RISK

Once the hazard, consequence, and probability analyses have been completed, the computation of the risk is anticlimactic and straightforward. The distinctions between the risk of exposure to damage and the risk of damage is perhaps most evident if the question of human injury and fatality risk is examined. The risk of exposure would be a numerical probability value on an annual per person basis of being within the possible range of effects, whereas the risk of damage for the exposed population is the annual per person probability of being injured or fatally injured. The difference between the two relates to fatality thresholds, protection, and countermeasures. The range of effects, perhaps both distance and time, associated with either risk measure is useful for analysis of transportation corridors.

A comparison of the project risk values or peaks to other activities and a sensitivity analysis comprise the risk evaluation step of the analytic approach. In the evaluation step, sensitivity analyses will pinpoint critical areas or perhaps assumptions requiring further scrutiny.

The discovery of risk peaks and an examination of their origin points the way for needed mitigation actions, including perhaps operational restrictions. A risk peak is a combination of circumstances of either or both consequence and probability origin that contributes a significant portion of the risk. The computerized HAZ-EX program is of significant value in identifying and pinpointing peaks and risk reduction considerations.

In summary then, a few pages from the computer output can apprise decision makers of the safety aspects of the proposal. If a working definition of acceptable risks were then available, the reviewer could be easily satisfied as to the acceptability of the applicant's plans as proposed or whether modifications would be necessary.

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# Crash Testing of Nuclear Fuel Shipping Containers

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**In an attempt to understand the dynamics of extra severe transportation accidents and to evaluate state-of-the-art computational techniques for predicting the dynamic response of shipping casks involved in vehicular system crashes, a program was organized to investigate these areas. This program, which began in 1975, encompasses the following distinct major efforts. The first of these uses computational methods to predict the effects of the accident environment and, subsequently, to calculate the damage incurred by a container as the result of such an accident. The second phase involves the testing of one-eighth-scale models of transportation systems. Through the use of instrumentation and high-speed motion photography, the accident environments and physical damage mechanisms are studied in detail. After correlating the results of these first two phases, a full-scale event, involving representative hardware, is conducted. To date two of the three selected test scenarios have been completed. Results of the program to this point indicate that both computational techniques and scale modeling are viable engineering approaches for the study of accident environments and physical damage to shipping casks.**

For the past several years the U.S. Energy Research and Development Administration (ERDA) through the Division of Environmental Control Technology has pursued a coordinated program to address the problems and perspectives of the transportation of radioactive materials. A part of that program has been the collection and analysis of data on the frequency and severity of accidents involving trains, highway vehicles, and aircraft within the United States. Significant correlations of these data, along with the basic data collection, are contained in the Transportation Environment Data Bank at Sandia Laboratories (1). This information has been used in a variety of programs.

As significant as this data collection is in the determination of the risk of exposure to accidents in the transportation segments of the nuclear fuel cycles, it does not relate the severity of the accident to the damage inflicted on the containers used to ship radioactive materials. ERDA recognized this need and initiated programs to evaluate that relationship. The first such program involved testing of full-scale casks in severe environments at Oak Ridge and Sandia. Following successful completion of these tests, full-scale testing of complete cask transport systems in highway and rail transport modes was initiated.

When these two programs are completed, it should be possible to predict the probability of causing various levels of damage to shipping containers as the result of transportation accidents. The remaining step is to correlate package damage and release fractions (i.e., the consequences of damage). Although the transportation tests conducted to date have resulted in no release of contents or release of only some portion of the coolant, concerns have been expressed as to what would happen if the cask were to be breached by accident or by any other means. Future programs may be required to provide these correlations. However, it should be noted that some currently used models assume releases of 1, 10, and 100 percent of volatiles and gases as accident severity increases to the extreme (2). But, even with such conservative release fractions, the risk to the public is still found to be very low.

## PRELIMINARY TESTING

To prepare for full-scale testing of spent nuclear fuel shipping systems, we conducted drop tests of obsolete spent-fuel casks to demonstrate the integrity of containers in severe environments (3). In 1975, two lead-shielded containers were dropped 610 m from a helicopter onto undisturbed soil at Sandia's Edgewood, New Mexico, test site to determine damage caused by an extreme accident environment. Both of the containers used in this test were considered obsolete because they did not meet current fire requirements.

One cask, a simple cylindrical unit weighing 3 Mg, used for handling irradiated test capsules, penetrated 2.4 m into the hard prairie after impact at 396 km/h. The cask suffered no measurable deformation. At Oak Ridge National Laboratory, an identical cask was subjected to the standard drop test of 9 m onto an unyielding surface at their drop-tower facility (4). This cask suffered significantly more deformation and lead slumping due to the high deceleration forces incurred at impact. Weld failures also occurred in the outer shell of the cask as the result of the 9-m drop. However, this cask would have still safely contained the contents without release.

The second cask, a simple cylindrical unit mounted on a rectangular base plate weighing 7.4 Mg, had previously been used to ship and store spent fuel from an Oak Ridge research reactor. It penetrated 1.3 m after impact at 371 km/h. This cask experienced superficial deformation that would not have resulted in release of contents. The lead shielding slumped 20 mm as the result of deceleration forces during impact. Matching tests to the regulatory specification were not conducted on this cask.

These tests revealed that although the velocities were substantially higher, impact onto the hard prairie soil damaged the casks much less than the impact onto unyielding targets used in the 3-m regulatory drop test.

### Objectives

Little information exists on the response of casks to the environments to which they might be subjected in actual accidents, since at the time of an accident casks are not generally instrumented nor are cameras available to record events. As part of the program, therefore, full-scale shipping casks and transport systems were subjected to very severe accident environments.

The test program has two major objectives:

1. To assess and demonstrate the validity of ERDA's analytical and scale-modeling programs for prediction of damage in accident conditions by comparison of predicted results with actual test results, and
2. To gain quantitative knowledge of extreme accident environments by measurement of the response of full-scale hardware under actual crash conditions.

The tests were not intended to validate present regulatory standards promulgated by federal agencies.

The full-scale test program was approached in three separate phases:

1. Mathematical analyses,
2. Scale-model tests, and
3. Full-scale tests.

Once the accident scenarios were chosen, the effects of this environment on the cask transport system were determined by both quasi-static and dynamic structural analyses. Calculations of the strength of materials estimated the static strength of critical parts of the structure. The dynamics of the system were studied by a previously validated and tested lumped-parameter computer code. Once the system dynamics were understood, parametric and sensitivity studies on the transport system were readily made. Damage to the cask was calculated with a finite-element code using input parameters estimated from the lumped-parameter code calculations.

The second phase of the program used scaling techniques to assess the damage to the container and transport systems in ⅛ scale. Structural models of the cask and transport system were constructed and subjected to scaled crashes. Results of the scale-model tests were then correlated with the analytical studies.

Full-scale testing to confirm the results was the final phase of the program. Since full-scale crash tests are spectacular events, considerable interest has been generated in the program. All tests were observed by representatives from industry and the government, private citizens, and the media.

### Test Scenarios

In selection of test scenarios, primary consideration was given to exposing the cask to very severe accident environments, amenability of the test to analyses and scale-model testing, and test costs. Response to the concerns of government, industry, and the public was also considered. A serious effort was made to select test scenarios that could be conceived as realistic and yet, on the basis of accident data on hand, were extremely severe. Substantial consideration was also given to the ability of test engineers to conduct the test properly without failures resulting from problems with the test setup. For instance, rail car roll-over and broadside skids with tractor-trailer rigs into massive barriers, which are difficult to perform in a repeatable manner, were rejected as unfeasible. Test scenarios were also considered that would trade an increase in severity for simplifications in the calculation and testing procedures.

On the basis of these criteria, the selected accident scenarios were

1. Crashes of a tractor-trailer rig carrying a spent nuclear fuel cask into a massive concrete barrier at 100 and 130 km/h,
2. High-speed (130 km/h) impact of a locomotive into a truck-mounted spent nuclear fuel cask at a simulated grade crossing, and
3. Impact at 130 km/h of a special rail car carrying a spent nuclear fuel cask, followed by exposure to a fire.

## ANALYSES

Before the full-scale tests were conducted, extensive analyses were performed to predict the response of the systems. These analyses considered the impact of

Figure 1. SHOCK tractor-trailer model.

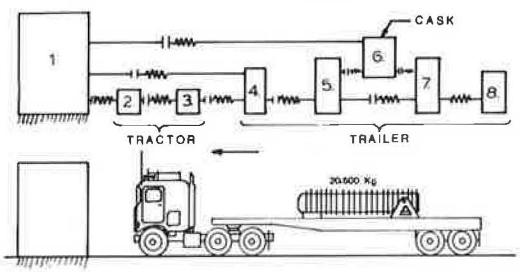
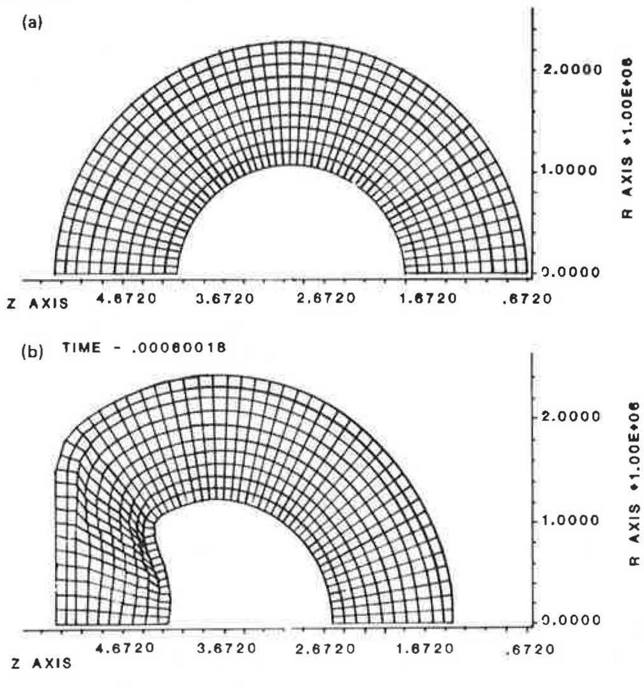



Figure 2. Analytical and scale model results for HONDO mesh: (a) undeformed and (b) deformed.




isolated casks on unyielding surfaces and entire transportation systems, including the impact of the cask on the same surface. In the first instance, the analyses gave insight into the generic behavior of lead-shielded casks. In the second, the analyses helped predict the behavior of the cask and transport system when subjected to the transportation accident environment.

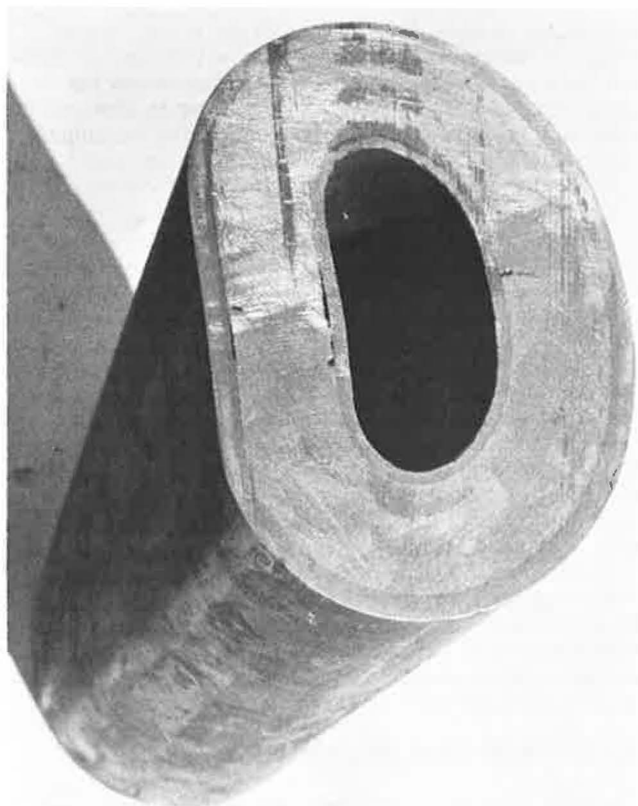
The full-scale tests were analyzed by validated computer codes, including both lumped-parameter and dynamic finite-element models.

## Lumped-Parameter Model (SHOCK code)

The overall systems were analyzed by SHOCK (5), a one-dimensional lumped-parameter code. With this code the system is represented by discrete masses and couplings. The coupling definitions are based on analytical estimates of the load-displacement behavior of the structure. Large permanent deformations are approximated by a hysteresis coupling. In addition to a hysteresis coupling, linear springs are also used in the models to represent elastic behavior.

Mathematical models for the three full-scale tests were constructed using this SHOCK code (6). Figure 1 illustrates the model for the tractor-trailer impact. Here the system, including the target, is modeled with eight discrete masses and ten couplings. Mass 1 (the

Figure 3. Cask deformation.



target) is held fixed, and the remaining masses are given initial velocities equal to the velocity of the test impact. In this model, coupling 3 and 4 represent the tractor-trailer kingpin connection, and couplings 5 and 6 and 6 and 7 simulate the cask tiedowns. Couplings 1 and 4 and 1 and 6 represent the interactions between the end of the trailer and the target and between the cask and target. These are given appropriate amounts of travel without loading. The rest of the couplings represent frame elements.

## Dynamic Finite-Element Modeling (HONDO code)

To better understand the generic behavior of casks subjected to severe impacts, some finite-element modeling was performed. Initially, a side impact was analyzed with the HONDO (7) code to understand the dynamics of a side-on cask impact into an unyielding surface. HONDO is a dynamic finite-element program that can model large deformations in two-dimensional or axis-symmetric solids. For the problem of a side impact, the code was modified to restrain node movement past the plane. The cask body was assumed to be in a state of plane strain and was given an initial velocity equal to the impact velocity.

Figure 2a illustrates the mesh for a model cask (6). The cask cross section, including the outer and inner shells and the lead shielding, is modeled. Figure 2b illustrates the severely deformed mesh after a 130 km/h side-on impact.

Figure 3 illustrates the $^{1}/_{8}$-scale model cross section after a side-on impact into a steel target at the same velocity. As can be seen, quantitative agreement is good between the code and the scale-model results.

## SCALE-MODEL TESTING

Evaluation of damage from free drops of full-scale shipping containers into essentially unyielding surfaces has been previously used as one of the bases for qualifying spent-fuel casks. Such testing is expensive, particularly since simpler, less expensive techniques are available. Many studies have shown the applicability of scale-modeling techniques for studying the structural response of structures impacting into hard surfaces (8, 9). Recently, scale-modeling techniques have been applied to study the structural response of shipping cask systems subjected to severe transport environments. These techniques are described in greater detail elsewhere (10).

In order for scale-model testing to be useful, parametric and dimensional analyses must be conducted. On this basis, the scale hardware can be designed either as replica models (which are exact geometric material models) or as adequate models (which, while allowing some geometrical simplifications, will produce meaningful results). Both replica and adequate models have been used in this program.

Scale-model testing of the casks took two forms. Casks without their associated transport systems were subjected to varied impact conditions to gain a better understanding of damage mechanisms. Later the cask and its entire transport vehicle were modeled and tested to determine the total system response.

## FULL-SCALE TEST EQUIPMENT

Financial constraints affected both test definition and equipment procurement. Because current-generation spent-fuel shipping casks cost from $500 000 for truck casks to $3.5 million for rail casks, it was necessary to use used or retired equipment. Out-of-service and older shipping cask systems, used commercial truck tractors, and a military surplus locomotive were obtained and modified to make them more representative of current designs. The casks used in the test program were similar in weight to modern casks; where they differ, the weight difference has been shown to be of little importance in the accident environment. In some cases, modifications such as impact limiters were made on the casks to make them more representative of current equipment. Every effort was made to obtain transport vehicles for the test program that were similar in both structure and weight to those actually in service. Therefore, the use of obsolete transport equipment had no effect on the results of the test program since computer analyses and scale-model test techniques are equally valid on both old and new equipment.

The three casks used in this test series, although differing in size, are of the same basic construction. Each has an inner and outer steel shell, with the annular region between filled with lead for shielding. In each case, the head is attached to the cask body with bolts. The casks used weigh from 20 to 62 Mg.

### Truck-Cask Impact Tests

In the truck-cask impact tests, an obsolete spent-fuel cask weighing 20.5 Mg was obtained complete with its normal transport trailer and tiedowns. In its original configuration, the cask was mounted with the head facing the rear of the trailer. Since most modern casks are shipped head forward, this test cask was reversed on the trailer to simulate current transport conditions. The cask was attached to the tiedown structure by bolted connections at the base and head of the cask. In reversing the cask, the original bolted and welded connections were duplicated to secure the tiedown structure to the trailer. Balsa-wood impact limiters designed by the techniques currently in use were added to the cask to evaluate the effectiveness of impact-limiting devices in accident situations.

A standard cabover, tandem-axle, diesel-powered tractor was procured for the test. Although the tractor was considered obsolete and worn out, the structural members of the tractor were in excellent condition. An identical tractor and trailer, complete with tiedown structure, was obtained for the higher velocity test to replace the rig demolished in the first crash. The cask, which was practically undamaged in the first test, was equipped with a new front-impact limiter and reused in the second test.

The impact target used in these tests was designed to be massive and rigid. It consisted of a heavily reinforced 626 Mg concrete structure, backed by more than 1580 Mg of earth. For all practical purposes, considering the masses and velocities involved in the tests, the target is essentially unyielding. An object of this size and weight is rarely, if ever, found along normal truck routes. To save costs, this target is also to be used in the special rail car impact test.

### Grade-Crossing Test

For the grade-crossing test, a 23-Mg cask, complete with trailer and tiedown structure, was obtained. The cask, similar in construction to the cask used in head-on barrier tests, was mounted on the trailer by a band tiedown system, as shown in Figure 4. A tandem-axle, gasoline-powered tractor supported the cask and trailer during the test.

A military surplus 109-Mg diesel-electric locomotive was obtained for the grade-crossing test. This locomotive was originally powered by a V-12 diesel engine through six traction motors in two three-axle trucks. Since the engine needed extensive repairs and was not required to accelerate the locomotive to the test speed, the pinion gears were removed to allow the locomotive to free-wheel. The weight of the engine and alternator in this design is supported by two I-beams that extended to the length of the locomotive. Although lighter in weight, the locomotive construction is quite similar to that of modern locomotives.

### Impact and Fire Test of a Rail Car and Cask

In the impact and fire test of a rail car and cask system, a 68.2-Mg rail car with a 61.8-Mg rail cask has been obtained for testing. This cask, while similar in construction to those tested earlier, is larger and capable of containing more spent-fuel elements. The special rail car system, which is equipped with three-axle trucks, is shown in Figure 5. Secondary cooling systems are shown at both ends of the car.

## PROGRAM RESULTS

### Truck-Cask Tests at 100 km/h

The basic dynamic response of the truck-cask tests was investigated analytically by a mathematical lumped-parameter model using the SHOCK code. As previously described, computational results from this model estimated expected deformations, displacement time, and velocity time histories for the transport system components.

A parametric study was performed to obtain information over a possible range of system responses.

Figure 4. 15 x 140 cask used in grade-crossing test.

Figure 5. Rail car system.

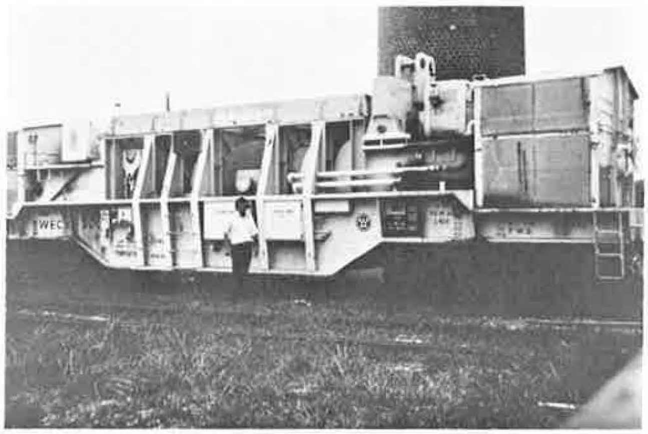


Figure 6. SHOCK predictions.

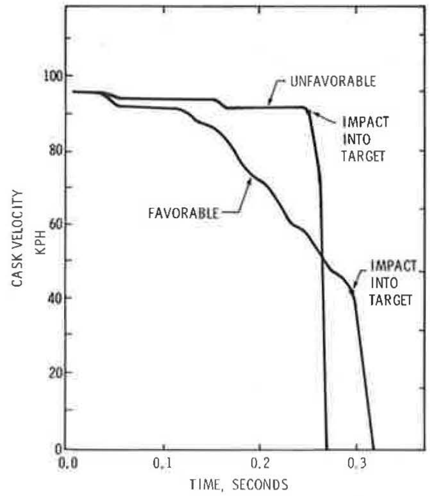
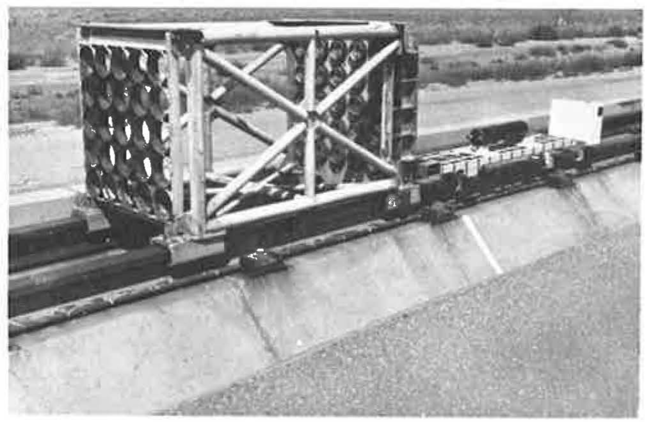



Figure 7. Cask transport model.



Most notably, the strength of the tiedown structure was varied to depict the reasonable limits of responses.

As indicated on Figure 6, when the tiedown is assumed to either not fail or fail late in the impact (favorable), the cask was continuously slowed as the components of the transport system crushed. Under these conditions, the container should impact the wall at less than 48 km/h (13.3 m/s).

In the worst-case condition (unfavorable) the tiedown structure in the SHOCK model was intentionally weakened so that the container would break away early in the impact, with little reduction in velocity. This resulted in the prediction of a large velocity change at impact with the wall, as shown in Figure 6. Such a large velocity change would crush the impact limiter and cause cask deformation. The favorable response condition was determined to be the more realistic case. From the graph, the cask impact velocity with the target would be about half of the initial velocity of the system. In this case, the impact limiter, designed for the 9-m drop test (impact velocity 13.4 m/s), would reduce the velocity of the cask even further, resulting in no structural deformation to the cask. The code predicted only partial crushup of the impact limiter.

## Scale-Model Test

A ⅛-scale model of the cask transport system shown in Figure 7 was tested at our rocket sled track facility. To assess damage to the cask structure, an adequate model (excluding fins) of the cask and impact limiter was constructed. The tractor-trailer model was designed with emphasis on the major masses and structural elements. Only those elements expected to contribute significantly to the cask dynamics were included. The model, therefore, simulated the major dynamics and resultant damage expected in the full-scale test.

Using a rocket, the model transport system was propelled into a scaled concrete wall at 97 km/h. A posttest view of the damage is shown in Figure 8. Scale-model results agreed closely with analytical predictions. High-speed data films showed that the transport and cask system response closely followed that predicted in the case where the tiedown did not fail. The impact limiter was partially crushed, and the cask was undamaged, except for minor deformations around the tiedown attachment points.

## Full-Scale Test

The first tractor-trailer test was conducted on January 18, 1977. Before testing, the cask was loaded with an unirradiated Savannah Core II reactor fuel assembly ballasted to the weight of a conventional pressurized water reactor (PWR) fuel assembly. The thermal environment of a normal spent-fuel cask, which contains an irradiated spent-fuel subassembly, was simulated by heating the test cask to 66°C. About 160 kg of water coolant were included in the cask to simulate its normal shipping environment. Rocket motors propelled the transport system up to speed, after which the tractor-

Figure 8. Posttest damage—scale-model test.

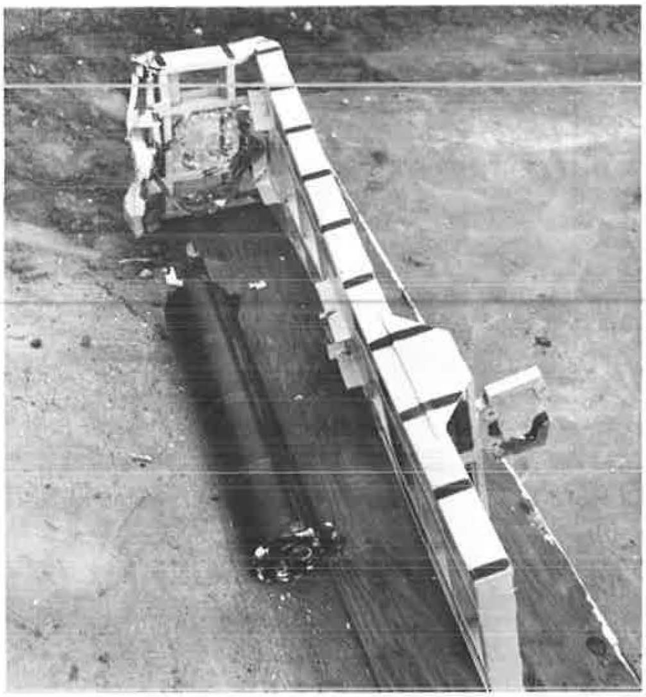
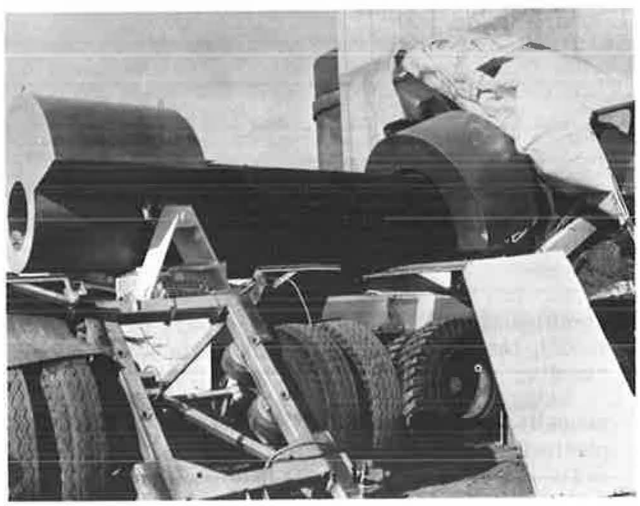


Figure 9. Posttest accident view—97.8-km/h test.



trailer rig, guided by rails, coasted into the impact zone at 97.8 km/h.

As predicted by the conclusions drawn from both the analytical and scale-model test results, the tractor was completely destroyed in the crash. The tractor's fifth-wheel attachment failed, and the trailer moved forward through the cab to impact the wall. Crushing and buckling upwards, the trailer and other crushed structure gradually reduced the velocity of the cask to about half of its original impact velocity. The impact limiter then contacted the bent trailer and other debris to slow the cask even further. Although the tiedowns did not break loose during impact, posttest inspection of the debris indicated that the cask tiedowns had almost failed. The cask remained horizontal, as predicted, until impact with the crushed debris and wall. Forces to the cask were limited by crushing of the tractor-trailer structure and by the compressive strength of the balsa

Figure 10. Comparison of SHOCK results.

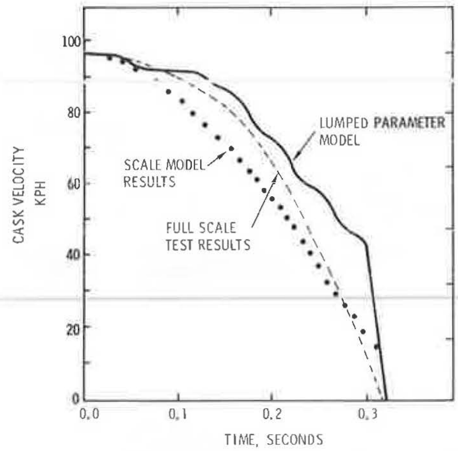
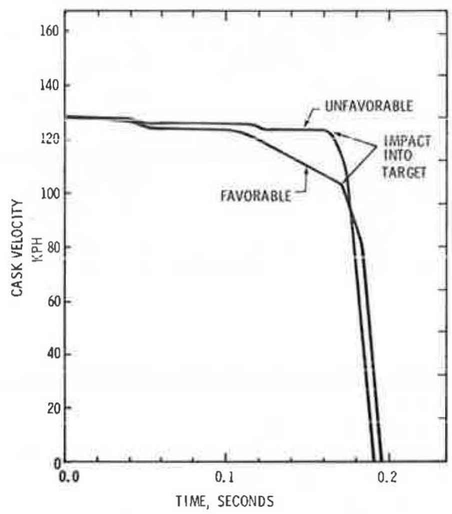



Figure 11. Pretest SHOCK comparison—130-km/h test.




wood in the impact limiter. Following the main impact, the cask and trailer rotated to about 30° relative to horizontal and returned to the roadbed in front of the target.

Figure 9 shows the posttest condition of the cask and transport system. The cask remained intact and sustained only superficial damage to the external fins and piping. Instrumentation near the cask head indicated strains below the yield strength of the material. Rigid body accelerations on the cask were about 20 $g$'s. The cask head was easily removed, and the fuel assembly was found to be intact and undamaged.

Overall response of the cask-transport system agreed well with pretest analytical and scale-model predictions. A quantitative comparison of the results is shown in Figure 10 (11), which illustrates both calculated and measured velocity-time histories.

Truck-Cask Impact Test at 130 km/h

For the second test, the same lumped-parameter SHOCK model was used to calculate the transport system response to a higher initial velocity (130 km/h). Again, the tiedown parameters in the model were varied to obtain information for a range of system response. Figure 11 shows the favorable and unfavorable system response calculated by the SHOCK model (11). Note that the curves for the two responses are not as widely separated as in the first case. This indicates that the system completely expends its capability to absorb kinetic energy during crushup, even in the favorable case. The influence of the tiedown structure would, therefore, have less effect in this test; the predicted impact velocity of the cask into the wall varied from 105 to 122 km/h. Since the structure of the trailer was identical to that of the trailer used in the 100-km/h test, it was assumed that the tiedown response would be similar; that is, the tiedowns would follow the favorable response curve and the impact velocity of the cask would be approximately 105 km/h.

To further analyze the damage to the cask, a finite-element computer code, HONDO, was used to calculate deformations to the cask with the SHOCK impact velocity as the input parameter. Figure 12a shows a finite-element model of the test cask before impact into an unyielding surface (11). Both the outer and inner steel shells are modeled with small elements. The lead, shown between the steel shells, has coarser elements. Figure 12b shows the test cask after a 105-km/h impact. Although bulging of the impacted end is significant, static analysis of the cask-head closure bolts indicated that the bolts would not fail. It was also predicted that the deformations might be severe enough to the head to cause minor seepage of fluid from within the container.

## Scale-Model Tests

In the scale-model system tests, a test at the exact impact velocity of the second full-scale truck-cask impact test was not performed. Therefore, test results cannot be readily compared. Other scale-model tests of casks without their associated transport systems produced results that agreed with the HONDO predictions.

## Full-Scale Test

Since the cask sustained little damage in the first test, it was cleaned, repainted, and remounted on an identical trailer. A similar cabover tractor was obtained for the second test. The cask was again loaded with a Savannah Core II fuel assembly, filled with water, and heated to 66°C.

The second truck-cask impact test was conducted on March 16, 1977, at a velocity of 135 km/h. As predicted by pretest analyses, the tractor and trailer were demolished. The fifth wheel failed, and the trailer moved forward through the cab and buckled. As predicted, portions of the impact limiter in contact with the cask were completely crushed, even though the tiedowns held until the final stages of impact. The cask again remained horizontal through the initial impact and rose with the trailer much as in the first test. Both cask and trailer came to rest in the upright position in front of the target.

Figure 13 shows the condition of the cask and transport system after the second test. After removal of the cask from the trailer, seepage at a rate of about 2 drops/min was detected from the cask head. The seepage later stopped after release of about 100 cc of fluid. Inspection of the cask revealed that the head was peened onto the cask and that the front of the cask had bulged. Several dents found on the surface of the cask head (Figure 14) were caused by the impact of the trailer fifth-wheel pin, which was forced in front of the cask by buckling of the trailer. Slight bending of the front portion of the cask occurred due to nonsymmetric impact conditions. As predicted, the front portion of the cask was permanently deformed (bulged). Rigid body accelerations measured on the cask were about 70 *g*'s (11). The cask head was removed with great difficulty. Inspection of the fuel assembly revealed deformation of the impact end. Some fuel-pin buckling occurred; however, no clad failure was detected.

The overall response of the cask transport system agreed well with pretest analytical predictions. A quantitative comparison of the results is shown in Figure 15 (11), which illustrates both the calculated and measured velocity time histories. Posttest measurement of model- and full-scale cask diameters and lengths revealed close agreement between measured deformations.

## Grade-Crossing Test at 130 km/h

An analytical investigation of a grade-crossing accident involving the 130-km/h impact of a 186 Mg locomotive into a 22.7-Mg spent-fuel cask at a grade crossing was performed as the first step in this portion of the program (12). In this analysis, various configurations were evaluated. The first involved a superstructure impact in which the frame of the locomotive passes beneath the cask. Results of this analysis indicated that cask damage would be limited to minor deformations from impact with the engine-alternator unit of the locomotive. The second configuration involved a full-frame centerline impact between the cask and locomotive. This impact condition would occur only if the cask is placed on a lowboy transport trailer that is not used to transport current commercial spent-fuel casks. This analysis indicated that the cask would be moderately deformed after a centerline impact with the locomotive frame.

Later investigation of current shipping-cask configurations indicated that either a glancing frame or superstructure impact would occur in a two-track rural grade-crossing collision. The glancing frame impact, the more severe case, was selected for the full-scale test.

The major thrust of the remainder of the analysis involved using the finite-element HONDO code. The frame and cask impact condition is depicted in Figure 16. The HONDO model indicated that the twin I-beams of the frame would be crippled and form a ramp, causing the cask to be lifted into the superstructure. Once into the superstructure, the forces acting on the cask would be limited by crush up of the thin structural shell of the locomotive. Since the impact forces generated by the frame would be limited by crippling of the I-beam members, the increasing locomotive or train mass would cause a negligible increase in damage to the cask.

## Scale-Model Test

One-eighth scale models of the test locomotive and cask-trailer system were constructed. The major structural elements and masses of the locomotive were modeled to adequately simulate the dynamic response of the structure (Figure 17). The front end of the frame of the model locomotive was accurately modeled to duplicate the full-scale locomotive.

The model locomotive was accelerated by a small rocket to an impact velocity of 126 km/h. In this scaled impact, the frame of the locomotive struck the cask a glancing blow. As predicted by the analyses, the I-beam section of the frame failed by buckling to form a ramp that lifted the cask into the superstructure (Figure 18). Posttest inspection of cask damage showed that the fins were scraped away by the frame and that two 2.5-mm depressions were formed at the point of impact with the

Figure 12. HONDO model: (a) preimpact and (b) postimpact.

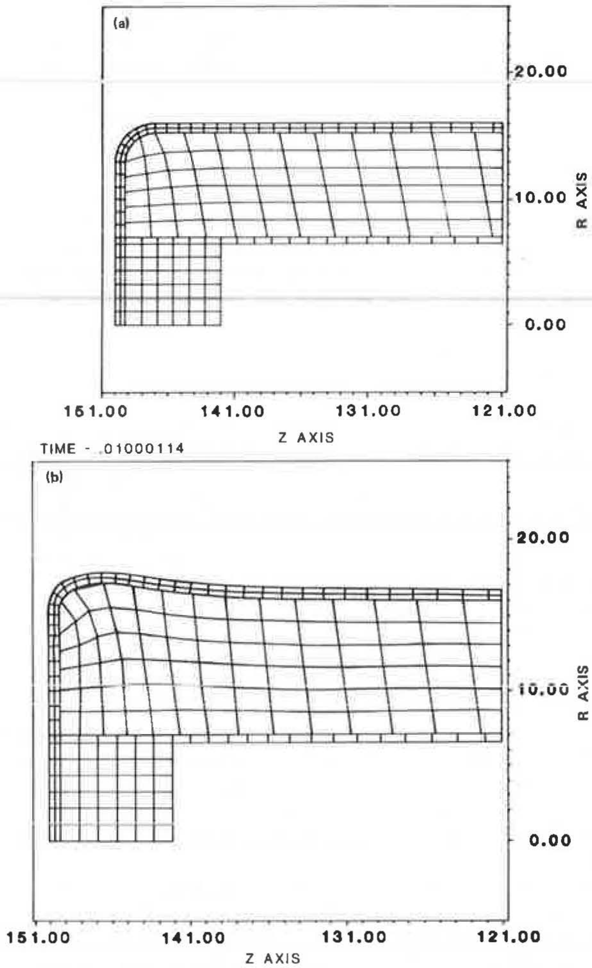



Figure 13. Posttest view—130-km/h truck test.

I-beams, but the cask shell was not ruptured.

## Full-Scale Test

The locomotive grade-crossing test was conducted on April 24, 1977. The test cask was loaded with a fresh Savannah Core II fuel assembly. Rockets accelerated

Figure 14. Cask head—130-km/h truck test.

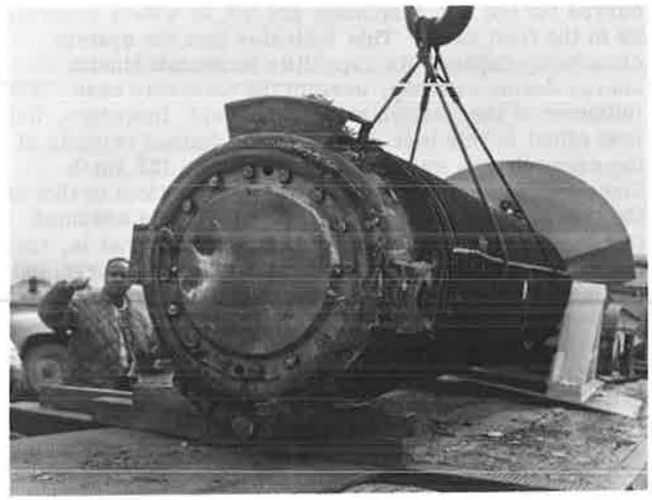
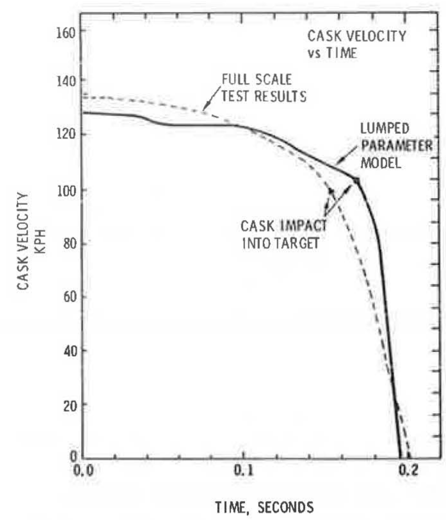


Figure 15. Comparison of analytical and full-scale results.




the 109-Mg locomotive to test speed (Figure 19), after which it coasted to an impact at 131 km/h. As predicted by pretest analysis and scale-model test results, the frame of the locomotive was crippled and formed a ramp, which allowed the cask to rise into the superstructure (Figure 20). As shown in Figure 21, failure of the locomotive frame closely resembled that in the model test. After superstructure crush up, the cask rolled to the right side of the locomotive, tumbled in the dirt, and came to rest between the rails. Posttest inspection of the cask indicated that the deformation behavior of the cask was very similar to that of the scale model. Two 26-mm depressions, which were caused by the impact with the I-beam members of the frame, were left on the surface of the cask. Leak testing of the cask after impact indicated a small leak in the head seal when the cask was pressurized. This leakage, had the cask contained water, would have caused essentially no risk to the public. The cask head was removed without difficulty and the fuel assembly was found to be intact. There was some bowing of the fuel pins; however, no clad failure was detected.

Comparison of the damage to the cask and locomo-

Figure 16. HONDO model.

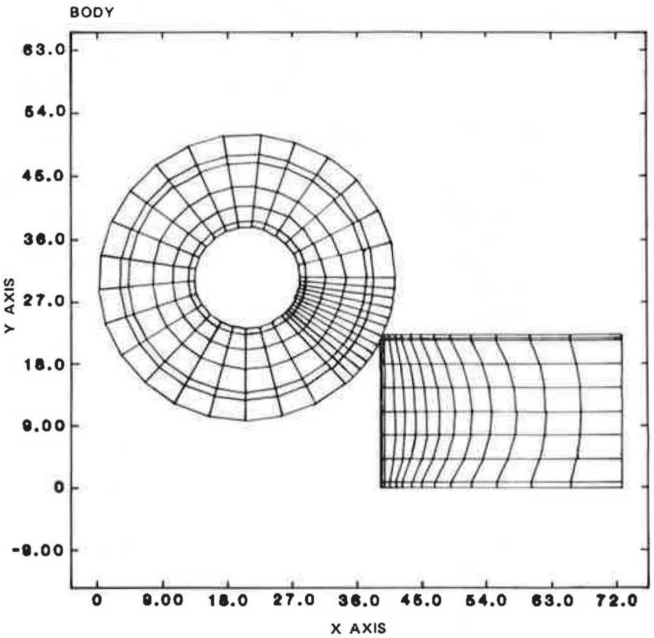



Figure 17. Scale locomotive model—scale test of grade-crossing crash.

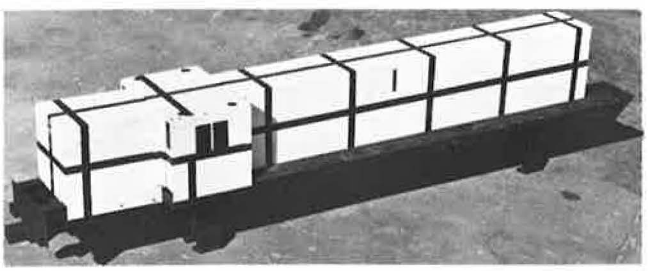
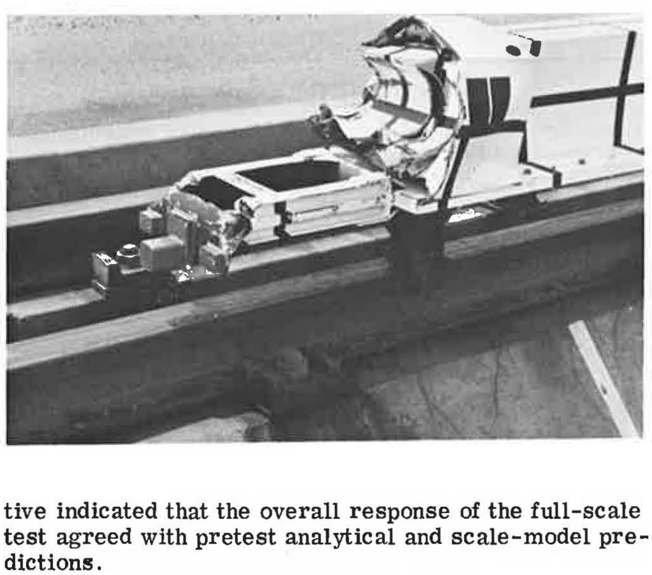


Figure 18. Posttest view of locomotive model—scale test of grade-crossing crash.



tive indicated that the overall response of the full-scale test agreed with pretest analytical and scale-model predictions.

## ACCIDENT SEVERITIES AND PROBABILITIES

The test scenarios selected generally fall within the

Figure 19. Rocket-powered locomotive—full-scale grade-crossing test.

Figure 20. Full-scale impact—full-scale grade-crossing test.

Figure 21. Frame buckling damage—full-scale grade-crossing test.

extra severe or extreme categories described in the 1972 Atomic Energy Commission report (13). These conditions have been estimated in risk assessment studies of transportation accidents to be events of very low probabilities; no such accidents involving spent-fuel casks have ever occurred.

With the data from the studies on transportation accident severities, one can conservatively calculate the probabilities of occurrence for the various accident scenarios considered. Assuming that 3500 truck shipments (3200 km each, year 1990 estimates) are made per year, the probability of occurrence for the 100 km/h truck impact into a massive barrier is once every 70 years; and for a velocity of 130 km/h, approximately once every 1000 years, or no more than once every 1.13 $\times 10^7$ km traveled.

Using the same shipment conditions for the grade-crossing accident, the probability calculations indicate that for a velocity of 130 km/h, the predicted frequency of occurrence is somewhat less than once every 4500 years.

In the final planned test, which involves the impact of a special rail car and cask into a massive concrete barrier followed by a fire, the probability calculations for total shipment distance of 11.3 million km indicate that, for a velocity of 115 km/h, the probability of occurrence for impact is expected to be approximately once every 5900 years, and for a velocity of 130 km/h, no more than once every 18 000 years. These values do not include the combined impact and fire environment, which are at least 1000 times less likely to happen.

In the three full-scale impact tests conducted to date, the accidents of the severities described have not breached the container; therefore, had these casks been involved in such severe accidents during the transport of spent fuel, the public would not have been exposed to irradiated fuel elements.

## CONCLUSION

The program objectives have been met successfully thus far. It has been shown that current analytical and scale-modeling techniques can predict vehicular and cask damage in extremely severe accident environments. In addition, much data have been collected on the response of transport systems in accident environments. These tests have shown that the spent-fuel casks tested are extremely rugged containers capable of surviving very severe accidents. The strong implication is that modern casks, designed and constructed to more rigid requirements, will survive equally well. Moreover, the capability to predict their survivability without full-scale testing has been shown to be feasible through mathematical analysis and scale-model testing.

## ACKNOWLEDGMENT

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# Safe Transport of Munitions

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**The U.S. Department of Defense is conducting a study to determine procedures and methods that are technically and operationally feasible and economically acceptable to prevent, or limit, the effects of explosives incidents in rail cars and mass detonation of containerized munitions in port areas and aboard ships. Selected U.S. Department of Defense components, whose inherent mission, expertise, and physical assets are appropriate to developing solutions, will conduct technical and operational feasibility studies. Each performing agency will coordinate its areas of study with other governmental and industrial organizations. The 13 tasks have been categorized into six major areas of consideration. These include background information, traffic patterns, equipment, fire protection, buffering, and sea containers. The study, including a final report, is programmed to be completed within 33 months, ending in September 1980. The total cost is estimated to be approximately $3 million, which will be funded by both the Army and the Navy.**