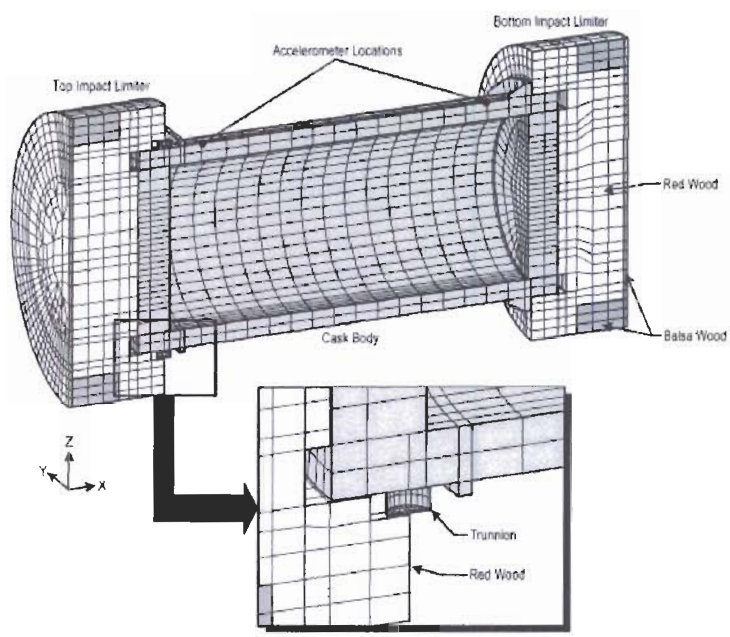

Figure 11

Figure 11 shows a rather detailed model, the impact limiters are modeled explicitly and the shells in the impact limiter are modeled explicitly. It is called modified because the standard foam model in DYNA does not accommodate strain rate sensitive properties. Strain rate sensitive properties are accommodated in the analysis.

For the impact limiter, a compression only interface is specified which allows it to slide. The bolts are modeled to determine whether they will maintain their integrity during an impact. The steel and lead cask body are shown as just two elements. The same material requirements (e.g., moisture, density, crush strength, and pressure strength), material orientation, assembly of the components, and acceptance criteria for the material that are used for full-scale casks are used for the 1/4-scale casks. In addition, the materials specified for the impact limiter attachment bolts, which are made of highly ductile stainless steel, are also used in the 1/4-scale model. These scale model construction practices allow comparisons to be made between the scale model tests and the analysis of a full-scale cask to determine the impact limiter crush and the maximum accelerations experienced by the cask body.

Confirmatory tests are important not only to obtain numerical data but also is important to understand the physical phenomena. NAC has found that no matter how rigid the cask body, it still performs basically like an elastic body.

Once the test data are obtained, they can be plotted and compared to the analytical data. The lower curve in Figure 12 is the drop test data; the higher one is the LS-DYNA curve. The curves can be smoothed by filtering the data. One of the features that can be implemented during post-processing of the electronic data is to perform a Fast Fourier Transform (FFT) that presents acceleration versus the frequency content.

NAC examines the FFT to verify that the test was good. There is a great deal of technology in accelerometers. NAC shopped around to select a testing facility because accelerometer technology is not a trivial matter. After the test data are obtained, they must still be carefully examined. The FFT is a good way of determining the filter frequency that should be used. It is very important to verify the cutoff frequency. Making the filter frequency too low, cuts out exciting modes in the cask, thereby reducing the acceleration.

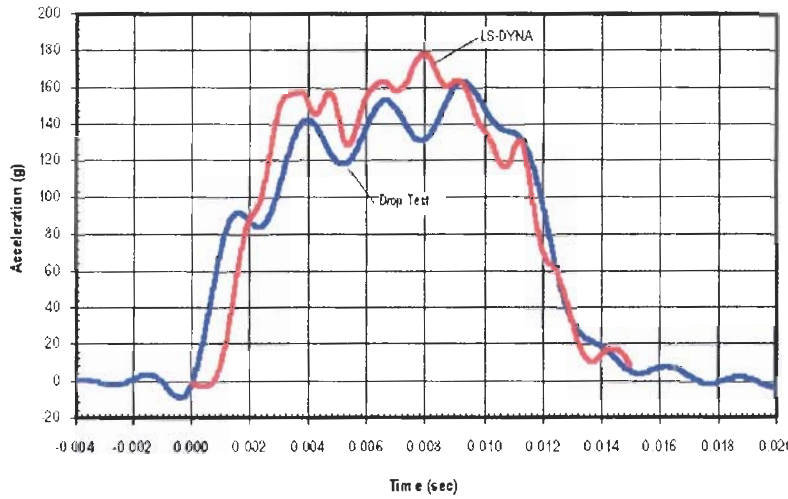

Figure 12

Before a test is performed, NAC submits the analytical results to NRC so that if the results were changed, the staff would be able to judge the significance of the change.

Figure 12 shows excellent agreement between the scale drop test and the analytical model. It should be kept in mind that the 1/4-scale load of 180g relates to a full-scale load of 45g. The actual acceleration used in the stress evaluation is 60g which results in an initial level of conservatism of 30 percent.

One of the reasons NAC concluded that the design was safe was the inherent conservatisms and margins of safety in the design. Although drop testing is performed onto a rigid surface, technically, there are no rigid surfaces in nature. The amount of elastic energy stored in the pad is infinitesimal when compared to the amount of energy being absorbed in the impact limiter.

When the attack on the World Trade Center occurred on September 11, 2001, one of the first things that NAC's engineering department analyzed was a fully loaded 747 crashing into vertical concrete dry storage casks. The results of that analysis, which concluded that a breach of containment would not occur, were presented to NRC staff.

NAC also provides other conservatisms in its analyses by concentrating the load in simplified stress analyses. A simplified stress analysis is actually a very complex model with a number of interfaces. One thing that NAC noticed in the force deflection curves was a 20–30 percent margin in its impact limiter designs. In addition, the stress analyses of the system showed that the accelerations reached during the drop tests were significantly lower than the results of the design stress calculations. The analysis used in the ASME code for an elastic analysis of stainless steel completely neglects the ductility of the stainless steel. This is a substantial conservatism.

In the early 1990s, NAC used 1/4-scale model testing to develop its NAC-STC cask. The basket was 1/4 scale, the shells were 1/4 scale, the bolts were 1/4 scale, and the pedigrees of the materials used were maintained. However, NAC ran into a problem with the impact limiter because the company had performed static tests using aluminum shells to try to conserve some weight. During the side drop test, the aluminum did not maintain the correct orientation and the impact limiters did not work correctly. This resulted in the cask body impacting upon this massive steel block in two locations producing a force of 1200g on the scale model which correlates to a force of 300g to a full-scale cask. This was 5½ times the cask's design g-load.

Immediately after the test, NAC pulled the basket out to assess the damage and noticed that the parts of the basket which were outside the point of contact exhibited no permanent deformation. Deformation to the basket at the point of contact was minor. None of the rows had any signs of permanent damage, none of the lip bolts failed, the containment was maintained, and the criticality configuration was maintained.

In summary, NAC believes the analysis methodologies can adequately and conservatively predict the impact limiter response. One of the largest contributors to the conservatism is that the ASME code methodology, using an elastic analysis, neglects the ductility of the stainless steel. In addition, another significant conservatism is that very few things are rigid in this world, especially when impacted by a quarter million pound object. NAC believes this demonstrates that current designs for transportation packages include a large margin of safety.

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NAC INTERNATIONAL

NAC International Transport Cask Analysis and Testing Experience

Dr. Michael C. Yaksh

November 19, 2002

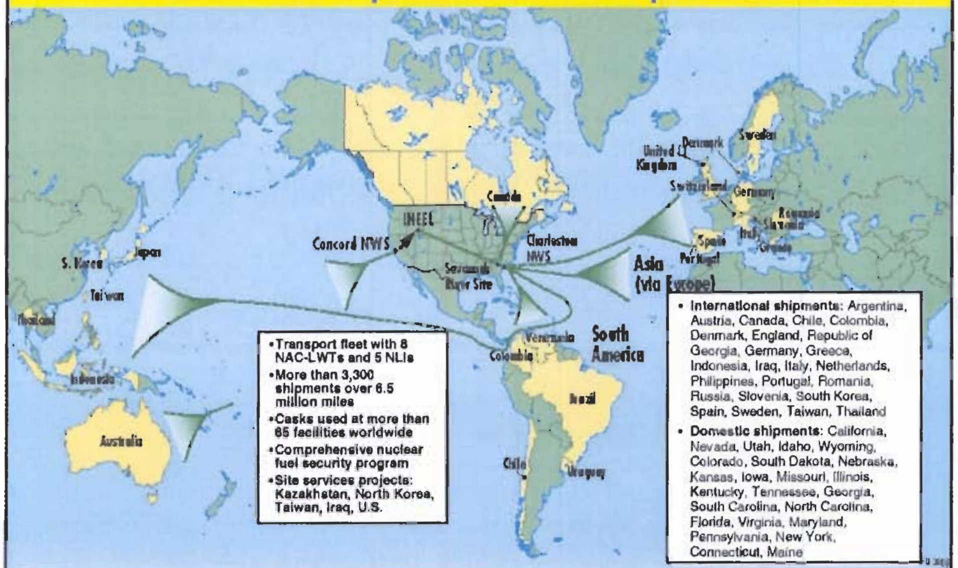
Atlanta Corporate Headquarters 3930 East Jones Bridge Road Norcross, GA 30092 770-447-1144 Fax 770-447-1797 www.nacintl.com

NAC Transport Cask Licensing Experience

Cask Designation	CoC No.	No. of CoC Rev./Application	NRC or IAEA Approval
NLI-1/2	71-9010	39/Transport	NRC/IAEA
NAC-1	71-9183	13/Transport	NRC/IAEA
NLI-10/24	71-9023	8/Transport	NRC/IAEA
NAC-LWT	71-9225	23/Transport	NRC/IAEA
NAC-STC	71-9235	2/Transport	NRC/IAEA
NAC-MPC	71-9235	2/Transport	NRC/IAEA
UMS®	71-9270	Transport	NRC/IAEA
Advanced UMS®	Pending	Transport	NRC/IAEA

NAC INTERNATIONAL 2

NAC Transportation Experience



- Transport fleet with 8 NAC-LWTs and 5 NLIs
- More than 3,300 shipments over 6.5 million miles
- Casks used at more than 65 facilities worldwide
- Comprehensive nuclear fuel security program
- Site services projects: Kazakhstan, North Korea, Taiwan, Iraq, U.S.

- **International shipments:** Argentina, Austria, Canada, Chile, Colombia, Denmark, England, Republic of Georgia, Germany, Greece, Indonesia, Iraq, Italy, Netherlands, Philippines, Portugal, Romania, Russia, Slovenia, South Korea, Spain, Sweden, Taiwan, Thailand
- **Domestic shipments:** California, Nevada, Utah, Idaho, Wyoming, Colorado, South Dakota, Nebraska, Kansas, Iowa, Missouri, Illinois, Kentucky, Tennessee, Georgia, South Carolina, North Carolina, Florida, Virginia, Maryland, Pennsylvania, New York, Connecticut, Maine

NAC INTERNATIONAL

Overview

- NAC does not perform 10CFR71 cask licensing by testing, but by analysis with confirmatory testing
- Demonstration of integrity of the cask system uses both testing and analysis
  - Testing confirms required structural response where analysis methods may need validation
  - Analysis allows loading conditions to be examined in which testing is not practical
- Testing confirms analysis methodology

NAC INTERNATIONAL

Overview (continued)

- A number of systems are required for maintaining cask integrity, which may involve more than a containment requirement
  - Impact limiter to absorb energy due to impact with a rigid surface
  - Robust cask body shells, lids, bolts and seals to maintain containment
  - Robust internal structure to maintain geometrical location of the fuel for criticality control
- NAC history of designs / testing / usage for transport applications is extensive

NAC INTERNATIONAL 5

NAC Cask Testing Experience

System	Design Weight (lb)	Impact Limiters	Test Type *	Test Location
NAC-UMS	260,000	Redwood/balsa	1, 2	Naval Surface Warfare Center; Oak Ridge National Lab; Sandia National Lab
CY-STC	260,000	Redwood/balsa	1, 2	Naval Surface Warfare Center; Oak Ridge National Lab; Sandia National Lab
NAC-STC	250,000	Redwood/balsa	1, 2, 3	NAC International; AEA, Winfrith, UK
NAC LWT	52,000	Honey comb	1, 2, 3	Hexcell; Oak Ridge National Lab
NLI 1 / 2	52,000	Balsa	None	None
Californium	52,000	Foam	1 (NS-4-FR)	NAC International

(*) 1. Materials testing.
2. Scaled cask body and impact limiters.
3. Scaled basket within scaled cask body.

NAC INTERNATIONAL 6

Typical Methodology for Impact Limiter Energy Absorbing Materials

- Material Testing
  - Material testing is performed on samples to define the stress-strain curves
    - For a range of strain rates to be expected in the impact
    - Temperature variation is from –40°F to 200°F
    - Multiple directions of material orientations
    - Multiple tests to observe variability of the properties
    - Material tested by NAC: redwood, balsa, foam, aluminum honeycomb, NS4FR neutron shielding

NAC INTERNATIONAL 7

Typical Methodology for Impact Limiter Energy Absorbing Materials (continued)

- Material Testing (continued)
  - The testing is used to define the extent of variability of parameters associated with material
  - Material testing is required to produce accurate analysis results required by NRC
    - Maximum acceleration agreement between analysis and testing
    - Agreement of acceleration time histories between analysis and testing

NAC INTERNATIONAL 8

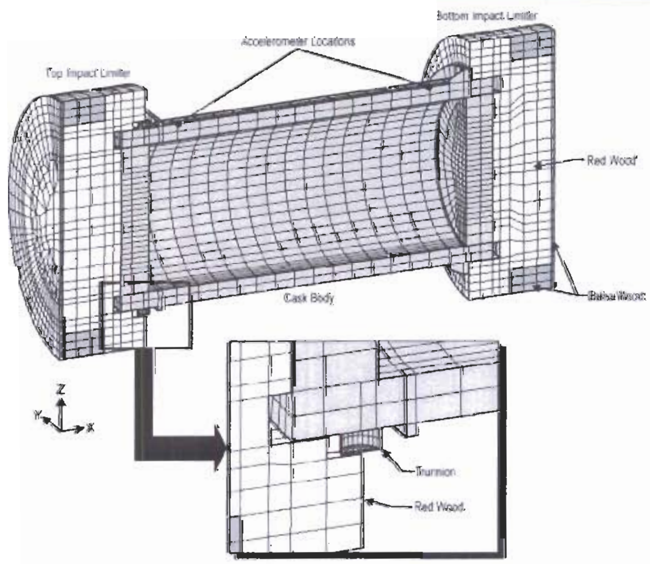
Analysis Methodology

- Objective of the analyses
  - Full scale cask analysis: to ensure that the design objectives are met
    - Acceleration limitations are specified to allow limited decoupling of the evaluations
    - Evaluation using the maximum temperature ranges is performed
    - Cask drop orientation is varied
    - Sensitivity studies are performed
  - Scale model cask analysis: to permit the methodologies to be benchmarked for scale model testing
    - Analytical methods
    - Manufacturing methods

NAC INTERNATIONAL 9

Analysis Methodology (continued)

NAC uses LS-DYNA to perform the evaluation of the full-scale and scale-model cask response



NAC INTERNATIONAL 10

Scale Model Testing

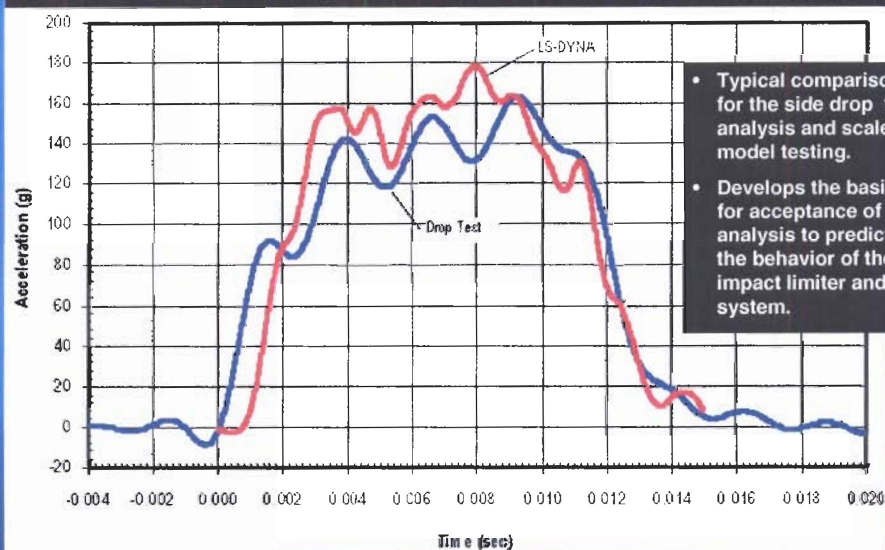
- Scale model manufacturing employs the same procedures and methods as required for the full scale design
  - Material requirements
  - Material orientation
  - Assembly of the components
  - Acceptance criteria for the material
- Scale model testing produces data for comparison with analytical predictions
  - Extent of crush of the impact limiter
  - Maximum accelerations
  - Overall acceleration response of the system
  - NRC requires conformance of testing to maximum accelerations <u>and</u> time history of cask accelerations predicted by analysis

NAC INTERNATIONAL

11

Scale Model Testing (continued)

Comparison of Quarter Scale Analysis and Test Results for the Side Drop (bottom accelerometer)



- **Typical comparison for the side drop for analysis and scale model testing.**
- **Develops the basis for acceptance of analysis to predict the behavior of the impact limiter and system.**

NAC INTERNATIONAL

12

Inherit Conservatisms and Margins in the Design

- Drop testing uses a rigid surface backed by a semi-infinite mass
- Loading is concentrated at the ends and not along the cask
- Force deflection curves from the scale model testing show 20-30% more capacity than required for the full-scale cask design
- Stress analyses of the system use accelerations which are larger than those obtained in the test and predictions
- Most analyses employ ASME Code methodology for the accident evaluation for the basket and for the containment
  - Neglects ductility of stainless steel
  - Uses Code acceptance criteria (very conservative with respect to "failure")

Inherit Conservatisms and Margins in the Design (continued)

- Conservativism of NAC's approach has been demonstrated in one side drop test of the NAC-STC at Winfrith, U.K.
  - Cask body and basket model was a quarter scale of the full scale design
  - Cask body and basket were subjected to 5 times the design accelerations (300g full scale)
  - Basket at point of impact showed minor deformation
  - Basket outside the point of impact showed no permanent set
  - No cask body containment welds exceeded yield
  - No lid bolts failed; cavity environment was maintained
  - Criticality configuration was maintained

Summary

- Analysis methodologies have been shown to adequately and conservatively predict the impact limiter response
- Inherit conservativism exists in the methodologies
  - ASME Code methodologies
  - Impact limiter margin
  - Inherit conservativisms in the structural evaluation
  - Drop testing on essentially unyielding surface
- Design and testing methodologies demonstrate that current NAC cask designs provide large margins of safety during transport

NAC INTERNATIONAL

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2.4.4 TWG Questions Regarding Transportation Package Vendor Analysis and Testing

Dr. Wymer noted that there are three different kinds of gamma shielding material exist including stainless steel, lead, and depleted uranium (DU) and asked what the difference in performance and cost was for the materials. Mr. Yakh responded that DU was used for the NLI-1/2 until the COC was renewed in accordance with 10 CFR Part 71.13, as a B(U)F-85 designated package. The NLI-1/2 now uses lead which is easy to pour. Dr. Singh supplemented this response by further explaining that there are two competing considerations in a cask design. A certain diameter must be maintained (about 96 inches) and there must be a certain gamma attenuation capability. Lead has a much greater density than stainless steel, or any form of steel, therefore, it provides better gamma shielding capability in a small diametrical space. However, lead is a very weak structural material and tends to creep under sustained loads. Therefore, if the cask is made out of steel, or stainless steel, the cask will have gamma shielding, as well as structural capability. If a lot of lead is used and less steel, the cask will have more effective gamma shielding capability.

Dr. Singh further stated that the cost depends on the extent of welding done in the cask, which is the manufacturing cost. The material cost is fairly constant. For example, a lead pour, which is heated and requires temperature control, is more expensive than installing lead bricks which are premanufactured. Again, there are competing considerations. The most significant cost element in making the cask is probably the extent of the welding work that is performed and maintaining the cask's dimensions.

Dr. Wymer noted that one of the things that occurs, yet not many stakeholders outside of this industry realize, is that lead, in an accident or test impact, may tend to flow a little bit and change the position of the weight. Mr. Yaksh responded that he did not agree with this statement. NAC has performed extensive testing, exposing the lead up to 5 times the design g-load, and did not identify any slumping or bulging of the inner or outer shells.

Mr. Shih stated that Dr. Singh was correct. Normally, no dimensional constraint exist, (e.g., Transnuclear's TN-68 dual purpose cask which is only designed for transport in the United States), steel is used. However, Transnuclear's MP-197, which will be used not only in the United States, but also in Europe, has outside diameter constraints which require the use of lead-filled stainless steel.

Mr. Levenson asked for clarification as to whether the vendors really meant that the regulators sometimes control the technology and the economics. There are different requirements for European shipments and American shipments which result in different designs. Mr. Shih responded yes. Dr. Singh added that the regulators contribute to the technology.

Dr. Garrick expressed that he was impressed with the vendors' confidence in scale model testing from two points of view, the first being the demonstration of safety meaning cask integrity, and the second being the authentication of analysis models. Dr. Garrick questioned whether, with respect to these two points, anything could be learned from full-scale tests that could not be learned from scale model testing. Dr. Singh replied that a certain scaling algorithm is used when scaling any physical test for a structure or a component. The mass, volume, and local rigidity of the materials will be scaled. However, compromises are involved. Unless the test is being performed for one specific loading and one specific orientation, any scale model would be ideal for that particular test, but it will be approximate, or even depart, from the scaling for other loadings.

Dr. Garrick stated that full-scale tests would have the same problem for one particular angle, one particular load, etc. Dr. Singh acknowledged that Dr. Garrick was correct but that the full-scale test, whichever loading was applied, will provide the response of the structures. When anything is scaled down to a 1/4 scale, it is possible to scale up the response to the full-size structure for that specific load, or approximately, for loads which are close to it in nature and application. However, when studying a wide variety of loads, the scale models depart from it. Scale models do serve a function as they are much less expensive and many of them can be run. For example, Holtec conducted numerous scale model tests during the certification process for the HI-STAR cask. Holtec could not have conducted that many tests on a full-scale cask. Therefore, scale models casks have their place, however, a full-scale test does provide a much higher level of confidence. There are limitations to scaling down a structure.

Dr. Garrick acknowledged that what Dr. Singh said may be true with respect to demonstrating the integrity of the cask. However, Dr. Garrick questioned whether, as far as analytical models are concerned, scale model testing would sufficiently support the analysis of a full-scale design. Dr. Singh responded that scale model testing is a useful tool used today to benchmark a model. Scale model test results are used to benchmark the analytical model to predict the cask response. Dr. Singh concluded that this is a satisfactory way to do things.

Dr. Garrick questioned whether, from an investment standpoint, it is worth the extra expense to develop a full-scale model to reduce the uncertainty in the analytical model, by ever so small an amount, if the uncertainties were accurately presented in the first place. Dr. Singh stated that he did not mean to suggest that scale model testing would not provide a high level of confidence with respect to the ultimate performance of the structure. Instead, it is a case of available funds versus the level of exactitude, or rigor, or quality of information needed. Dr. Singh added that, as a scientist and as an engineer, he would prefer to perform a full-scale test but it is very expensive. Scale models serve the function to establish a high level of confidence in the behavior of the structure.

Dr. Wymer noted that many things are successfully engineered without the use of full-scale models and questioned the experts in attendance as to what added benefits are achieved from full-scale tests. Mr. Yaksh stated that one thing that needs to be pointed out more is that experience has shown that the 1/4-scale model tests are not only used for analytical model confirmation, but also to work out manufacturing details. It is much easier to work on a 1/4-scale model that weighs 4 tons than a full-scale model weighing 100 tons. There is really a dual purpose for the 1/4-scale model; it is just not benchmarking data. A scale model helps to determine how full-scale cask will be manufactured.

Mr. Shih stated that in his presentation, he listed three reports (Figure 13), that studied, extensively the correlation between the scale model and a full-scale cask. Based on these three reports, if the scale factor is one-quarter or greater, then the correlation is excellent. In addition, based on the information gathered by high-speed cameras during testing, 1/3-scale models and full-scale models behave almost identically.

Scale Model Drop Tests

> **Justification**

- **The Validity of the Scale Model Test and the Scaling Relationships Have been Studied Extensively by Several Experts**
  - "Drop Testing of Package Using Scale Model" (LLNL)
  - "Design and Testing of Scale Model Transport System" (Sandia)
  - "Study of Mechanical Strength of Cask with Scale Model" (Ecole Polytechnique)
- **Scale Model Testing is Authorized by IAEA and Historically Accepted by USNRC**
- **Scale Model Testing is Widely used for the Qualification of Type B Packages Throughout the World (USA, France, Germany, UK, and Japan....)**

> **Advantages**

- Reduce Fabrication Cost
- Reduce Cost and Potential Difficulties on Schedule due to Availability of the Target
- Reduce the Potential Difficulties of Performing the Test

Figure 13

Dr. Ryan questioned whether weight was the limiting design parameter for highway casks. Mr. Yaksh responded no, that a design could exceed 52,000 pounds provided an overweight truck was used to transport it.

Mr. Levenson questioned that if a rather drastic design change is made, would the designer have more confidence using data from one full-scale test, which tests one data point, or using data from multiple tests of small-scale models, which provide multiple data points, but at a scale. Mr. Yaksh responded that he would rather have more data points, because variability in manufacturing would not be picked up with one data point. However, it would be picked up with multiple data points. Hence, NAC has greater confidence that any variability present has been observed because of the number of tests performed. When NAC builds the full-scale cask, staff will build it like the cask was designed and analyzed. Dr. Singh agreed with Mr. Yaksh, noting that a cask is not an isotropic homogenous body. If one test is conducted in any given direction, the model will respond to that particular loading. The actual cask, of course, has an infinite number of loadings and directions in which it can be loaded. So a number of scale model tests gives analysis the ability to benchmark the model much more accurately than they could with one full-scale test. Mr. Shih also agreed, noting that the reason is the cask. Drop tests are performed in different orientations because different cask components respond differently in different test orientations. For the basket, the worst case is a side drop. However, for the cask lid, the worst case is the corner drop through the lid. One full-scale drop test will not represent the entire worst case loads for each component.

Mr. Levenson stated that it was interesting the three vendors agreed. He related a story from the days of the Manhattan Project about a physicist named Sam Untermier who is thought to be the inventor of the BWR. In later years, Sam Untermier argued that it was never necessary to get more than a single data point because physicists could understand everything from first principles. A physicist knew just where to put the curve because the shape of the curve came from theory. However, the vendors did not agree with this concept.

Mr. Ammerman commented that what the vendors stated is exactly correct for structural testing. However, for thermal testing, it is impossible to relate the test results of the scale model to a full-scale cask. For example, as Dr. Yaksh stated in his presentation, to scale the structural impact forces one simply divides by 4 to determine the g-load on a full-scale cask. That works fine for structural testing, but the same correlation does not exist for thermal testing. There are different regimes in a thermal test. The heat transfer is done by three modes, radiative, convective, and conductive. Not all of these modes scale in the same manner. For example, the radiative heat transfer scales with the temperature of the force; the conductive heat transfer scales with temperature. Therefore, when there is a mixed mode of heat transfer, the scaling laws become too complex. If two modes are ignored during a test in favor of the dominant one, the analyst can perform scale model testing.

If a scale model test results in a leak rate value of X, it demonstrates very little about what the rate would be for the full-scale cask unless the leak rate is zero.

Mr. Brach added that the discussions on full-scale testing and scale model testing did not include NRC's strategic goal to increase public confidence. The staff must consider this goal in addition to the issues of science and safety. Mr. Levenson stated that the TWG is well aware of the public confidence issue but that the Working Group prefers to focus on the technical aspects of spent fuel transportation. He added that the TWG realizes that not everything the staff does is purely technical; efforts can be modified by other pressures.

2.4.5 Stakeholder Questions Regarding Transportation Package Vendor Analysis and Testing

Mr. Resnikoff noted that Dr. Yaksh stated that the deceleration values from a cask drop established a deceleration load of 188g. However, a LLNL study indicated that the Holtec cask would sustain damage at 63g. Therefore, it appears that the cask and cladding would be severely damaged at an impact of 188g. Dr. Yaksh responded that a full-size cask would not receive a 188g load from the drop test. In order to determine the full-scale cask g-load, results from the 1/4-scale test must be divided by 4. Therefore, the 188g load on the scale model equates to a 47g load on a full-scale cask which is less than the 63g load cited in the LLNL study.

Mr. Resnikoff did not believe that was true. Dr. Yaksh responded that it was true and that the other structural experts in attendance would concur. Mr. Fischer agreed with Dr. Yaksh. Mr. Levenson added that the g-load that the vehicle or cask experiences is not identical to the g-load that the fuel experiences. There is significant energy absorption in many places between the cask and the fuel.

Mr. Resnikoff questioned whether the type of carriage on which the Holtec cask would be transported had two double axle carriages at each end, as shown in a slide depicting the airplane engine impacting the cask. Another view showed single double axle carriages at each end. Mr. Resnikoff also questioned whether the carriages were movable or rigid. Dr. Singh responded that Holtec was not designing the rail car. Holtec designed the cradle that is connected to the rail car. For modeling purposes, the platform was used. The wheels were modeled. The model assumed a rigid body. The analysts wanted to determine if there was energy dissipation through deformation and whether the cask would separate from the rail car. Holtec did not focus on the railroad design aspect of the car.

2.5 NRC Fire Testing

2.5.1 NRC Staff Review and Analysis of the Baltimore Tunnel Fire, July 2001, Christopher Bajwa

Mr. Bajwa, an engineer with NRC's Spent Fuel Project Office (SFPO), stated that he would discuss some of the pertinent details of the Baltimore Tunnel fire, the staff's coordination with the NTSB, a preliminary analysis of the performance of a spent fuel transportation cask in a severe fire environment, a fire model of the Howard Street tunnel fire developed by NIST, and a revised analysis conducted by the staff analyzing the effects of the Howard Street fire on a transportation cask.

The Baltimore Tunnel fire occurred in July, 2001, in the Howard Street Tunnel in downtown Baltimore, next to Camden Yards. That particular tunnel is a single-rail tunnel about 1.65 miles in length. The train traveling through the tunnel was a CSX freight train. It derailed and a fire ensued near the west portal of the tunnel. The tripropylene tank provided the fuel for the fire. When the car derailed, it punctured a hole approximately 1.5 inches in diameter in the tank. It is believed that the braking mechanism broke, flipped up, and punched a hole in the car causing the tripropylene to spill out and subsequently be ignited.

The Commission asked the SFPO to look at and analyze the Baltimore Tunnel fire to determine if it had any impact on the transportation of spent nuclear fuels. Specifically, the SFPO was to determine whether there were any regulatory implications for this particular event. The staff met with NTSB on several occasions, the first being in September 2001. At the time, NTSB indicated that it would look into the fire and quantify the thermal conditions that were found. However, as the investigation progressed, NTSB focused on the derailment and decided it would not look into the fire.

The NRC staff focused on the fire because it would likely have the biggest impact on the spent fuel transportation cask. The NTSB provided information, data, and technical expertise on rail events to assist the staff's investigation of the fire event. The NTSB also made the rail cars available for the staff's inspection after they were removed from the tunnel.

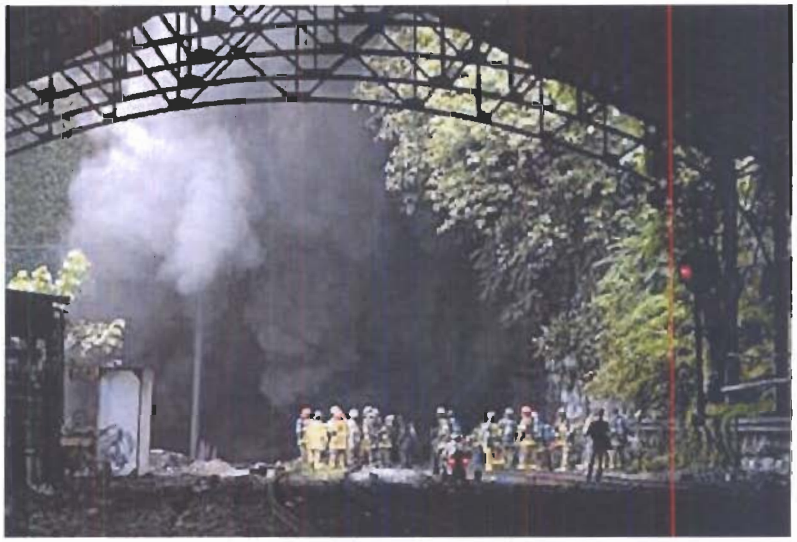


Figure 14

To get a full understanding of this accident, the SFPO performed a preliminary scoping analysis to determine how a spent fuel transportation cask might react if exposed to a severe fire. In addition, the staff wanted to ensure that there would not be an immediate public health and safety concern with the performance of the cask in an accident of this type.

The Holtec HI-STAR cask was selected for the study partly because the cask has been certified for use by NRC and partly because if the PFS facility is licensed and becomes operational, hundreds of shipments will be made using the Holtec Hi-STAR cask. Staff developed analytic thermal model of the Hi-STAR cask using the ANSYS finite element analysis program.

10 CFR Part 71.73 requires transportation packages to be designed to withstand hypothetical accident conditions. One condition is that a package can withstand a fully engulfing fire at a flame temperature of 1475 °F for 30 minutes. All NRC-certified casks must meet that requirement.

Given that the thermal conditions present in the tunnel at that time were unknown, SFPO's analysis of this event was performed at 1500 °F for 7 hours. The preliminary scoping analysis included boundary conditions of convection and radiation on the outside of the package, and conduction, radiation, and convection on the inside. The initial steady state thermal conditions (i.e., normal conditions for transport) included a 100 °F ambient temperature. A 20-kilowatt heat load from the spent fuel was modeled inside the cask. For the fire, the convection heat transfer was increased on the surface of the cask to simulate a turbulent fire environment.

From the preliminary analysis, staff determined that there would be no cladding failure for the fuel. Staff based this conclusion on the short-term temperature limits for the spent fuel cladding. In addition, the analysis determined that there would be no canister failure based on the stresses and on the creep criteria. Based on these results, staff concluded that no radioactive release would have occurred.

Having completed a scoping analysis, the staff had a general idea of how the cask might perform when exposed to a severe fire. However, the staff wanted to get a better idea of what actually happened in the Baltimore Tunnel. Therefore, NIST was contracted to quantify the thermal conditions that existed in the tunnel during the event. To accomplish this, NIST used the fire dynamics simulator (FDS) code. FDS is a computational fluid dynamics code that models combustion, heat release rates, and gas flow in a variety of fire environments. It has been used with very high success to model fires in the nuclear power plants. The analytic model used by NIST was validated using data obtained by the Federal Highway Administration (FHA) in its Memorial Tunnel fire test program. The FHA tested several different sizes of fires in an abandoned tunnel to quantify the kind of temperatures and the kind of flow regimes that would be encountered in tunnels. NIST also validated the FDS code using data from these experiments. The analysis results from the NIST fire model were then used as input to the staff's revised cask analysis model.

NIST used a computational grid that extended the entire length of the Howard Street Tunnel. NIST used a finer grid in the areas of concern surrounding the fire and in the rail car areas immediately in the vicinity of the fire. NIST modeled the rail cars in the derailed configuration. The NTSB provided a diagram that showed how the rail cars were laid out after the derailment. NIST used this diagram to model the rail cars in its fire model.

The combustion of hydrocarbon fuel, which tripropylene essentially is, was also modeled. There was no ventilation in the tunnel at the time of the accident because the ventilation system was not operating. Therefore, the NIST model did not use any ventilation. Finally, the NIST model reached steady state conditions in the hot gas layer (above the railcars), boxcar surfaces, and tunnel wall surfaces in about 30 minutes. In other words, there was very little change in the temperatures of the gas and components mentioned above after about 30 minutes into the simulation.

NIST modeled the fire flaming up between two cars. There were two cars on either side of the tripropylene tanker car. Because the fire was shooting up between these two cars, it was impinging directly on the tunnel and then spreading out along the length of the tunnel. Therefore, the temperatures in this particular fire model were greatest at the top of the tunnel (Figure 15).

The SFPO also contracted with material and fire experts at the Center for Nuclear Waste Regulatory Analyses (CNWRA) to analyze samples from the tunnel and samples from the rail cars that were removed from the tunnel. CNWRA staff performed metallurgical analyses on

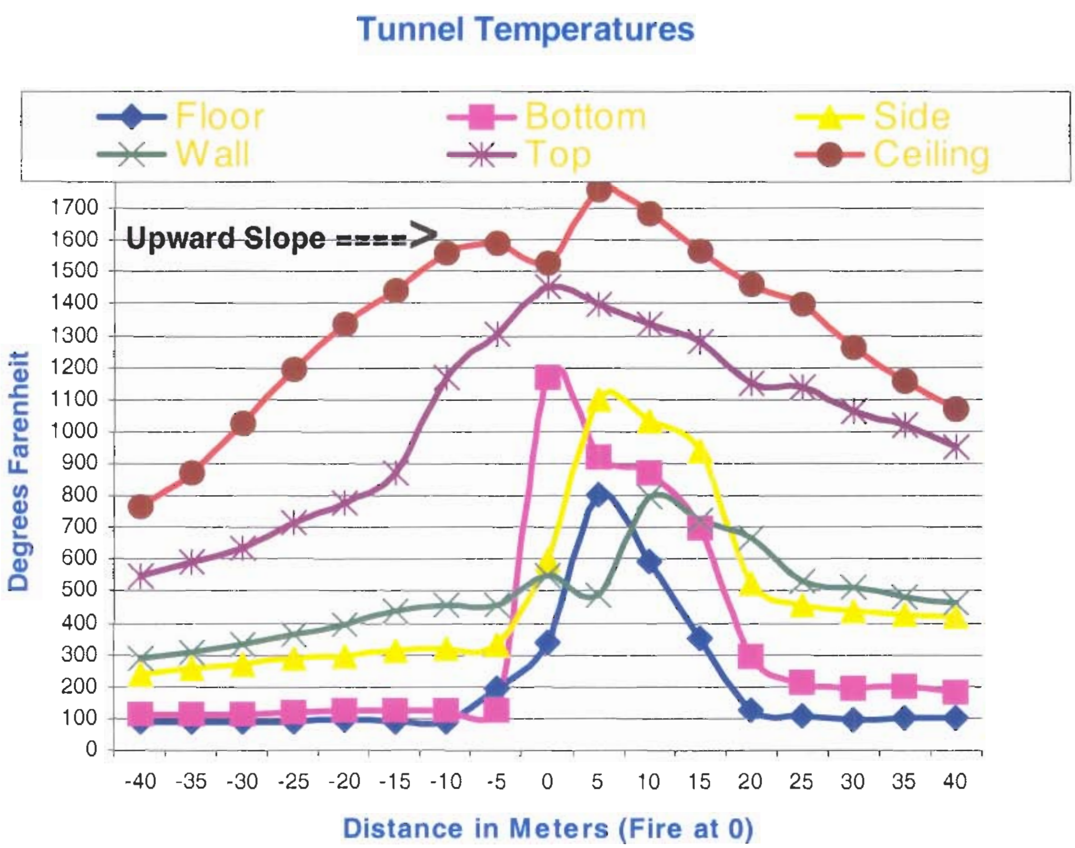


Figure 15

several material samples and components removed from the rail cars that were in the tunnel during the fire. The experts were able to inspect the materials that came out of the tunnel and determine the temperatures of the fire. The analyses conducted by CNWRA indicated that the temperatures predicted by the NIST model were consistent with the physical evidence that was analyzed.

Staff then applied the data from NIST to two separate assessments of a spent fuel transportation cask finite element analysis model. The first assessment was with the cask center located 20 meters, or approximately one rail car length, from the fire. Staff chose this distance because, per Federal regulations, any radioactive material package must be at least one box car away from any hazardous materials package. The Howard Street Tunnel is a single rail car tunnel and it is very unlikely that a spent fuel cask traveling through the tunnel will come any closer than one box car's length away from a fire.

The staff's model is a 2D cross-section model with about 27,000 elements (Figure 16). It explicitly models all of the gaps and the various features of the basket (which contains 24 fuel assemblies), the MPC, the gamma shields, gamma plates (which are carbon steel plates), the HOLTITE-A neutron shield, and the stainless steel outer skin. A 3D model is currently under development to better capture the effects of a fire on other components of the spent fuel cask.

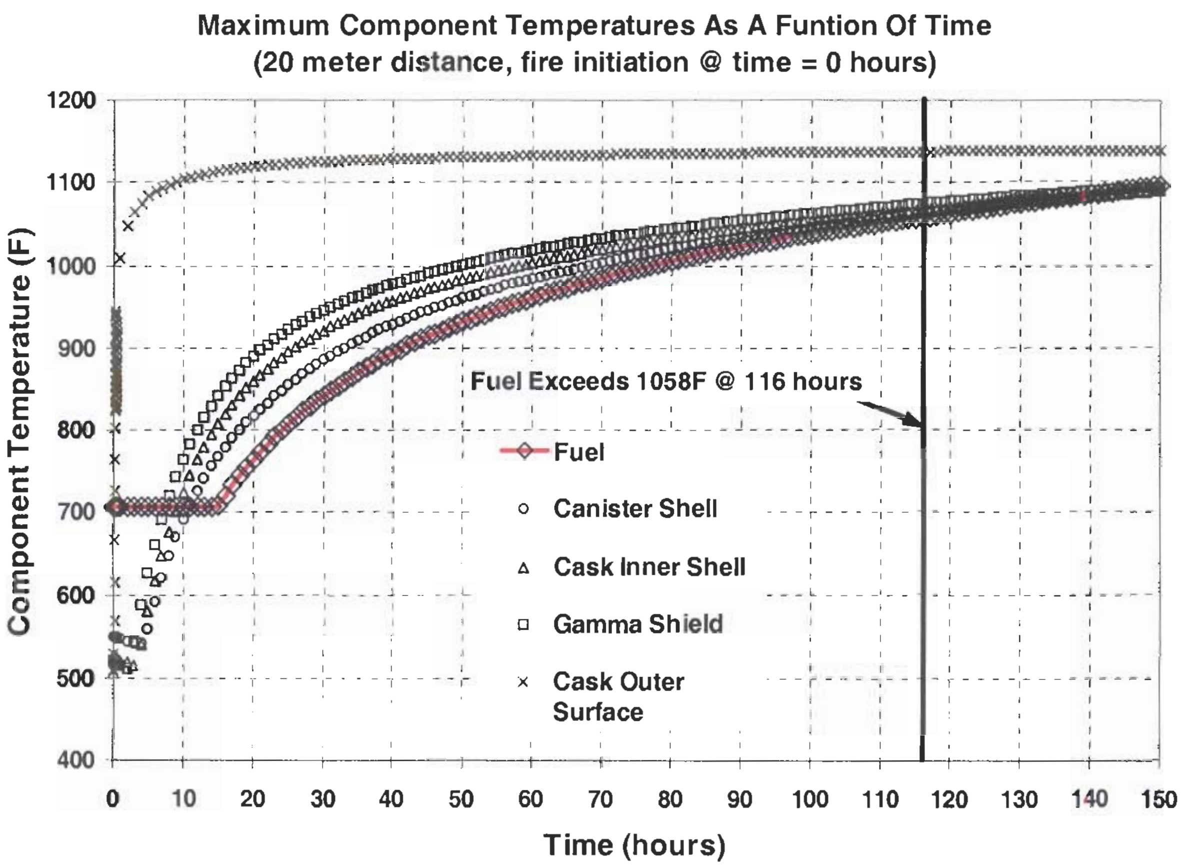


Figure 16

Dr. Garrick questioned what the curves would look like if the model assumed ventilation. Mr. Bajwa noted that ventilation would introduce more oxygen to the fire which most likely would increase temperatures.

The maximum component temperatures were presented as a function of time for the 20-meter case. Based on the analysis results, the fuel temperature does not appear to start heating up for about 15 hours into the fire transient when the cask center is located 20 meters from the fire source. The fuel exceeds the 1,058 °F short-term temperature limit (Ref. 7) at about 116 hours into the transient, assuming the maximum fire temperature for this entire length of time. Staff also graphed a similar plot for the maximum component temperatures as a function of time for the 5-meter case. Obviously, temperatures increase closer to the fire. The fuel temperatures still take about 10 hours before they start to rise from their normal condition. In this case, the 1058°F short-term temperature limit is not reached until 37 hours into the fire.

It is important to note that the 1,058°F short-term temperature limit is not the temperature at which the fuel bursts open. The staff has accepted this temperature as a short-term fuel cladding temperature limit. The temperature limit was actually determined experimentally by exposing fuel cladding to 1058°F for time periods of 30 days to 70 days. The experiments showed no significant cladding degradation or failure. It is not a limit beyond which there is gross fuel cladding failure.

Using stress and creep standards from ASME, staff analyzed the time to failure for the canister (a welded pressure vessel) and determined that the cask and fuel cladding maintained their structural integrity.

Currently, the most severe portion of the fire in the Howard Street Tunnel is believed to have occurred within the first 3 hours; the burning that occurred after that time was actually in the nonhazardous cargo. A number of box cars had paper and paper products in them. Those obviously ignited at some point and burned, but at a much lower temperature than the tripropylene. The consequences of a spent fuel cask being involved in a fire such as the one that occurred in the Howard Street Tunnel are minimal. As a result, the health and safety of the public would have been protected if such a fire had involved a spent fuel transportation cask.

Further, the AAR has developed a performance standard for transporting spent nuclear fuel by rail. That standard will most likely prevent hazardous materials, such as tripropylene or kerosene, from being shipped on the same train as a spent fuel cask. The staff's preliminary conclusion was that additional regulatory requirements are not required to protect spent fuel shipping casks from severe fires if current regulations are followed. Following the AAR performance standard for shipping of spent fuel will add an additional margin of safety.

2.5.2 TWG Questions Regarding NRC Fire Analysis

Dr. Ryan asked for additional information regarding the 1058°F fuel cladding temperature limit. Mr. Bajwa stated that the SFPO currently accepts this criterion as the maximum temperature a cask design is allowed to let the fuel reach for not in excess of 30 days. Dr. Ryan questioned whether the limit was a regulatory number with associated conservatisms. Mr. Bajwa acknowledged that it was.

Dr. Garrick questioned whether the results were independent of the age and burn-up of the spent fuel, as well as the possibility of damaged fuel. Mr. Bajwa stated that the analysis did analyze damaged fuel or high burn-up fuel.

Dr. Wymer noted that the Holtec cask uses aluminum honeycomb impact limiters wrapped in steel and questioned what assumptions were made about how the aluminum behaved at those temperatures. Mr. Bajwa noted that the analysis looked at the center line temperature of the cask; temperature response of the aluminum impact limiters was not analyzed. Dr. Wymer noted that if the aluminum had melted and sagged, it would have a different geometry and questioned how that would have affected the fire analysis. Mr. Bajwa responded that it was possible for the aluminum to melt (the melting point is approximately 600°F), however, the impact limiters do not affect the way the cask is supported in the cradle. Therefore, the cask would not move as a result of the impact limiter melting.

Dr. Wymer questioned whether the results would have differed if the cask used lead shielding. Mr. Bajwa speculated that the greatest affect would probably be that the lead would melt and the cask would lose its shielding capability. It is difficult to determine the structural consequences without further analysis. However, the lead would absorb quite a bit of heat while melting leading to a heat sink after a certain period of time.

Mr. Hodges, Deputy Director, SFPO, noted that the calculations assumed that the maximum fire temperature went on essentially indefinitely. In the Baltimore fire, based on the events that occurred, the intense fire probably lasted for about 3 hours. If there had not be a water main break to cool things down, the fire would probably have lasted about 6½ hours. Therefore, even in the worst case in which all of the fuel in the tank car is burned, the fire will not go on indefinitely. Although this analysis is better than what was done initially, it is still somewhat of a bounding analysis and includes substantial margin.

2.5.3 Stakeholder Questions Regarding Transportation Package Vendor Analysis and Testing, and NRC Fire Analysis

Mr. Resnikoff stated that he found the analysis very impressive and questioned what the response was of the cask's neutron shield, particularly if the cask were to melt, and how the doses would increase and affect firefighters. Mr. Bajwa responded that, for the thermal evaluations, the neutron shield was modeled intact during the fire to increase the amount of heat that was getting into the cask. Mr. Resnikoff asked whether the neutron shield could melt and, if so, what the effects would be to the emergency responders. Mr. Bajwa responded it could melt if it reached the melting temperature. However, the analysis did not assess the effects on dose due to melted shielding. Mr. Bajwa though such effects should be considered in the future.

Mr. Grumski, MHF Logistical Solutions, Inc., noted that administrative controls are put on shipments and, like any nuclear power plant, there are also engineering controls. These latter controls represent the cask design and protection of the cask; administrative controls apply to how spent fuel is shipped. Spent fuel would not be shipped through a tunnel like the Howard Street Tunnel. The shipment would probably be done by a private train service or special train service. Those controls are regulated not only by DOT and NRC, but also by the shipper. Therefore, the tunnel fire scenario modeled is very unlikely to occur in the real world.

Mr. Fronczak, AAR, countered that the scenario modeled is very possible if shipments were made using regular train service under the current general regulatory scheme. However, he agreed that AAR's performance standard and shipping spent fuel in dedicated trains would have eliminated the fuel source. However, if shipments are made by regular freight services under a current regulatory scenario, the tunnel fire scenario is a very real possibility.

Mr. Gutherman, Holtec, clarified that, with respect to the 1058 °F temperature limit, the cladding temperature value used for emergency core cooling systems in operating reactor plants is 2200 °F. This represents a margin of almost 1200 °F. The melting point of zirconium or zircalloy cladding is some number of degrees above 2200 °F.

Ms. Gue, Public Citizen, took issue with Mr. Bajwa's concluding statement that the health and safety of the public are protected. This study has been presented with a blanket conclusion that no radiation would have been released that could be damaging to the public. However, the study did not consider the fire's effect on shielding and how that might impact emergency response efforts. Ms. Gue explained that the public loses confidence in the NRC when it presents studies that are somewhat misleading. Ms. Gue suggested that NRC better communicate what the studies involve and not just state conclusions.

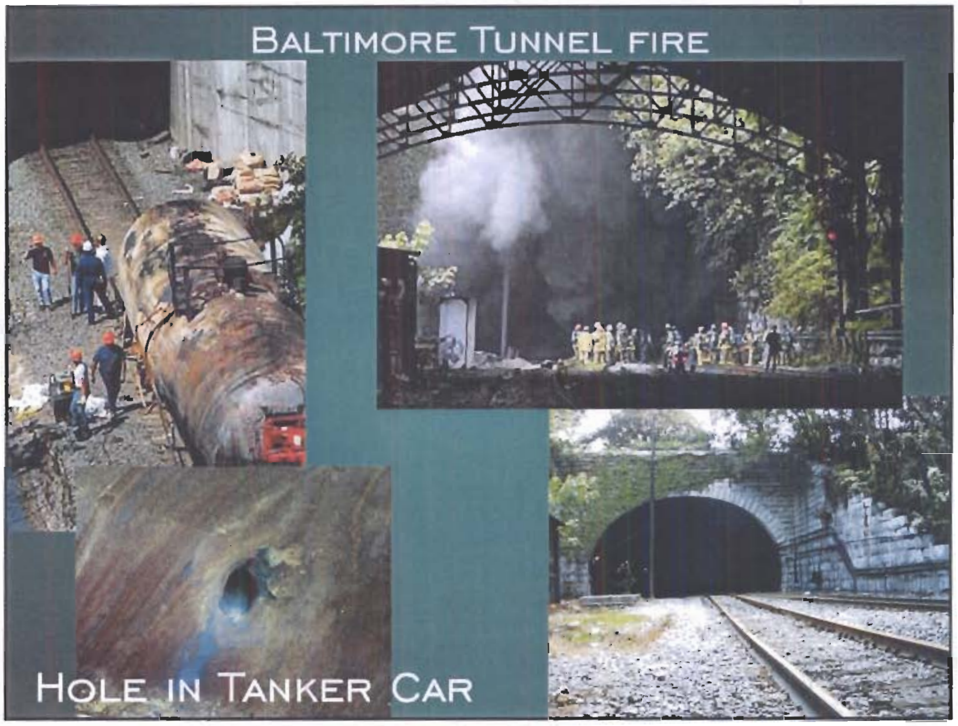
Staff Review and Analysis of the July 2001 Baltimore Tunnel Fire Accident

Christopher S. Bajwa
Spent Fuel Project Office, NMSS
U.S. Nuclear Regulatory Commission
Presentation to the Advisory Committee on Nuclear Waste
November 19, 2002
Rockville, MD

Introduction

- Baltimore Tunnel Fire Accident
- Coordination with NTSB
- Preliminary Scoping Analysis
- NIST Tunnel Fire Model
- Validation of NIST Fire Model
- Refined Cask Analytic Model
- Conclusions

2



COORDINATION WITH NTSB

- NTSB – LEAD INVESTIGATIVE AGENCY
- DERAILMENT WAS PRIMARY CONCERN
- NTSB PROVIDED INFORMATION, DATA AND TECHNICAL EXPERTISE ON RAIL EVENTS
- PROVIDED ACCESS, THROUGH CSX, TO RAIL CARS & TUNNEL

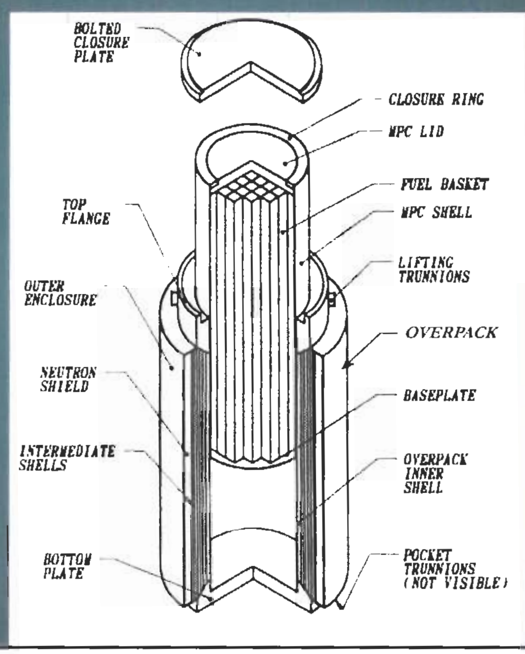
4

Preliminary Scoping Analysis

- Selection of a Spent Fuel Transportation Cask
- Finite Element (ANSYS®) Model
- 10 CFR 71.73 Requirements
- 7-Hour Bounding Analysis

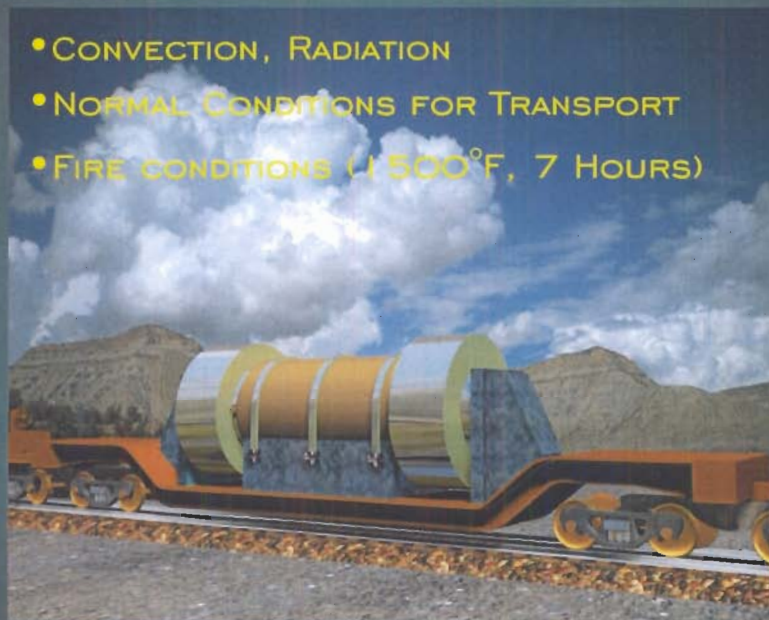
5

Spent Fuel Transportation Cask



Boundary Conditions

- Convection, Radiation
- Normal Conditions for Transport
- Fire conditions (1500°F, 7 Hours)



7

Preliminary Results

- No cladding failure (based on temperature)
- No canister failure (based on stresses at temperature and on creep criteria)
- No radioactive release

8

NIST Tunnel Fire Model

- Fire Dynamics Simulator (FDS)
- Validated with Memorial Tunnel Fire Test Program Data
- Results used as input to revised analysis

9

Howard Street Tunnel Fire Model

- Railcars in derailed position
- Grade of tunnel modeled
- Tripropylene pool used as fuel
- No ventilation in model
- Steady State conditions reached 30 minutes into simulation

10

NIST Howard Street Tunnel Fire Model

Analysis of Physical Evidence

- Further data to support NIST results
- CNWRA Material and Fire experts
- Samples obtained from Rail Cars
- Metallurgical Analyses Conducted
- Results reported by CNWRA consistent with NIST temperature results

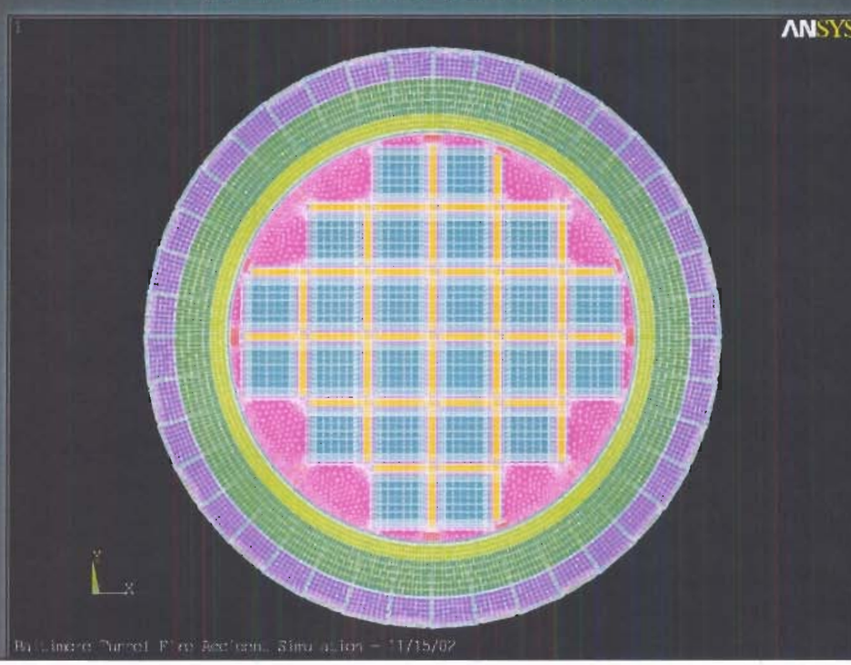
12

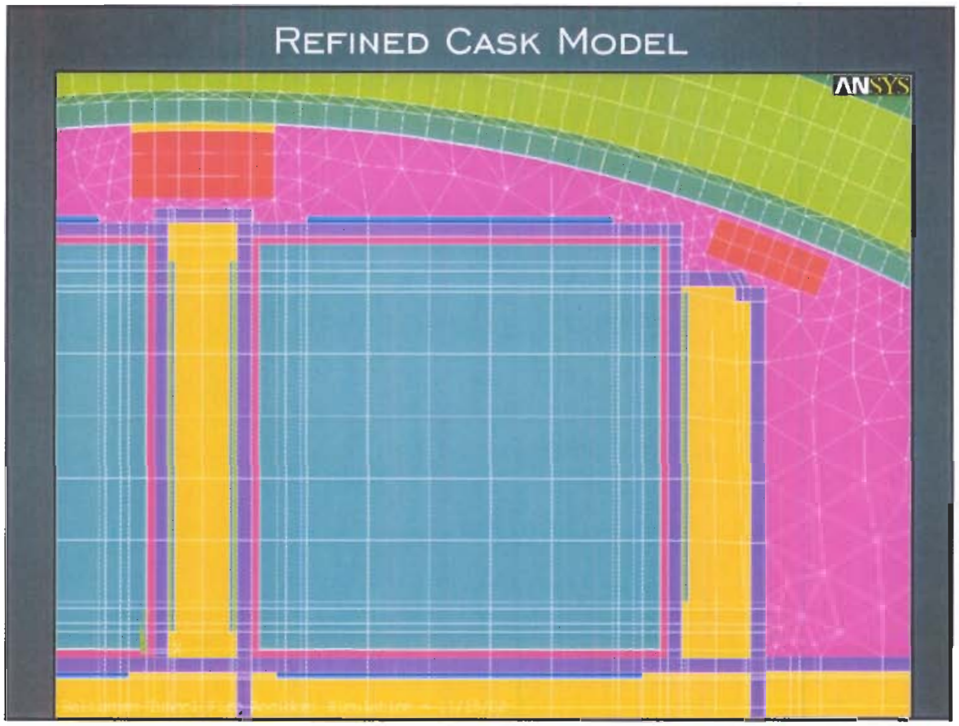
Revised Analysis Based on NIST Data

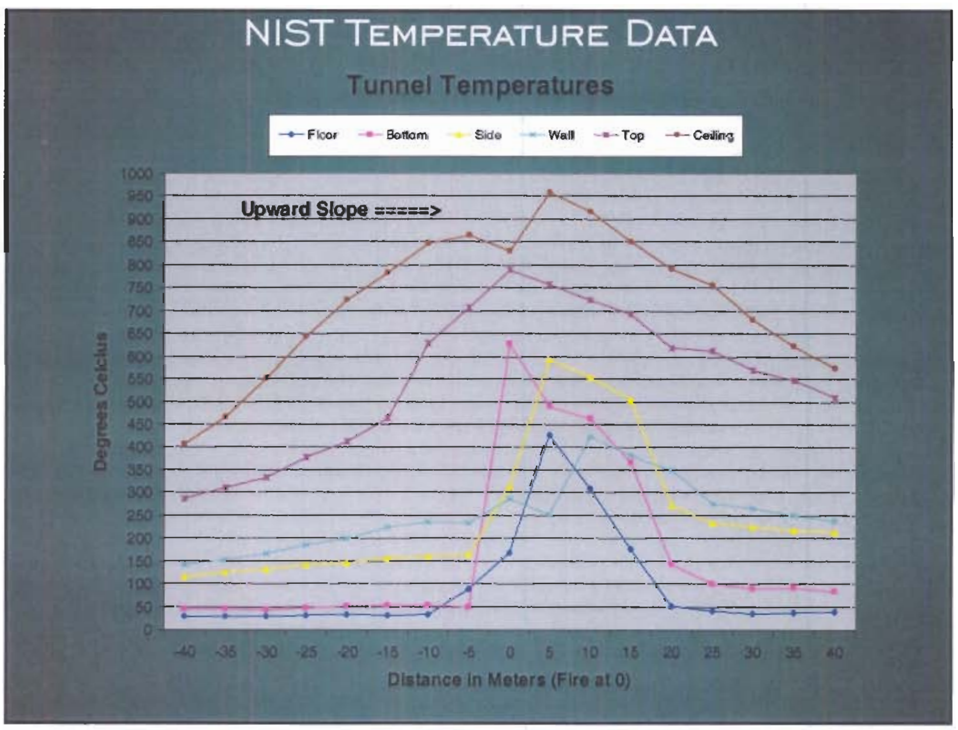
- Assessments Applied NIST Data (temperature and flow)
- Assessment – 1: Cask center 20 Meters (one rail car length) from fire per federal regulations (49 CFR 174.85)
- Assessment – 2: Cask located adjacent to fire (5 meters from fire to center)
- 2D Cross-Section with support cradle
- 3D Model under development

13

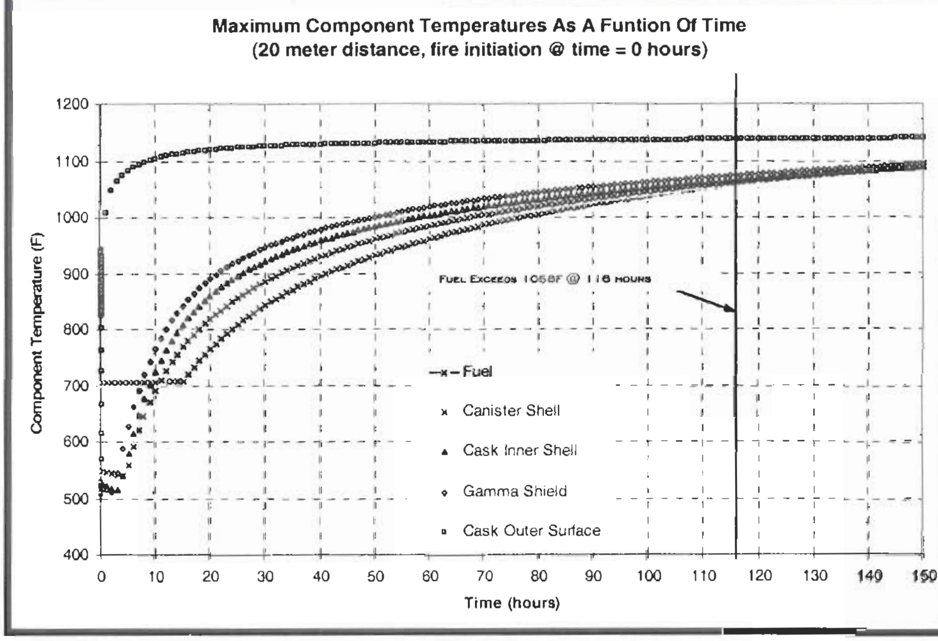
Refined Cask Model



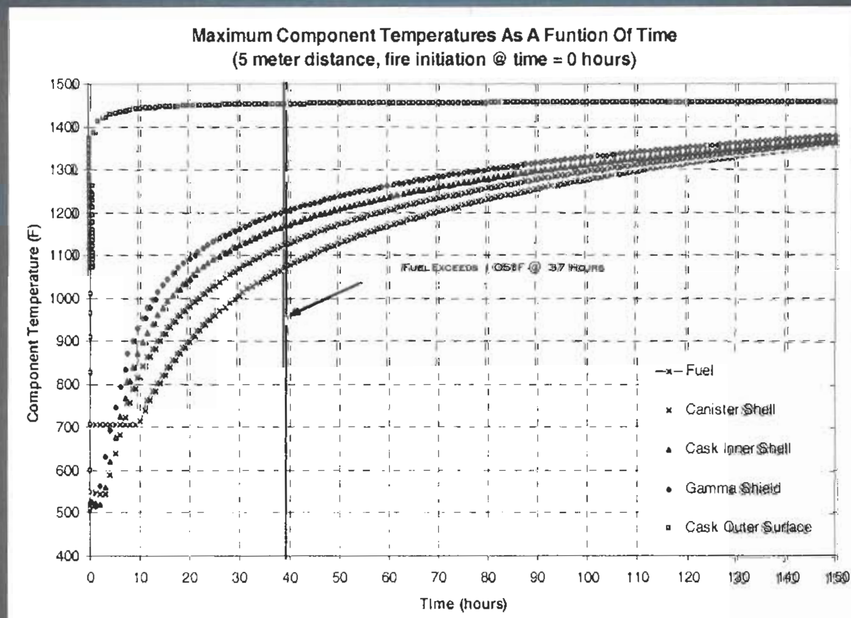

REFINED CASK MODEL
ANSYS


NIST TEMPERATURE DATA
Tunnel Temperatures
Floor
Bottom
Side
Wall
Top
Ceiling
Upward Slope =====>
Degrees Celcius
Distance in Meters (Fire at 0)

20 M Results From Revised Analysis



5 M Results From Revised Analysis

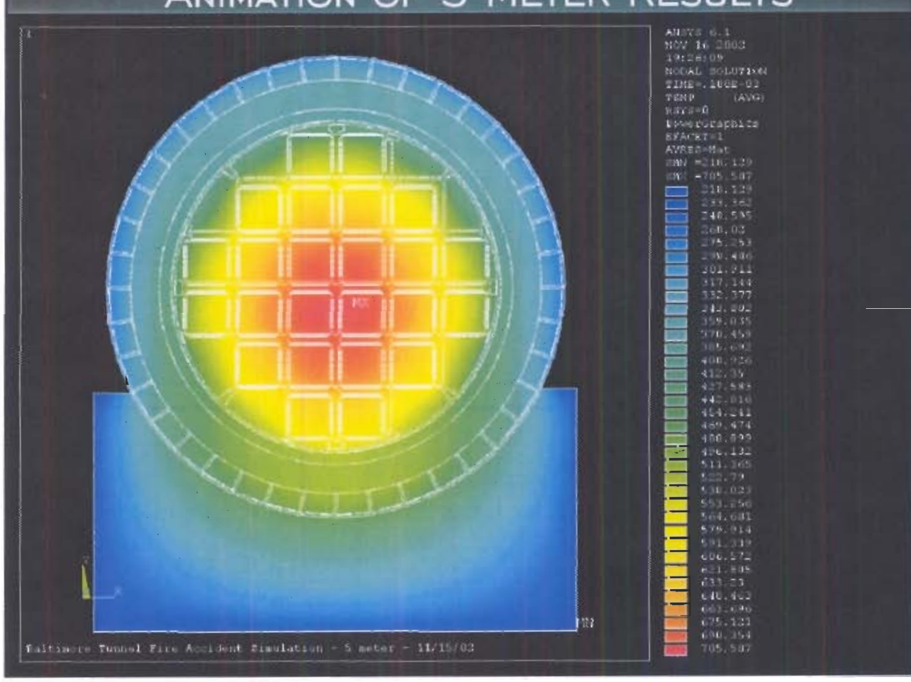


Results From Revised Analysis

- Time to exceed short term fuel temperature limits (1058°F)
  - For 20 meters over 100 hours
  - For 5 meters over 30 hours
- Time to canister failure
  - For 20 meters over 30 years
  - For 5 meters over 30 years

19

Animation of 5 Meter Results



Conclusions

- Cask Performance
- Consequences of fires
- Health and Safety of the Public Protected
- AAR performance standard for transporting spent fuel by rail
- Preliminary Conclusion: additional regulatory requirements not necessary if current regulations and AAR performance standards are followed

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Acknowledgements

- Mr. Harold E. Adkins, Jr. (PNNL)
- Mr. Brian Koeppel (PNNL)
- Dr. Kevin McGrattan (NIST)
- Mr. Jay Kivowitz (NTSB)

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2.6 Analysis and Testing Compared to Actual Rail Experience

2.6.1 Comparison of Analysis and Testing to Actual Railway Experience, Bob Fronczak, AAR

Mr. Fronczak, AAR, has been involved in the railroad industry for 25 years. He discussed analyses contracted by AAR to review crush loads, collisions with structures and falls, thermal event frequencies, and structural strength of rail cars. These are four major issues that concern the AAR. Mr. Fronczak also discussed the AAR performance standard for spent nuclear fuel.

With regard to cask integrity, the AAR has recommended for many years that the rail industry ship spent fuel at 35 mph with a standing pass rule that if one train meets another train carrying spent nuclear fuel, one train needs to stand while the other one passes at a speed no greater than 35 mph. This recommendation is based on the 30-foot drop test which accelerates a cask to 30 mph.

In preparation for the opening of Yucca Mountain, the AAR commissioned two reports in 1998 to analyze and communicate to the public how NRC studies relate to the actual environment. During this time, the AAR reviewed the Modal Study very closely.

One of the reports was commissioned to Trances and the other to the Texas Transportation Institute. Both of these reports were given to NRC about 2 years ago in preparation for the PPS.

The Trances report concluded that in some railroad accidents, spent fuel casks might not be able to withstand the forces. Based on this conclusion, the AAR commissioned the second report. The second report assessed the consequences of an accident that resulted in a radiological release. That report determined that if a radiological release were to occur, the public health would not be affected, assuming that no one was right next to the cask at the time of the incident.

Analyses of crush loads are not required by NRC regulations. Rail, by definition is multiple packages being transported together. In a derailment, the AAR considers crush loads to be a very real possibility. However, the Modal Study identified the frequency of crush loading as being 1/10th of that of impact loading and only 0.8 percent experienced impact with a coupler or significant frame member of other vehicles. Therefore, the AAR believes that NRC should analyze for crush loads.

Thirty percent of train accidents in 2001 involved derailment of more than five cars. As the speeds increase in derailments, more cars are derailed and the accidents are more significant.

Dr. Hornberger asked if a "crush load" referred to one car piling on top of another. Mr. Fronczak responded affirmatively. Analysis of crush loads is a regulatory requirement for small packages. While the likelihood of a crush load with a large package is small, the AAR believes that, in a North American rail environment, it is a real possibility. The standard rail freight vehicle is centered at 263,000 pounds going up to 286,000 pounds.

Mr. Fischer pointed out that the Modal Study did analyze a General Electric locomotive (weighing 300 or 400 tons) landing on top of a cask. Mr. Fronczak noted that this was not what the AAR's consultant found.

Another source of information on this topic is the FRA database which includes the number of cars involved in derailments. The AAR-RPI tank car safety research and test project also maintains a 30-plus year database of over 30,000 damaged tank cars. However, to acquire the data for crush loads in that database would require manually reviewing individual records, but they are available.

The Modal Study used highway data to evaluate impacts with structures and falls. The AAR believes that the railroad environment is substantially different than the road environment. The AAR concluded that the Modal Study likely underestimated the frequency of rock cuts, impact with embankments, water crossings, and large structures that are unique to rail shipments.

For thermal event frequencies, the Modal Study identified that 81 percent of fires last less than 1 hour; 99 percent of fires last less than 7 hours. However, the Eggers data, which were evaluated but not used, identified that 50 percent of fires last less than 11 hours and 99 percent of fires last less than 130 hours. Therefore, the AAR believes that using the Eggers data in the Modal Study would have been a more conservative choice. In addition, in 1996, in Weyauwega, Wisconsin, a train derailment involving liquid petroleum gas resulted in a fire that lasted 18 days, or 360 hours, during which time the town had to be evacuated.

Mr. Fronczak also stated that the AAR believes the Modal Study underestimated the structural strength of rail cars. The Modal Study used 100,000 pounds per foot or 1 million pounds for a 10-foot-wide locomotive and 1.6 million pounds for a 16-foot-long cask. However, locomotives are designed to withstand 1 million pounds of force at the coupler without permanent deformation. The AAR's finite element analysis indicated that 3 million pounds would be applied at the coupler height and 10 million pounds at the frame's neutral axis.

The AAR has a performance standard for trains shipping spent nuclear fuel. This standard is different than most of the other standards that are in the AAR's manual of standards and recommended practices in that it includes all the cars on the train. The standard requires static and dynamic modeling before construction and requires full-scale characterization and both static and dynamic testing of each car and the train. All testing is performed at a test facility before the car is approved by the AAR Equipment Engineering Committee. The car is then analyzed; a report must be submitted after 100,000 miles of operation to ensure that it is still meeting the standard.

The road worthiness criteria, or performance requirements in the standard, exceed today's standard freight car designs. An enhanced performance truck is required to meet the design criteria in this new performance standard. It is also required to have electronically controlled pneumatic brakes. This reduces the stopping distance significantly. In a loaded coal train, about a 30 percent benefit is achieved in stopping distance.

The AAR envisions that a fairly short, dedicated train will be used to transport spent fuel, therefore, not all the benefit of a reduced stopping distance will be realized. However, this does provide a conduit between all the cars in the train for on-board monitoring of some defect parameters.

The performance standard requires monitoring for things like truck hunting, where the trucks will actually go back and forth. Again, that is a mode of derailment. Wheel flats, you might hear that as cars go by, as that wheel pounds. That is another mode of derailment. Braking performance, and vertical and lateral longitudinal acceleration are also monitored.

The monitoring required by the performance standard includes hot box detectors, spaced periodically along the tracks, to look for hot bearings. These will monitor the actual bearing temperature on board and will be able to stop the train if there were a potentially hazardous increase in temperature.

Figure 17 is a schematic diagram of how the AAR envisions a spent fuel train. The figure shows two locomotives. The train will not require two locomotives because of weight; the second locomotive provides redundancy in case the first locomotive fails en route.

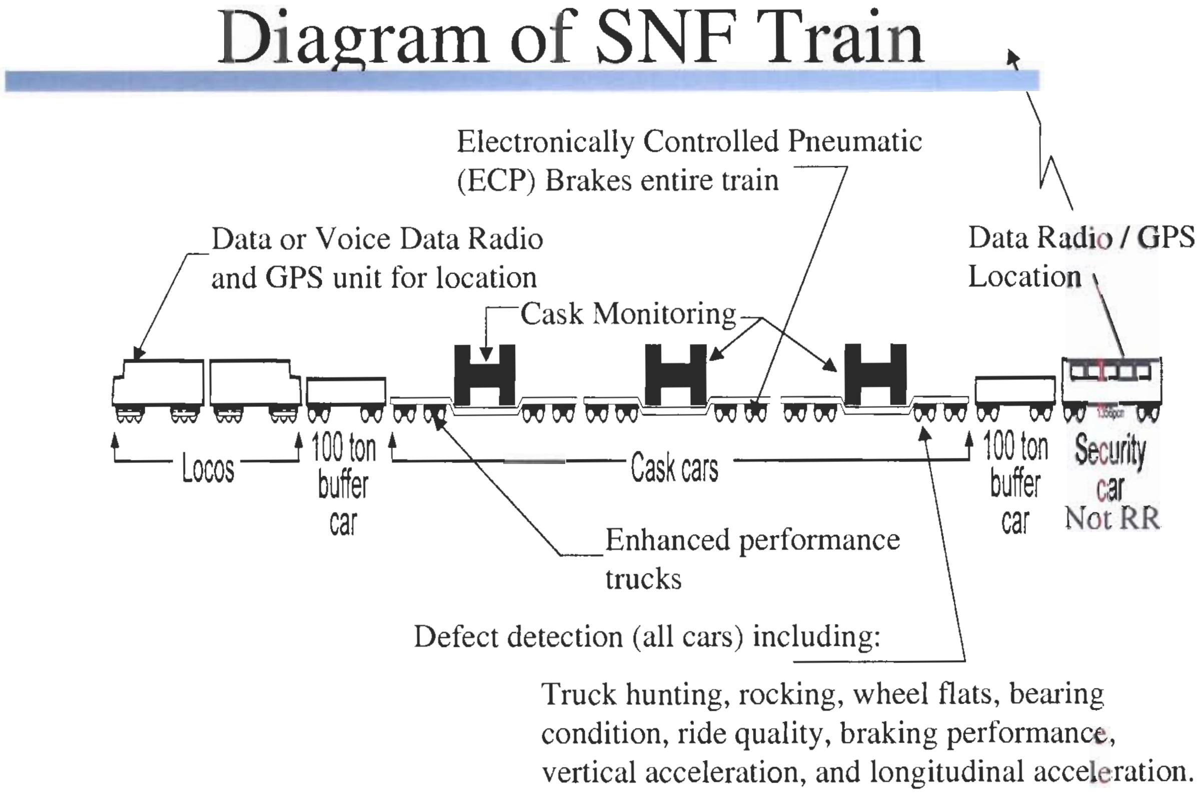


Figure 17

A buffer car will be placed between any occupied vehicle and the first cask car. The buffer car needs to be of consistent size and weight with the other cars in the train. There is a security car at the end of the train. The AAR believes that the security car should be a personnel car or perhaps a retrofitted passenger car. This would allow permanent occupancy of the people who would be escorting the shipments so security personnel would not need to be switched en route. The enhanced performance truck and defect detection equipment is located throughout the entire train.

The AAR has implemented some other performance features including OT-55. This is the AAR's recommended operating practice for hazardous materials. OT-55 includes increased track and equipment inspection requirements and increased defect monitoring. Specifically

OT-55 requires the wayside hot bearing detectors to be spaced more frequently than on other sections of track, increased maintenance frequency, increased employee training, and there is a maximum speed limit of 50 mph. Although in the past, the AAR recommended a maximum speed limit of 35 mph with a standing pass, it is now recommending a maximum speed limit of 50 mph with no passing restriction.

PFS is the first organization to design spent nuclear fuel equipment to the new performance standard. Its prototype cask car was manufactured by Trinity Industries. The overall weight of the cask car-cradle combination is 476,000 pounds which is much heavier than a typical rail car. The car is a span bolster, eight-axle vehicle. There is a two-axle truck on each side. It is depressed well.

The modeling and characterization for this cask car has been completed. The on-track testing is currently being performed at the AAR transportation technology center in Pueblo, Colorado, and should be completed by the end of 2002.

The performance standard does not require dedicated trains because of a Supreme Court will decision prohibiting a dedicated train requirement. However, many of the benefits of the performance standard are lost if shipments are not made by dedicated trains because the on-board defect detection systems will be negated. PFS is designing its system as a dedicated train system incorporating all of the requirements of the performance standard.

PFS Railcar at TTCI for Testing

Figure 18

In summary, the AAR believes that testing issues should address crush loads, collision with structures, etc. The AAR is committed to incorporating technology improvements into the transportation of spent fuel and high-level waste and will continue to look for beneficial ways to achieve this commitment.

2.6.2 TWG Questions Regarding Comparison of Analysis and Testing to Actual Railway Experience

Dr. Ryan commented that he had learned quite a bit about rail shipments during the presentation and asked whether any materials were now being transported under a dedicated train arrangement. Mr. Fronczak responded that most shipments of spent nuclear fuel have been made by dedicated train, whether a dedicated train was requested or not. For instance, the U.S. Navy requests regular train service, but Union Pacific and BNSF will not ship spent fuel that way. By contrast, most of the DOE shipments have been made by dedicated train at the Department's request [(e.g., the foreign research reactor shipment made out of Concord, California, to Idaho National Engineering and Environmental Laboratory (INEEL)]. DOE also planned for shipments from West Valley, New York, to INEEL to be made by dedicated train.

Dr. Ryan questioned whether any materials in commerce, other than spent fuel, are currently being shipped using a dedicated train with enhanced monitoring. Mr. Fronczak responded no.

Dr. Ryan questioned whether performance numbers (tip-over, derailments, and car failures) for a dedicated train segment were better than other shipments. Mr. Fronczak responded that there is a lack of data on the use of dedicated trains. However, a significant amount of data on regular trains does exist. Dr. Ryan offered that it might be interesting to separate the data as a means of answering the question, "What am I buying?"

Dr. Garrick stated that he had written a paper about 20 years ago that concluded that the use of dedicated trains does not improve safety. Dr. Garrick participated in hearings with the Interstate Commerce Commission (ICC) in the 1970s which concluded that there was no scientific basis for requiring dedicated trains to be used for the shipment of radioactive materials. The hearings were a very high-level discussion of all the scientific information in the 1970s and were attended by representatives of all the major railroads and the AAR, as well as the scientific community. The issue was discussed very thoroughly at that time. Dr. Garrick believes that the user has the privilege to finance a dedicated train, however, the TWG must deal with scientific evidence. Dr. Garrick agreed with Dr. Ryan's previous question, noting that if today's contemporary thinking about risk were applied that to the different kinds of cargoes that are currently on the railroads, then from a risk standpoint, radioactive shipments would come out at the top in terms of being the most safe. Dr. Garrick questioned what has happened between the 1970s and now that would cause the AAR to feel as strongly as is does about the use of special trains.

Mr. Fronczak responded that the AAR and its members have felt for years that things can be done to make these shipments safer. The AAR feels that it owes it to the public. For example, in a scenario like the Baltimore Tunnel fire, a dedicated train would not have included flammable cargo. The FRA was mandated by Congress in 1994 to perform a dedicated train study. That study has not yet been published although FRA Administrator Rudder indicated that it would be completed in 2002. Mr. Fronczak suggested that the controversial nature of this study may be the reason why it has not yet been published.

Dr. Ryan questioned how the AAR prioritized the risks faced by the industry. Mr. Fronczak responded that this is accomplished by risk management. Such prioritization has led to significant safety increases. For example, there have been tremendous improvements in chlorine tank cars over the last 20 years. There have also been tremendous improvements in liquid petroleum gas transportation. Had the derailment that occurred in Weyauwega, Wisconsin, happened 30 years ago, fatalities would have resulted. The safety vents that are put on the cars, the thermal protection that is put on the cars, the bottom and top outlet protection that is put on the cars—all of those things have been done by industry initiatives and industry-funded research. There have been approximately 3 fatalities in the last 15 years caused by hazardous materials transportation by rail. In contrast, there are probably 18 to 20 fatalities per year on the highway. Therefore, the AAR believes it has significantly improved the transportation of hazardous materials by rail.

Dr. Hornberger stated that he was impressed with the requirements of OT-55D for hazardous materials and questioned whether the AAR is recommending dedicated trains for all hazardous material. Mr. Fronczak responded no. The AAR believes that the transportation of spent nuclear fuel should be made by dedicated trains for several reasons, including efficiency. In addition, Mr. Fronczak does not believe that NRC wants the casks and their guards sitting around in rail yards for 48 hours waiting to be switched into another train.

Dr. Hornberger acknowledged that the AAR's reasons are very sensible reasons. However, they have nothing to do with safety. Mr. Fronczak argued that there is less of a probability of derailment. The AAR does not want that incident to occur on the railroads. Dr. Hornberger noted that it was still unclear why the public would be concerned about a derailment of a spent fuel cask and not of a tank with ammonia, chlorine, or natural gas.

Mr. Levenson questioned whether the AAR's recommendation to use dedicated trains was based on a risk analysis. It did not appear that any data indicate that dedicated trains are really safer. Mr. Fronczak stated that the AAR reviewed a substantial amount of data for the current railroad design criteria regarding the derailment rates for the existing standard versus what could be expected if trains were designed to the new performance standard. The analysis indicated that the new design is safer in terms of fewer derailments with dedicated trains. However, Mr. Fronczak agreed that if multiple packages are shipped together, there is a possibility of the casks impacting each other. Hence, the new performance standard requires double shelf couplers so that those cars stay together when they are derailed. Dr. Ryan asked whether this analysis had been published by the AAR and Mr. Fronczak responded no.

Dr. Garrick acknowledged that the AAR has done a good job of stating why it is in favor of dedicated trains. Public confidence has to be a major consideration. However, the TWG is focused on the technical basis. As discussed, the ICC and the Supreme Court have not identified sufficient scientific evidence to support the need for dedicated trains to transport nuclear materials. Regardless, the railroad industry appears to continue to believe very strongly that dedicated trains are in order for a material that is probably much less of a risk to the public safety based on technical and scientific evidence, than many other materials that are routinely shipped. The TWG is trying to understand what has changed in the last 20 years that would account for the AAR position. Mr. Fronczak responded that PFS is convinced that spent fuel should be shipped on a dedicated train. Mr. Fronczak further pointed out that most all shipments of spent fuel are made by dedicated train.

Mr. Kobetz questioned what type of analysis was performed and what variables were considered for the Modal Study with regard to crush accidents. Mr. Fischer responded that he believed that the Modal Study analyzed a drop of a few feet onto the cask. It was a direct hit made to the top of the cask. The crush did not result in much damage. Therefore, the study researchers decided not to look further into that scenario because other scenarios were thought to be much more significant, as well as more credible.

Dr. Hornberger asked if the analysis depended upon the cars being launched airborne resulting in an impact load rather than a static load. Mr. Fischer responded that the load was flat across the top of the cask with a dynamic load factor (not a 30-foot drop). Mr. Yaksh commented that it was important to keep in mind that these transportation casks weigh about 200,000 pounds, and are designed to withstand roughly a 60g load. Putting it into perspective, a crush load from a 300-ton locomotive does not come close to a load 60 times 200,000 pounds. In addition, the locomotive is not a rigid item so the load will pass through and the transport cask is supported in such a way that the load will pass through. Mr. Fischer added that the locomotive was destroyed when the British ran it into the cask in Operation Smash Hit. The engine was actually torn up.

Mr. Levenson acknowledged, that in connection with the regulatory agency, railroads base their decisions on many different things and not just on the technical issues. However, the TWG must not involve itself in the economic and efficiency issues. Instead, the TWG must to focus on the technical issues.

2.6.3 Stakeholder Comments and Questions Regarding Comparison of Analysis and Testing to Actual Railway Experience

Mr. McCarville, Booz Allen Hamilton, noted that he had formerly worked for Edlow and Ashland and managed a number of spent fuel shipments by rail. In those shipments, the buffer cars were always empty. In the AAR scenario, there is a 100-ton buffer car. Mr. McCarville asked what analysis was performed to support that recommendation and configuration and how it would be procured. Mr. Fronczak responded that Union Pacific developed the loaded buffer car to meet the U.S. Navy requirement that its shipments be at the end of regular trains. Mr. Fronczak explained that in-train forces can be so large that they can actually lift a lighter car off the track and cause a derailment. Therefore, it is desirable that a car of consistent weight with the other cars in the train, and not just a lightly loaded or empty car, serve as a buffer car.

Mr. McCarville questioned whether an analysis had been performed on loads between the security car and locomotive with personnel in it, noting that if the 100-ton buffer car is right next to a personnel car it would seem that there would be some crush testing safety effects should be assessed. Mr. Fronczak stated that the performance standard requires that the personnel car meet the same design requirements as a freight car which have been analyzed in the Navy situation.

Mr. McCarville asked what a 100-ton buffer car would look like in terms of its configuration. Mr. Fronczak responded that it would be similar to a gondola car with ballasts in it.

Mr. Grumski, MHF, questioned what the average cost was per mile is of a dedicated train. Mr. Fronczak responded that the AAR did not get involved in costs at all. Its members deal with costs and the AAR is restrained by antitrust laws from talking about cost. However, some information is available. For instance, such information was discussed in the report on the Three Mile Island (TMI) shipments.

Ms. Gue, Public Citizen, asked whether the AAR has any enforcement capability with respect to its performance recommendations. Mr. Fronczak responded that the AAR is a nonprofit industry association whose members are the Class 1 railroads, including Burlington Northern, Santa Fe, Amtrak, Canadian National, Canadian Pacific, CSX Transportation, Norfolk Southern, Kansas City Southern, and Union Pacific Railroad. The AAR sets voluntary standards because its members regularly interchange equipment with one another. If the couplers did not have the same height, equipment could not be interchanged. In this context, Mr. Fronczak explained that the AAR standards are enforceable if something is transported in the interchange of the U.S. rail network. Carriers also make private agreements.

Ms. Gue questioned whether there was something that the AAR would do, similar to DOT or NRC, if it were a Federal regulator. Mr. Fronczak stated that these are recommended practices, that the AAR members have agreed to. The members would not agree to these practices if they were not already implementing them or wanting to implement them.

Ms. Gue stated that some experience with industry self-regulatory arrangements in other fields suggests that it has been somewhat of a limiting factor. She expressed concern, from a public interest perspective, about relying on industry self-regulation. As important as AAR's input is, Public Citizen would like to see some of these recommendations adopted by the Federal regulatory agencies, including the NRC, that have enforcement and oversight capabilities.

Ms. Gue hoped that it was clear to everybody that the large-scale shipment of high-level nuclear waste, such as that being contemplated to Yucca Mountain, does pose unusual risks and that high-level nuclear waste is not the same as a number of other hazardous materials that are currently being shipped. Furthermore, Ms. Gue believes that the combination of those risks should also be of concern. For example, shipping a spent fuel on a non-dedicated train introduces the possibility of having both an explosive or a flammable material in combination with a cask of high-level waste in the same accident situation.

Based on her public interest perspective, Ms. Gue expressed her concern about the kind of risk assessment recommendations that seem to imply a trade off between two risks when, in fact, the public is being asked to incur additional risk. Regulatory agencies, as well as the various industries involved, should do everything they can to minimize existing risks and to avoid exposing the public to additional risk.

Dr. Garrick stated that Ms. Gue should be held accountable in the same way that the presenters are held accountable when it comes to making such observations. He felt that Ms. Gue made a fairly dramatic observation about the uniqueness of risk with respect to the transportation of spent nuclear fuel and requested that she provide evidence, from a risk perspective, for this observation.

Dr. Garrick further stated that as an analyst, he believes analysis must be based on real evidence. He suggested that the only evidence to support Ms. Gue statements was opinions. He asked Ms. Gue to come forth with the evidence that supports her claims.

Ms. Gue responded that the nondebatable evidence is just the nature of the substance that is being discussed. Unshielded, a 10-year-old fuel assembly releases enough radiation within a matter of minutes to be lethal from just a few feet away. Ms. Gue acknowledged that unshielded fuel assemblies would not be shipped, but she believes that the intense danger of the material itself underscores the need for regulations to ensure the safety of shipping nuclear waste.

Ms. Gue further stated that it would be very useful for NRC to recommend to DOE that it release the specifics of the transportation plan with respect to Yucca Mountain. It is difficult to analyze some of the risks without information about which routes will be used by which mode of transportation. In addition, Ms. Gue would like to know how many tunnels comparable to the Baltimore Tunnel are actually on the routes that might carry high-level waste shipments to Yucca Mountain.

Finally, Ms. Gue observed that the agenda seemed to have focused only on the impact tests and the fire tests. She wondered why the Working Group did not examine the drop test and submersion issues, particularly given an apparent preference for train shipments. Further, DOE has indicated the use of some unusual barge shipments of waste on the waterways. Ms. Gue encouraged the Working Group to also look into that. She stated that Public Citizen is also concerned about the lack of inclusion in the regulatory requirements, as well as in the current PPS outlines, consideration of explosive impacts and the vulnerability of these shipments to terrorism.

Ms. Gue pointed out that with all of the conversation about the importance of public confidence and the regulatory and test activities that are being done to enhance public confidence, future meetings of the TWG in this type of forum should include representatives from some of the public interest organizations with a stake in the process. The only presenters outside of the agencies were representatives of the various industry interests.

Mr. Levenson explained that one of the reasons the speakers were limited is that the TWG is trying to focus only on the technical issues. There are many public issues; however, that is a whole different agenda. The TWG would be interested in a presentation by any public interest group that had a research organization and technical data.

Mr. Levenson questioned whether, with regard to multiple risks, the AAR allows box cars full of dynamite or TNT to be on a train carrying ammonia and liquid petroleum. Mr. Fronczak responded yes.

Mr. Resnikoff pointed out that the U.S. Navy sometimes ships exclusive use trains to carry missiles and torpedoes. There have been some horrendous accidents involving a train full of missiles and torpedoes. Mr. Resnikoff supported Ms. Gue's comments concerning sabotage. He added that it would be very helpful if NRC looked into this issue and published something about it.

Mr. Resnikoff agreed with Dr. Singh that, based on work performed in Utah, a jet engine would not penetrate a transportation cask. Furthermore, it is an almost impossibly small probability because the horizon is too low to allow a jet plane to hit a horizontal cask car. For example, it is almost impossible to hit the Pentagon without the plane hitting the ground first. Mr. Resnikoff thought it is more important to consider anti-tank missiles and bridges. This issue was not looked at in the Modal Study because a probability cannot be easily assigned to it.

Mr. Levenson again pointed out that although the workshop did not address terrorism activities, it does not mean they are not being looked at. What it suggests is that they are being looked at in a classified manner. Mr. Levenson concluded by stating that there are lots of things underway that cannot be discussed in public meetings.

Comparison of Analysis and Testing to Actual Railway Experience

Association of American Railroads

By: Bob Fronczak
AVP Environment and Hazmat

Of: Association of American Railroads

For: U.S. Nuclear Regulatory Commission
Rockville, MD
November 19, 2002

1

Outline

Association of American Railroads

- Testing Issues
  - AAR Cask Integrity work
    - Crush loads
    - Collisions with structures & falls
    - Thermal event frequencies
    - Structural strength of railcars
- Performance Standard for SNF Trains

2

Cask Integrity

Association of American Railroads

- AAR commissioned two reports:
  - "Rail Transport of SNF - A Risk Review," G.W. English, et.al., July 1995 (revised 11/95; 6/96; 12/97) (Report #1)
  - "Railroad Transport of SNF," James Rock, et.al, May 27, 1998 (Report #2)
- Sent to NRC January 2000

3

Report Conclusions

Association of American Railroads

- Conclusion Report 1:
  - SNF Casks might not be able to withstand forces conceivable in all railroad accidents.
- Conclusion Report 2:
  - Agreed with 1st report but, determined that public health would not be affected in the event of an accident.

4

Issues Raised in Report 1

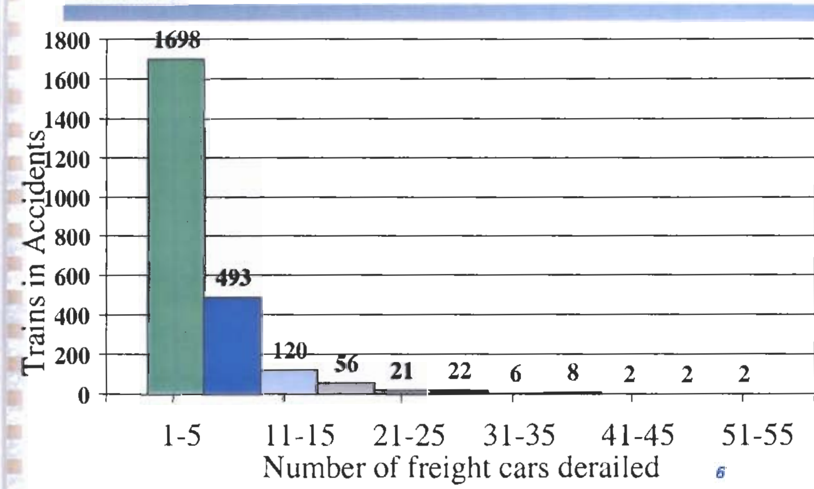
Association of American Railroads

- Crush loads:
  - Not required for large packages (only if mass less than 227#)
  - Rail cask = 125 tons (250,000#)
  - Real probability in rail accidents
    - By definition, rail transport involved multiple vehicles
- Modal Study:
    - Frequency of incidence of crush loading was assessed as one-tenth that of impact loading
    - Only 0.8% experience impact with a coupler or significant frame member of other vehicles.

5

30% of Trains in Accidents in 2001 Derailed More Than 5 Cars

Association of American Railroads



6

Sources of Information

Association of American Railroads

- FRA database includes the number of cars involved in derailments
- AAR-RPI Tank Car Safety Research and Test Project
  - Over 30,000 damaged tank cars in database (over 30 years of data)
  - Could be used to determine percentage subject to crush loads
  - Will require manual search of records

7

Collision with Structures and Falls

Association of American Railroads

- Modal study used highway data to evaluate impacts with structures and falls
  - Railroads different (more cuts and fills)
  - Underestimates:
    - Frequency of rock cuts,
    - Frequency of embankments,
    - Frequency of water crossings and
    - Possibly the frequency of large structures

8

Thermal Event Frequencies

Association of American Railroads

- Should evaluate thermal event frequencies more closely
- Modal Study
  - 81% fires < 1 hour
  - 99% fires < 7 hours
- Eggers
  - 50% fires < 11 hours
  - 99% fires < 130 hours
- Eggers would have been the more conservative choice
- Weyauwega WI 1996 fire lasted 18 days (360 hours)

9

Structural Strength of Railcars

Association of American Railroads

- Underestimated in Modal Study
  - 100,000 lb / foot
  - 1 million lb for a 10 ft-wide locomotive
  - 1.6 million lb for a 16 ft long cask
- Locomotives designed to withstand 1 million lb force at the coupler without permanent deformation
- Finite element analysis indicates that:
  - 3 million lb if applied at coupler height
  - 10 million lb if applied at the frame's neutral axis

10

Performance Standard for Spent Nuclear Fuel Trains

Association of American Railroads

- Includes all cars in the trains including buffer cars, security cars
- Requires static and dynamic modeling before construction
- Requires full scale characterization, static, and dynamic testing of each car and the train
- 100,000 mile evaluation period

11

Performance Standard for SNF Trains (cont.)

Association of American Railroads

- Roadworthiness exceeds standard freight car requirements
  - Enhanced performance trucks
- Requires Electronically Controlled Pneumatic (ECP) Brakes
  - Reduced stopping distance
  - Provides conduit for on-board defect detection

12

System Safety Monitoring

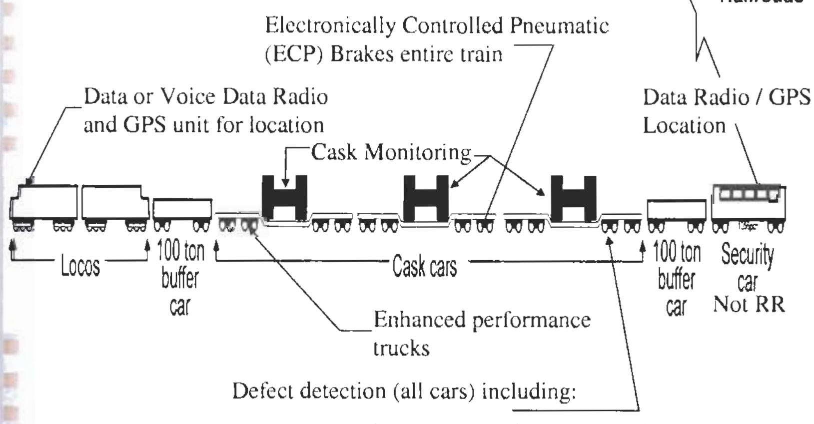
Association of American Railroads

- **On-Board Monitoring Systems**
  - Location Determination
  - Truck Hunting
  - Wheel Flats
  - Braking Performance
  - Vertical, Lateral, Longitudinal acceleration
  - Bearing Condition
  - Speed, Ride Quality

13

Diagram of SNF Train

Association of American Railroads



Truck hunting, rocking, wheel flats, bearing condition, ride quality, braking performance, vertical acceleration, and longitudinal acceleration.

14

Other Enhanced Safety Actions Affecting SNF Transportation

Association of American Railroads

- AAR OT-55-D
  - Track and Equipment Inspection
  - Defect Monitoring
  - Increased Maintenance Frequency
  - Increased Employee Training
  - Maximum Speed Limit (50 MPH)
- FRA Safety Compliance Oversight Plan Policy for HLRW and SNF Shipments

15

Private Fuel Storage LLC

Association of American Railroads

- First Shipper to Build SNF Equipment to AAR's New Performance Standard
- Cask Car Manufactured by Trinity Industries
- Overall Weight of Car, Cask, Cradle, and Impact Limiters is Approx. 476,200 lb.
- Modeling and Characterization Testing Complete
- Static and Dynamic Tests Planned for 2002

16

PFS Railcar at TTCI for Testing

17

Summary…

Association of American Railroads

- There are testing issues that should be addressed:
  - Crush loads
  - Collisions with structures & falls
  - Thermal event frequencies
  - Structural strength of railcars
- AAR is Committed to Incorporate Technological Improvements in Rail Transportation Designed to Enhance the Safety of SNF Shipments

18

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