SAND77-1462
Unlimited Release

Crash Testing of Nuclear Fuel Shipping Containers

Robert M. Jefferson, H. Richard Yoshimura

Sandia Laboratories

Nuclear Fuel Cycle Programs

SF 2900 Q(7-73)

DISCLAIMER

DISCLAIMER

SAND77-1462C

PREPRINT*

CRASH TESTING OF NUCLEAR FUEL SHIPPING CONTAINERS*

by

Robert M. Jefferson
H. Richard Yoshimura
Sandia Laboratories, Albuquerque, NM 87115

December 1977

Abstract

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, the Environmental Control Technology Division of ERDA undertook a program with Sandia to investigate these areas. This program, which began in 1975, encompasses the following distinct major efforts. The first of these utilizes computational methods for predicting 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 1/8-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 to studying accident environments and physical damage to shipping casks.

CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

Introduction

For the past several years the Energy Research and Development Administration (ERDA) through the Division of Environmental Control Technology has pursued a coordinated program addressing 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). Sandia has used this information in a variety of programs and, when requested, has also furnished it to other organizations.

As significant as this data collection is in determining the risk of exposure to accidents in the transportation segments of the nuclear fuel cycles, these data do not relate the severity of the accident to the damage inflicted upon 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 to 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.

With these two programs complete 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). While 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 happens if the cask were to be breeched by accident or 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, very low.

Preliminary Testing

To prepare for full scale testing of spent nuclear fuel shipping systems, Sandia Laboratories under ERDA/Environmental Control Technology (ERDA/ECT) sponsorship 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, NM, test site to determine damage caused by an extreme accident environment. Both of the containers used in this test were considered obsolete as they did not meet current fire requirements.

One cask, a simple cylindrical unit weighing 3 metric tons, used for handling irradiated test capsules, penetrated 2.4 m into the hard prairie after impacting at 396 kph. 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 metric tons, had previously been used to ship and store spent fuel from an Oak Ridge research reactor. It penetrated 1.3 m after impacting at 371 kph. 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 meter regulatory drop test.

Objectives of the Program

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. ERDA/ECT therefore sponsored a program at Sandia to subject full scale shipping casks and transport systems 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 predicting damage in accident conditions by comparing predicted results with actual test results, and

2. to gain quantitative knowledge of extreme accident environments by measuring the response of full scale hardware under actual crash conditions.

The tests are not intended to validate present regulatory standards (i.e., regulations promulgated by the U.S. Nuclear Regulatory Commission, Department of Transportation, and/or the International Atomic Energy Agency).

Sandia approached this full scale test program in three separate phases:

1. mathematical analyses,
2. scale model testing, 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. Strength-of-material calculations 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 1/8 scale. Structural models of the cask and transport system were constructed and subjected to scaled crashes. Scale model test results were then correlated with the analytical studies.

Full scale confirmatory testing 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, by private citizens, and the media.

Test Scenarios

In selecting 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, railcar rollover 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 kph,

2. high-speed, 130 kph, impact of a locomotive into a truck-mounted spent nuclear fuel cask at a simulated grade crossing, and

3. impact at 130 kph of a special railcar carrying a spent nuclear fuel cask, followed by exposure to a fire.

Analyses

Before conducting the full scale tests, extensive analyses were performed to predict the response of the systems. These analyses considered isolated casks impacting unyielding surfaces, and entire transportation systems, including the cask impacting 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.

Analytical Models

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-type 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

Figure 1. SHOCK tractor-trailer model.

model for the tractor-trailer impact. Here the system, including the target, is modeled with 8 discrete masses and 10 couplings. Mass 1 (the target) is held fixed, and the remaining masses are given initial velocities equal to the test impact velocity. In this model, coupling 3-4 represents the tractor-trailer kingpin connection, and couplings 5-6 and 6-7 simulate the cask tiedowns. Couplings 1-4 and 1-6 represent the interactions between the end of the trailer and the target, and 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 under-
stand 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 kph side-on impact.

Figure 2c 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, there is good quantitative agreement between
the code and the scale model results.

Scale Model Testing

Evaluation of damage from free drops of full scale ship-
ping 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 references have
shown the applicability of scale modeling techniques for study-
ing the structural response of structures impacting into hard
surfaces (8,9). Recently, these scale-modeling techniques have

2a. HONDO Mesh – Undeformed

2b. HONDO Mesh – Deformed

2c. Photograph of Cask Deformation

Figure 2. Analytical and scale model results.

been applied to study the structural response of shipping cask systems subjected to severe transport environments. These techniques are described briefly below and 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 $3,500,000 for rail casks, it was necessary to utilize 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 and, 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 use in the test program that were similar in both structure and weight to those actually in service. Therefore, using 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 metric tons.

Truck-Cask Impact Tests

In the truck-cask impact tests, an obsolete spent fuel cask weighing 20.5 metric tons was obtained complete with its normal transport trailer and tiedowns as shown in Figure 3a. 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 better simulate current transport conditions. The
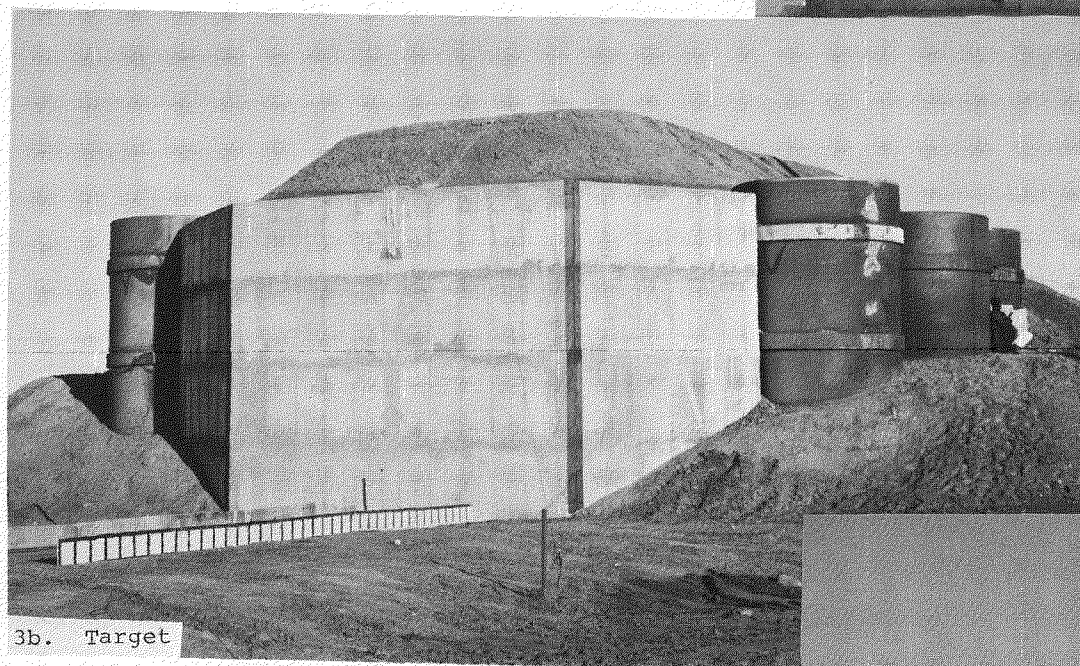
cask was attached to the tiedown structure by bolted connections at the base and head of the cask. In reversing the cask, the original bolted and welded connections were duplicated to secure the tiedown structure to the trailer. Balsa-wood impact limiters designed by the techniques currently in use were 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 very massive and rigid. It consisted of a heavily reinforced 626 metric ton concrete structure backed with more than 1580 metric tons of earth (Figure 3b). 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 railcar impact test.

3a. 15x129 Cask and Trailer

3b. Target

3c. 15x140 Cask

3d. Locomotive

3e. Railcar

Figure 3. Equipment used in testing.

Grade-Crossing Test

For the grade-crossing test, a 23 metric ton 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 with a band-type tiedown system as shown in Figure 3c. A tandem-axle, gasoline-powered tractor supported the cask and trailer during the test.

A military surplus 109 metric ton diesel-electric locomotive was obtained for the grade-crossing test. This locomotive, shown in Figure 3d, 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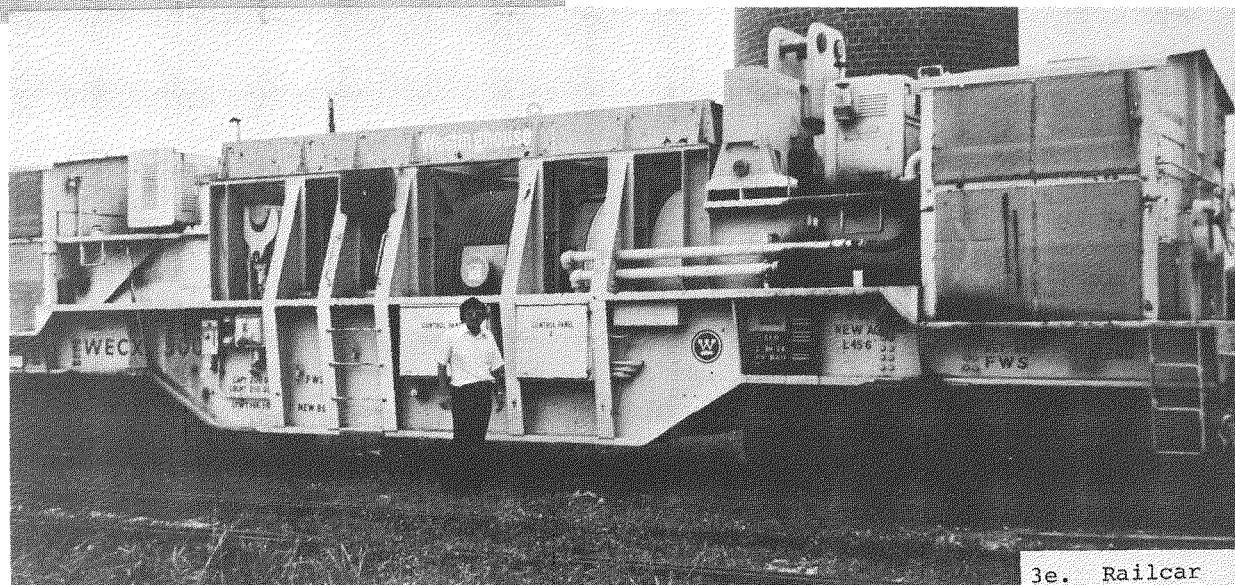 locomotive to the test speed, the pinion gears were removed to allow the locomotive to free-wheel. The weight of the engine and alternator in this design is supported by two I-beams running the length of the locomotive. Although lighter in weight, the locomotive construction is quite similar to modern locomotives.

Impact and Fire Test of a Railcar and Cask

In the impact and fire test of a railcar and cask system, a 68.2 metric ton railcar with a 61.8 metric ton 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 railcar system, which is equipped with three-axle trucks, is shown in Figure 3e. Secondary cooling systems are shown at both ends of the car.

Program Results

100 kph Truck-Cask Tests

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

As indicated on Figure 4, when it is assumed that the tie-
down either did not fail or failed late in the impact (favor-
able), the cask was continuously slowed as the components of
the transport system crushed. Under these conditions, the con-
tainer should impact the wall at less than 48 kph (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
velocity reduction. This resulted in the prediction of a large
velocity change at impact with the wall as shown in Figure 4.
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
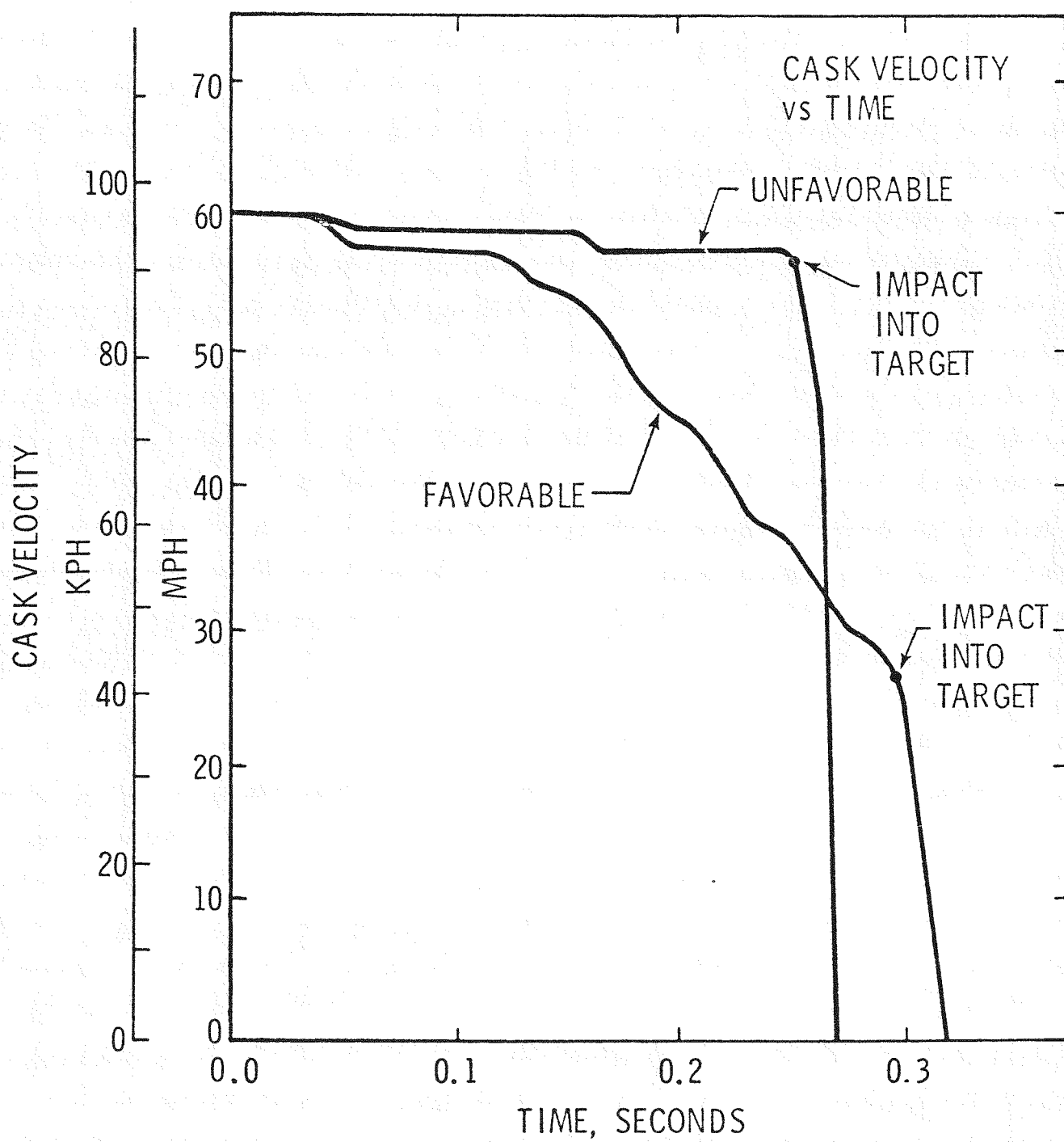cask impact velocity with the target would be about half the

Figure 4. SHOCK predictions.

initial velocity of the system. In this case, the impact limiter, designed for the 9 meter 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 1/8-scale model of the cask transport system shown in Figure 5a was tested at Sandia's 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 kph. A posttest view of the damage is shown in Figure 5b. 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
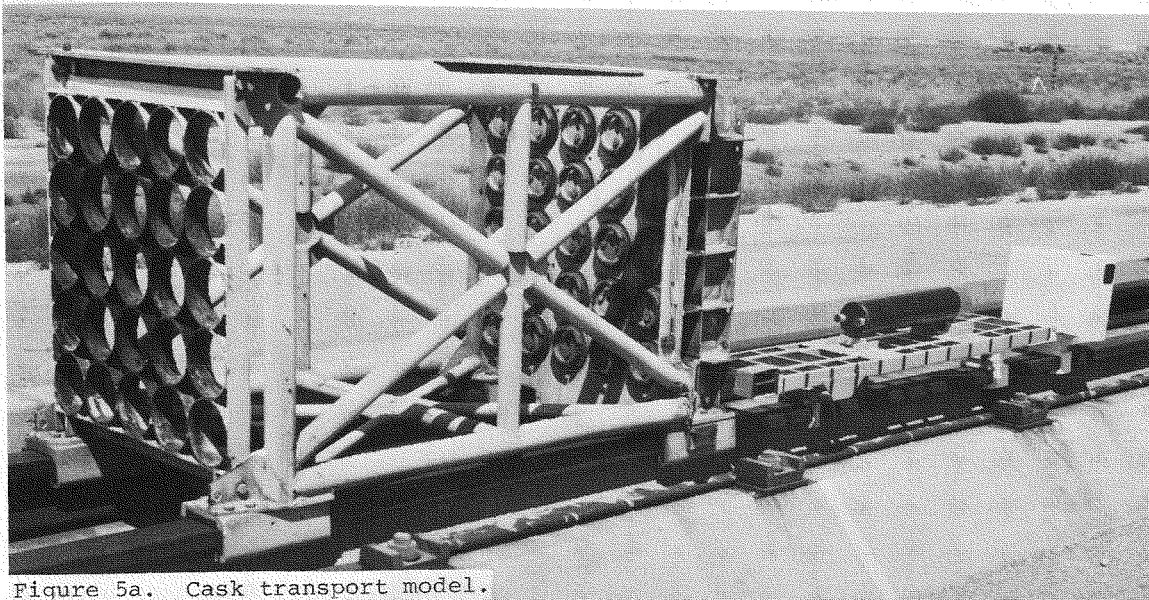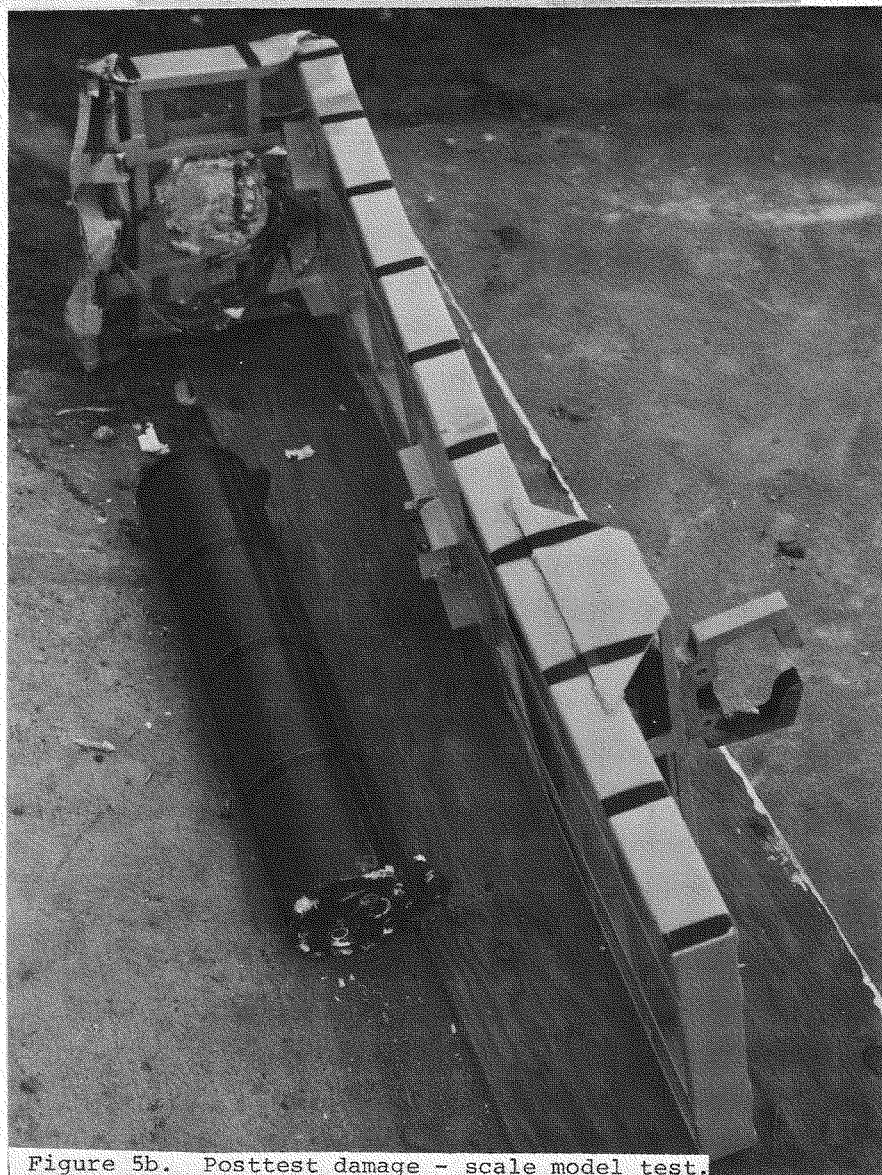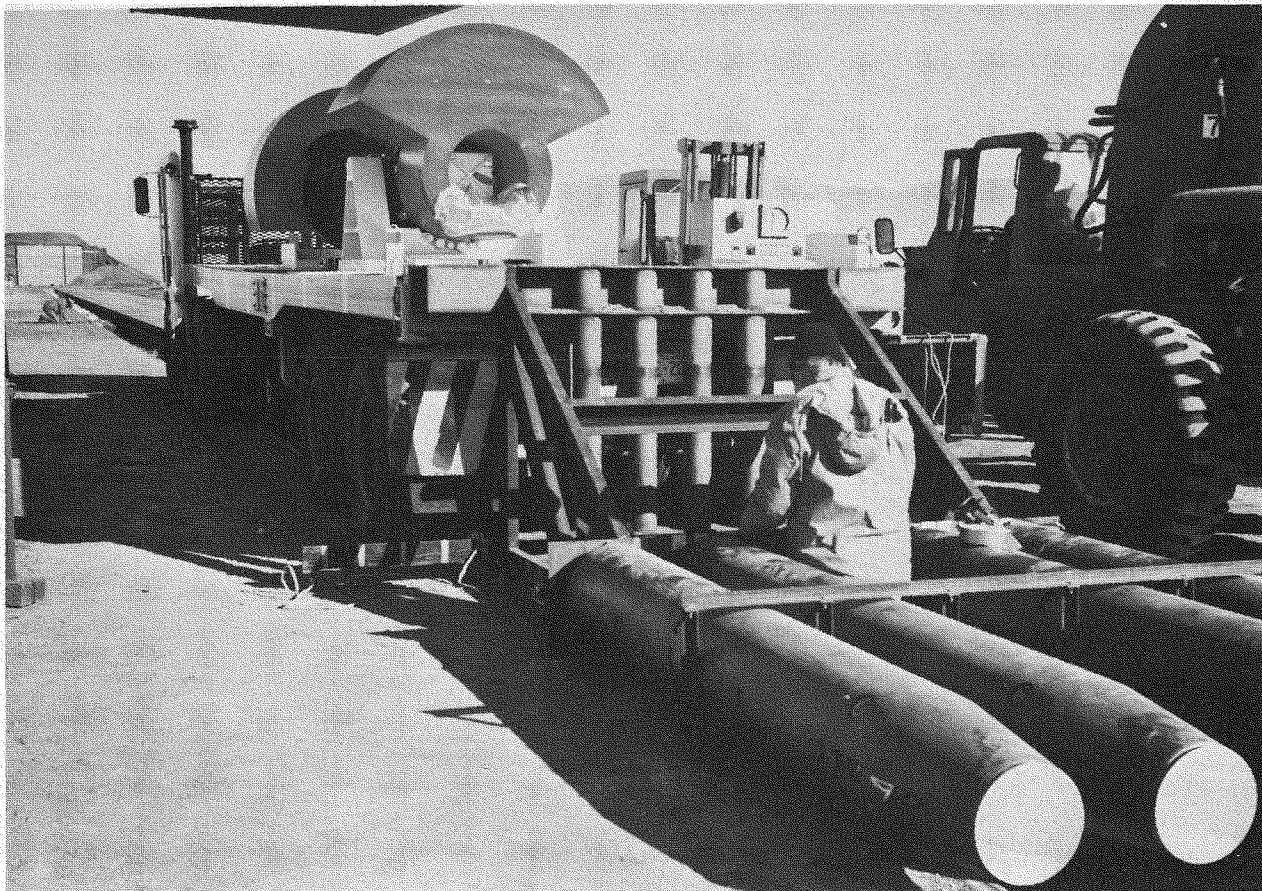
Figure 5a. Cask transport model.

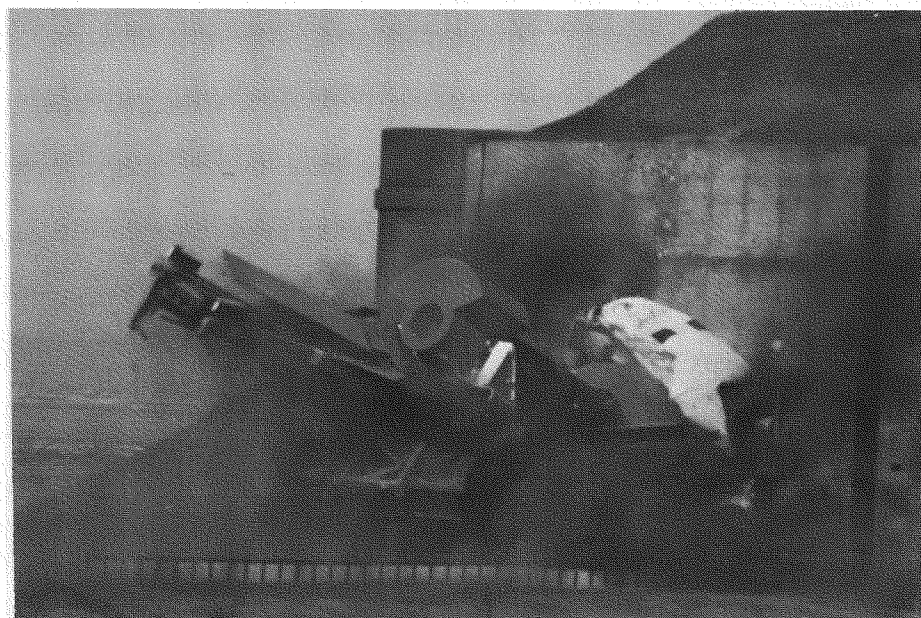Figure 5b. Posttest damage - scale model test.

ballasted to the weight of a conventional PWR fuel assembly. The thermal environment of a normal spent fuel cask containing an irradiated spent fuel subassembly was simulated by heating the test cask to 66°C. About 160 kg of water coolant was included in the cask to simulate its normal shipping environment. Rocket motors, propelled the transport system up to speed (Figure 6a) after which the tractor-trailer rig, guided by rails, coasted into the impact zone at 97.8 kph.

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 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 wood in the impact limiter. Following the main impact, the cask and trailer rotated to about 30 degrees relative to horizontal and returned to the roadbed in front of the target (Figure 6b).
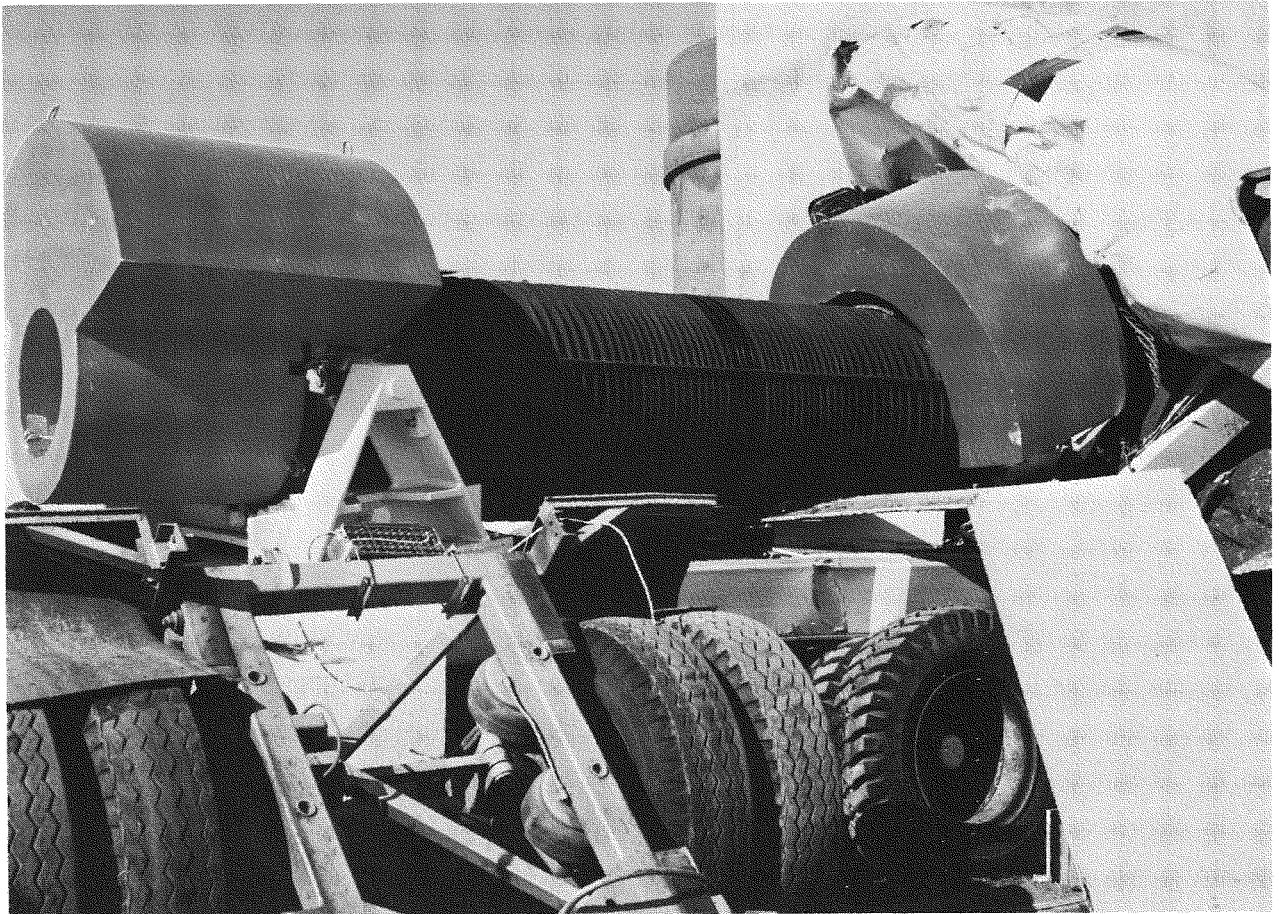
Figure 6c shows the posttest condition of the cask and transport system. The cask remained intact, sustaining only

6a. HAWK Rockets and Transport - Full Scale Test

6b. Impact

6c. Posttest Accident Views - 100 kph Test

Figure 6. 100 kph truck test.

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 7 (11), which illustrates both calculated and measured velocity-time histories.

130 kph Truck-Cask Impact Test

Analyses -- For the second test, the same lumped-parameter SHOCK model was used to calculate the transport system response with a higher initial velocity (130 kph). Again, the tiedown parameters in the model were varied to obtain information for a range of system response. Figure 8 shows the favorable and unfavorable system response calculated by the SHOCK model (11). Note that the curves for the two responses are not 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 with the predicted impact velocity of the cask into the wall varying from 105 to 122 kph. Since the structure of the trailer was identical to that of the trailer used in the 100 kph test, it was assumed that the tiedown response would be similar; that
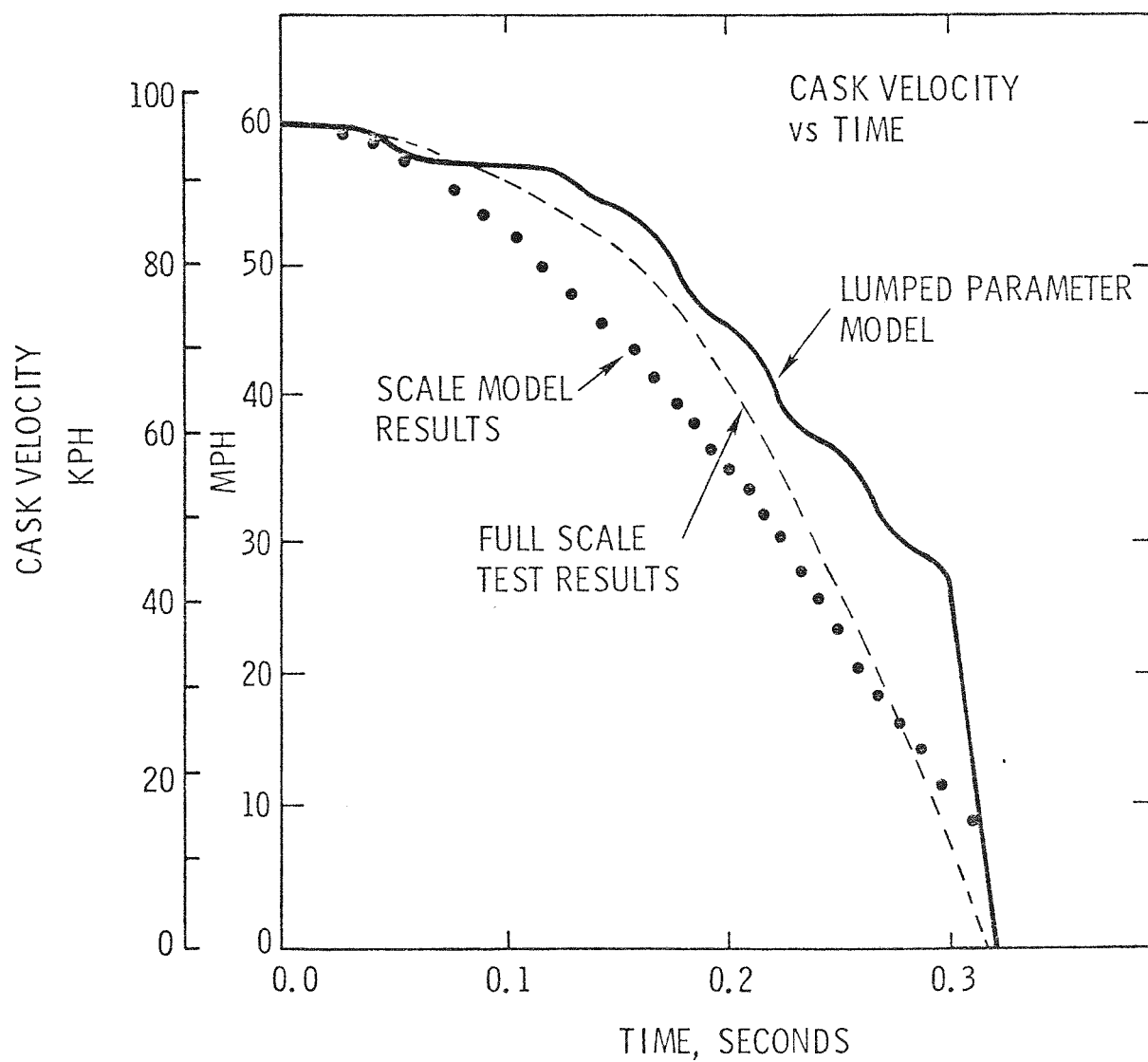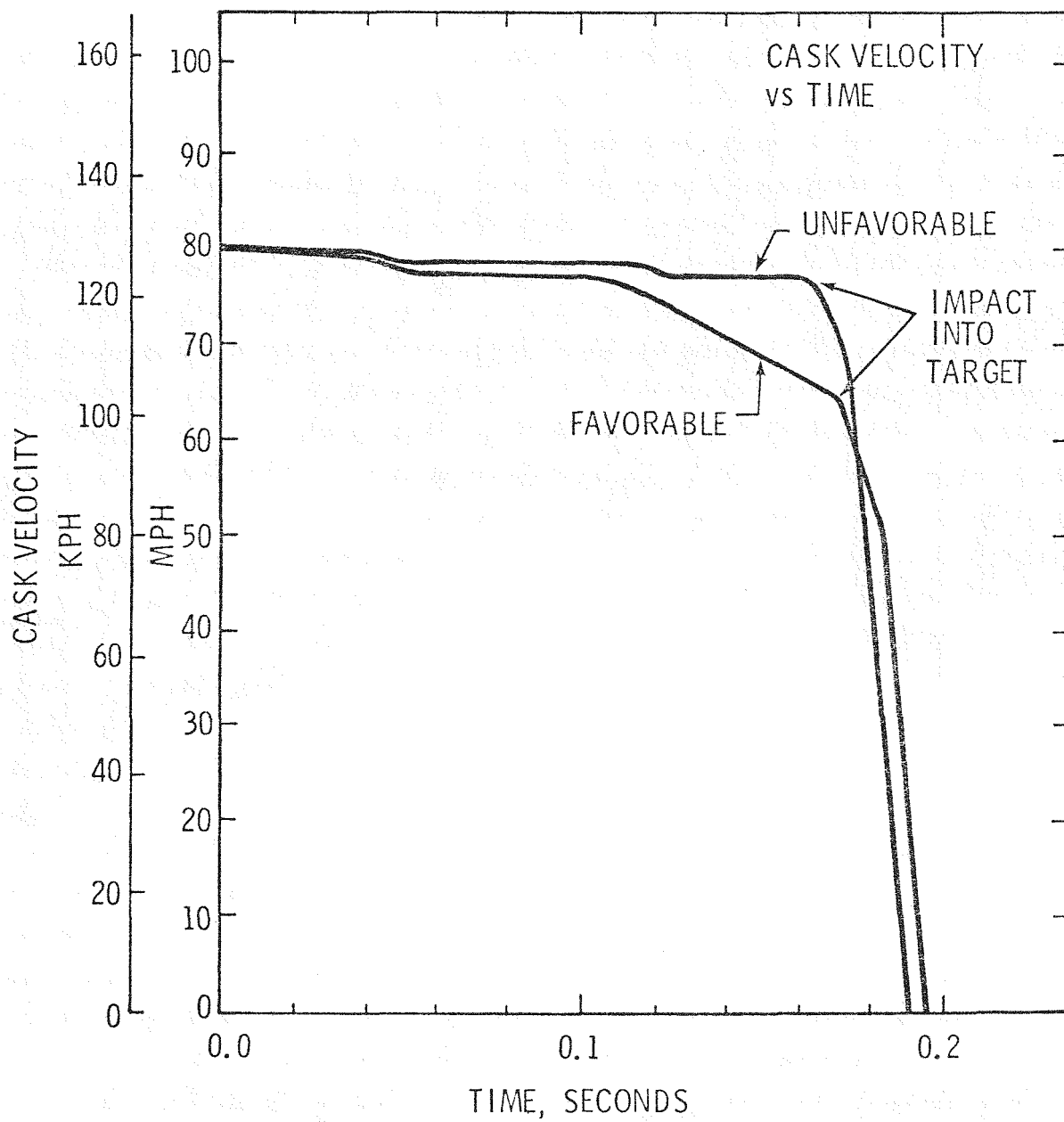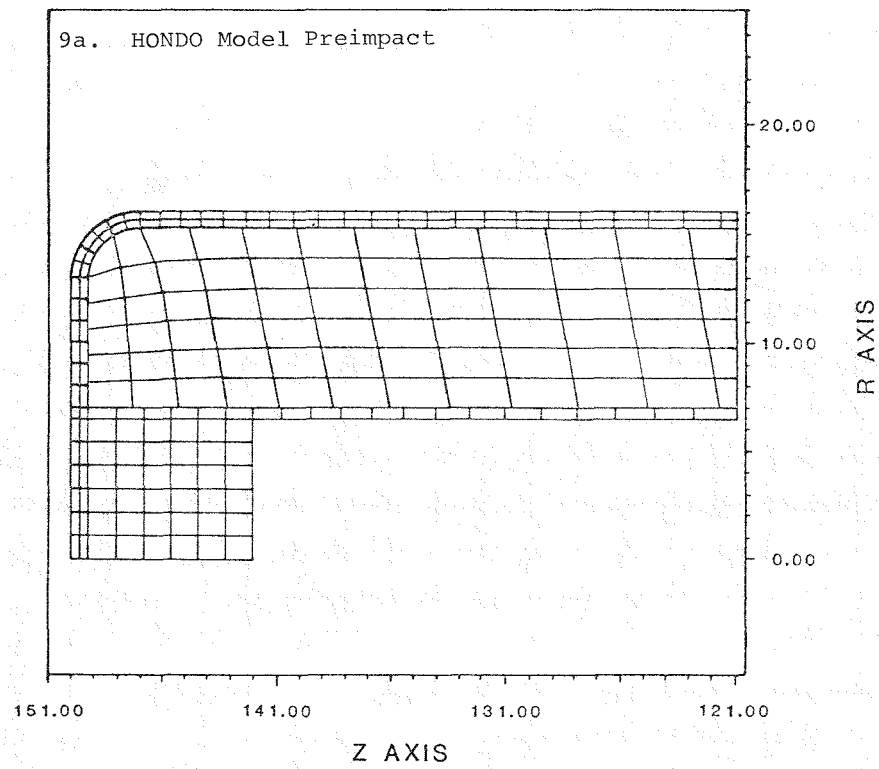
Figure 7.   Comparison of SHOCK results.

Figure 8. Pretest SHOCK comparison - 130 kph test.

is, the tiedowns would follow the favorable response curve and the impact velocity of the cask would be approximately 105 kph.

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 9a 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 9b shows the test cask after a 105 kph impact. Although there is significant bulging of the impacted end, 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 which 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.

9a. HONDO Model Preimpact

R AXIS

20.00

10.00

0.00

151.00   141.00   131.00   121.00

Z AXIS

TIME - .01000114

9b. HONDO Model Postimpact

R AXIS

20.00

10.00

0.00

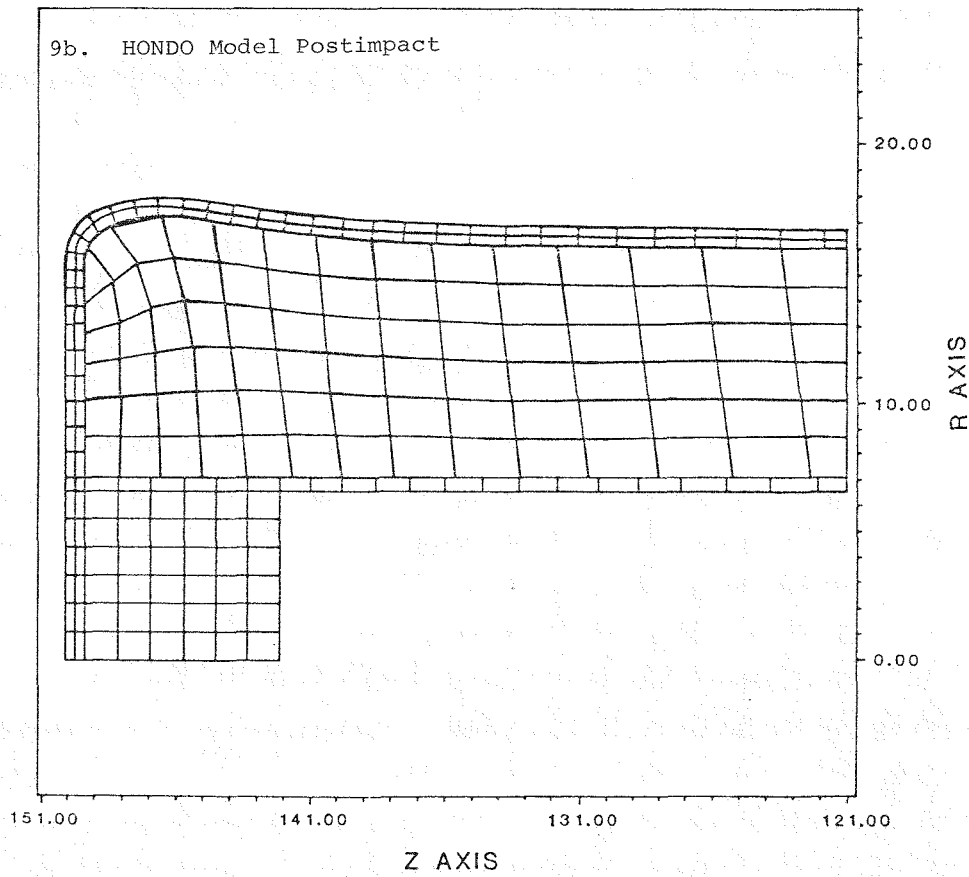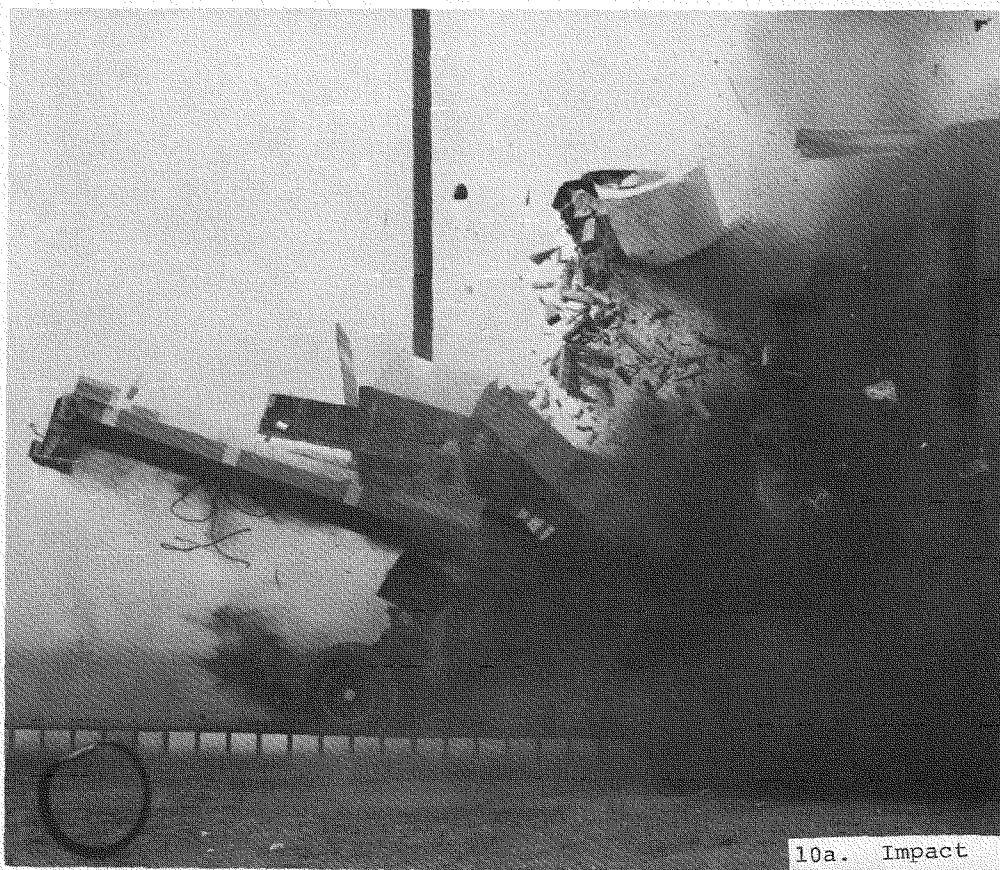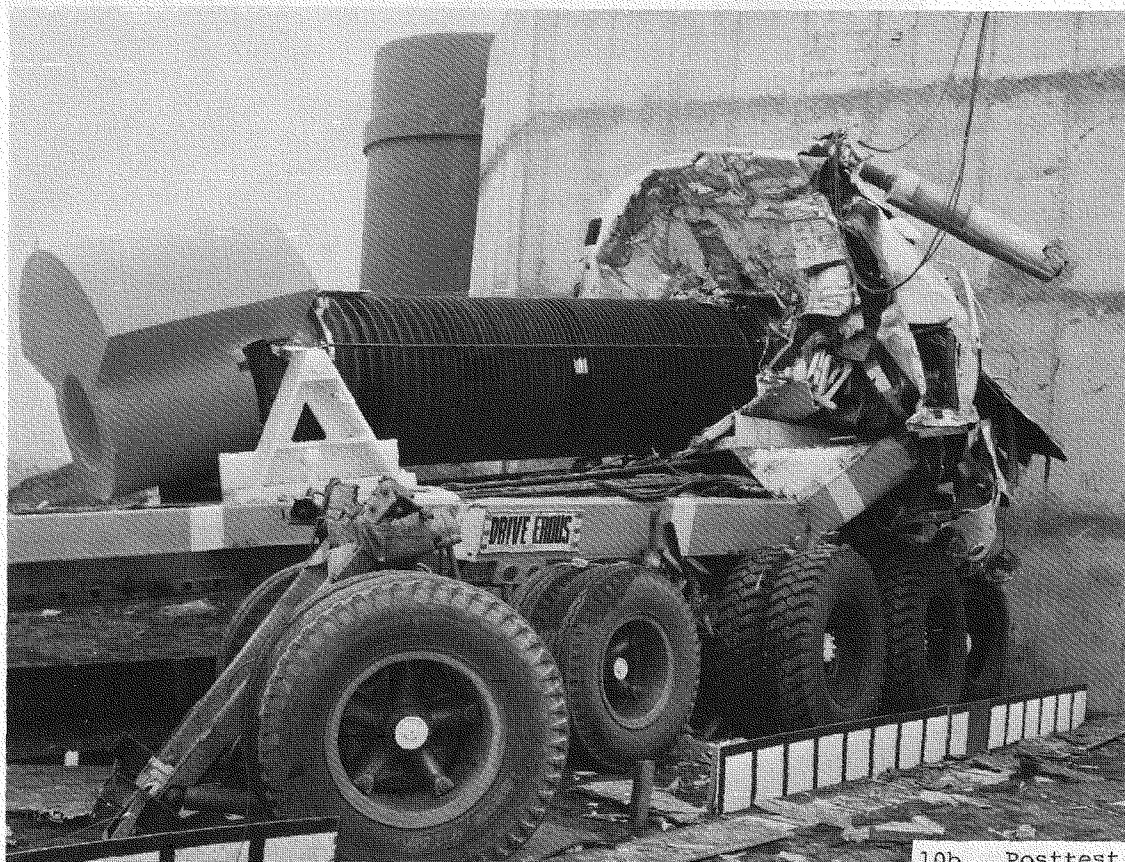151.00   141.00   131.00   121.00

Z AXIS

Figure 9. HONDO model.

The second truck-cask impact test was conducted on March 16, 1977, at a velocity of 135 kph. 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 (Figure 10a). Both cask and trailer came to rest in the upright position in front of the target.

Figure 10b 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 two drops per minute was detected from the cask head. The seepage later stopped after releasing 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 10c) 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 nonsymmmetric 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 after which inspection of the fuel assembly revealed deformation of

10a. Impact

10b. Posttest

10c. Cask Head

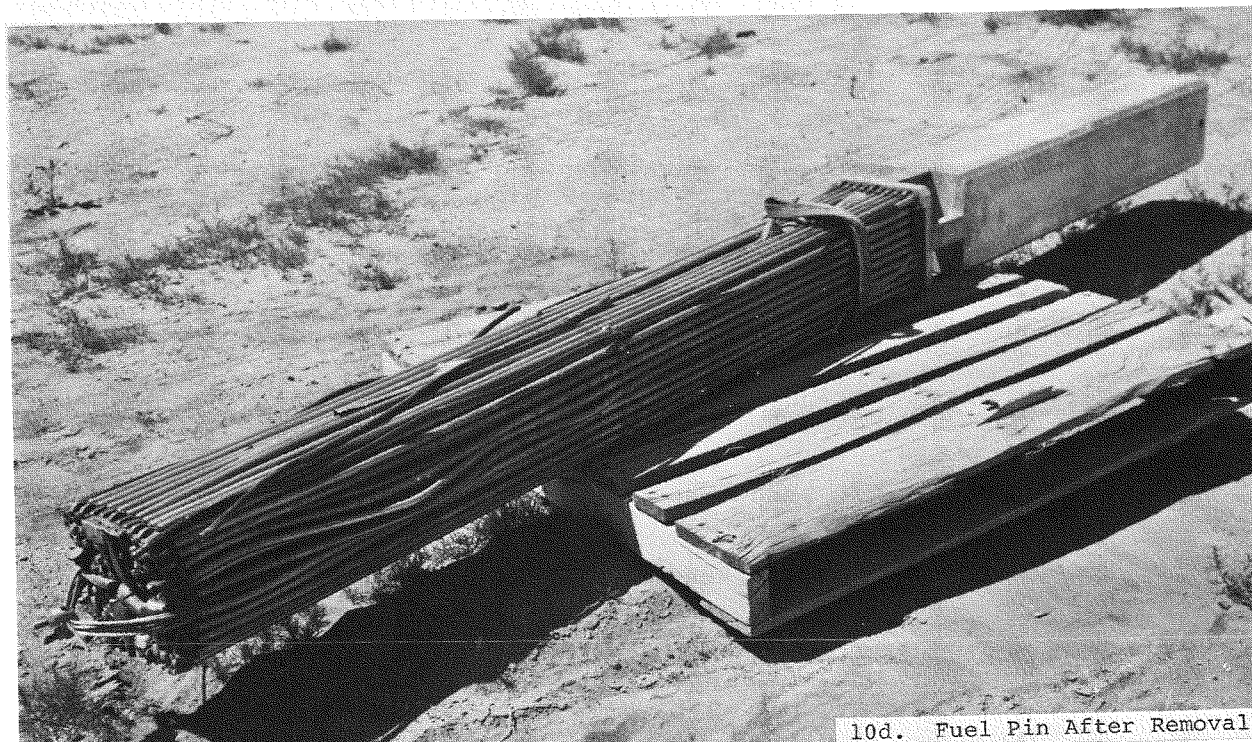10d. Fuel Pin After Removal

Figure 10. 130 kph Truck test.

the impact end. Some fuel-pin buckling occurred as shown in
Figure 10d; however, no clad failure was detected.

The overall response of the cask transport system agreed
well with pretest analytical predictions. A quantitative com-
parison of the results is shown in Figure 11 (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.

130 kph Grade Crossing Test

Analyses -- An analytical investigation of a grade-crossing
accident involving the 130 kph impact of a 186 metric ton loco-
motive into a 22.7 metric ton spent fuel cask at a grade cross-
ing 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 which is not used to transport
current commercial spent fuel casks. This analysis indicated
that the cask would be moderately deformed after a centerline
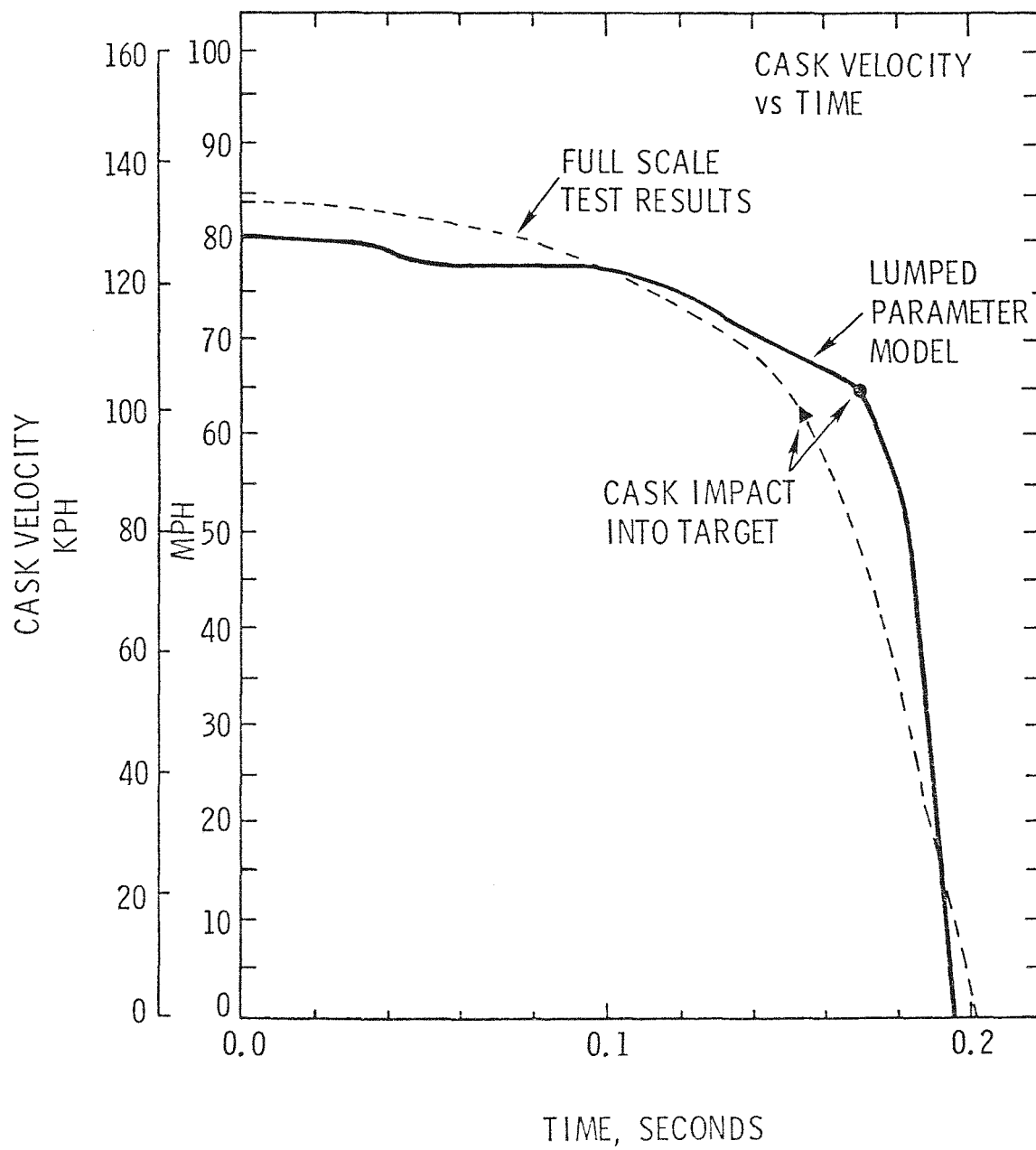impact with the locomotive frame.

Figure 11. Comparison of analytical and full scale results.

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

The major thrust of the remainer of the analysis involved using the finite-element HONDO code. The frame and cask impact condition is depicted in Figure 12. 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 upon 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 effect of increasing locomotive or train mass would be negligible in increasing damage to the cask.

Scale Model Test -- 1/8-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 13a). 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 kph. In this scaled impact, the frame of the locomotive struck the cask a glancing blow. As
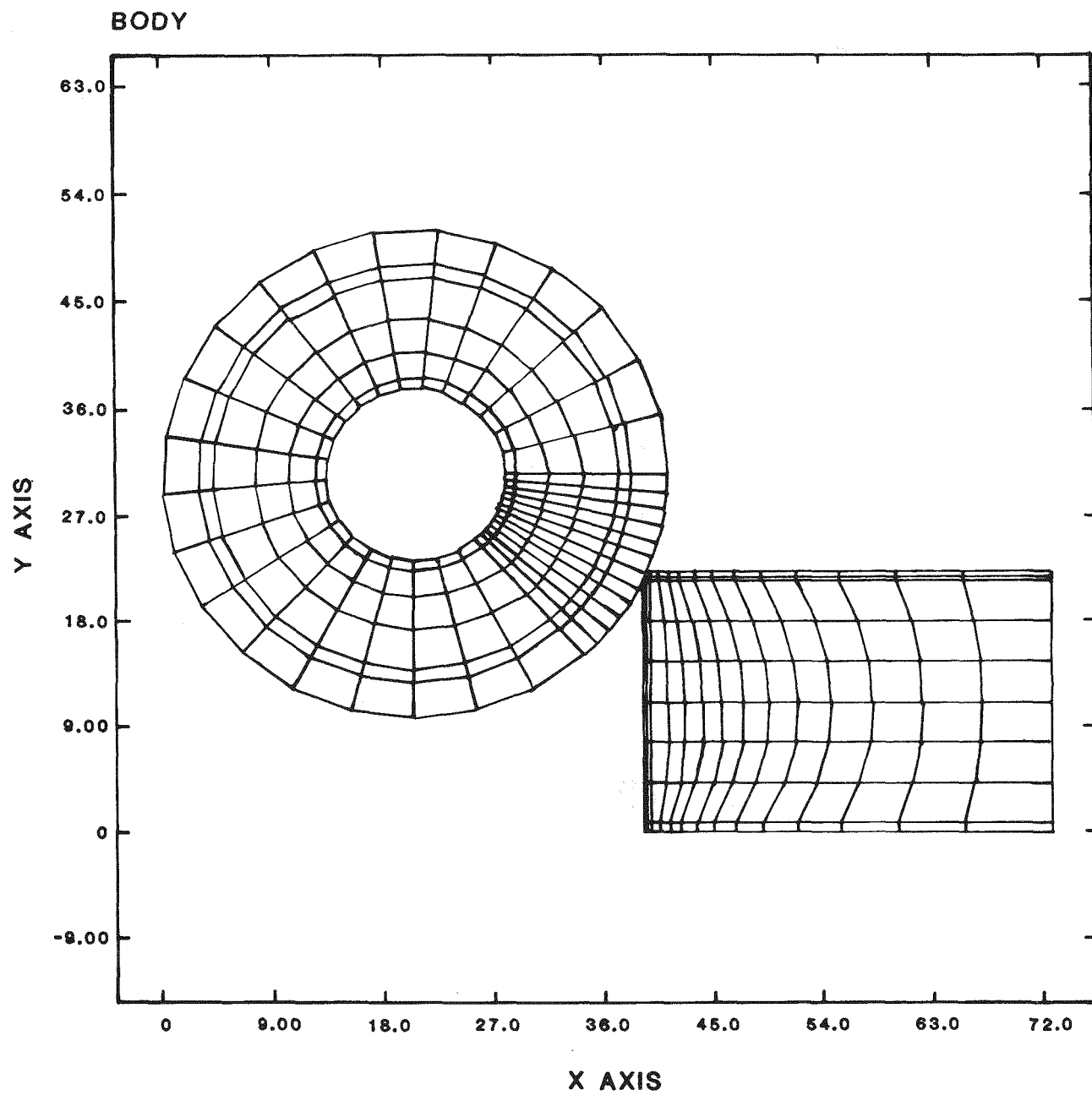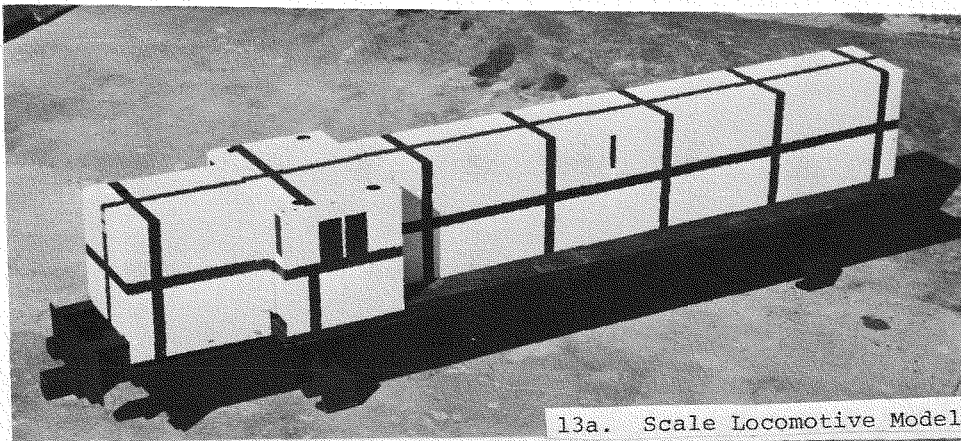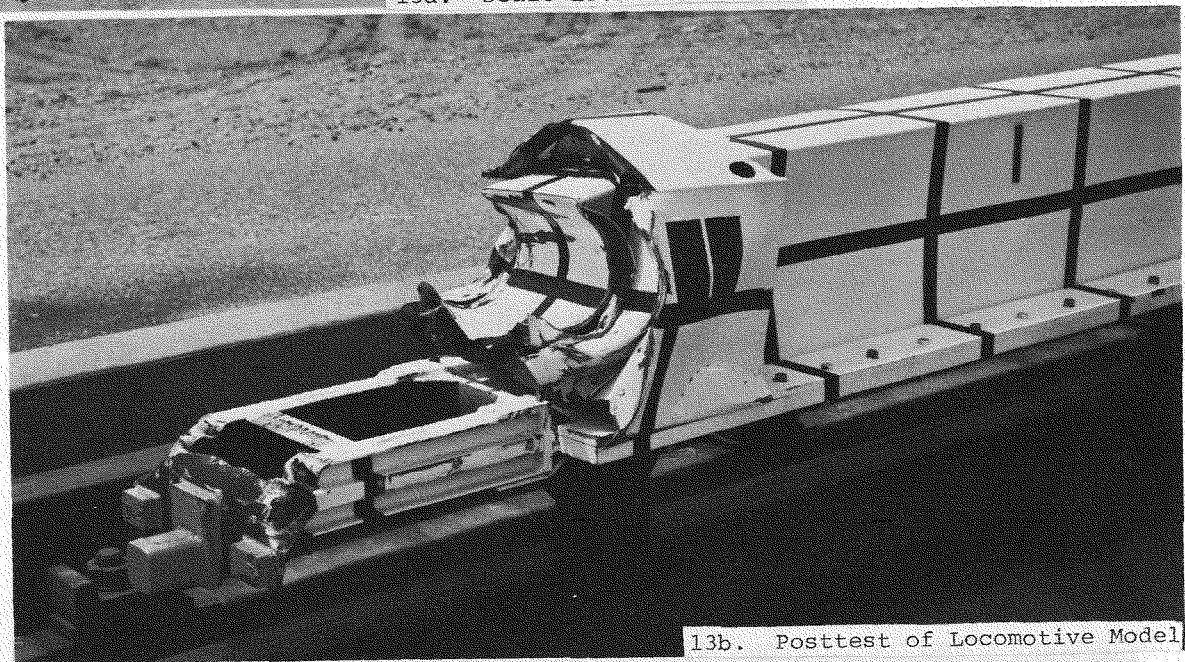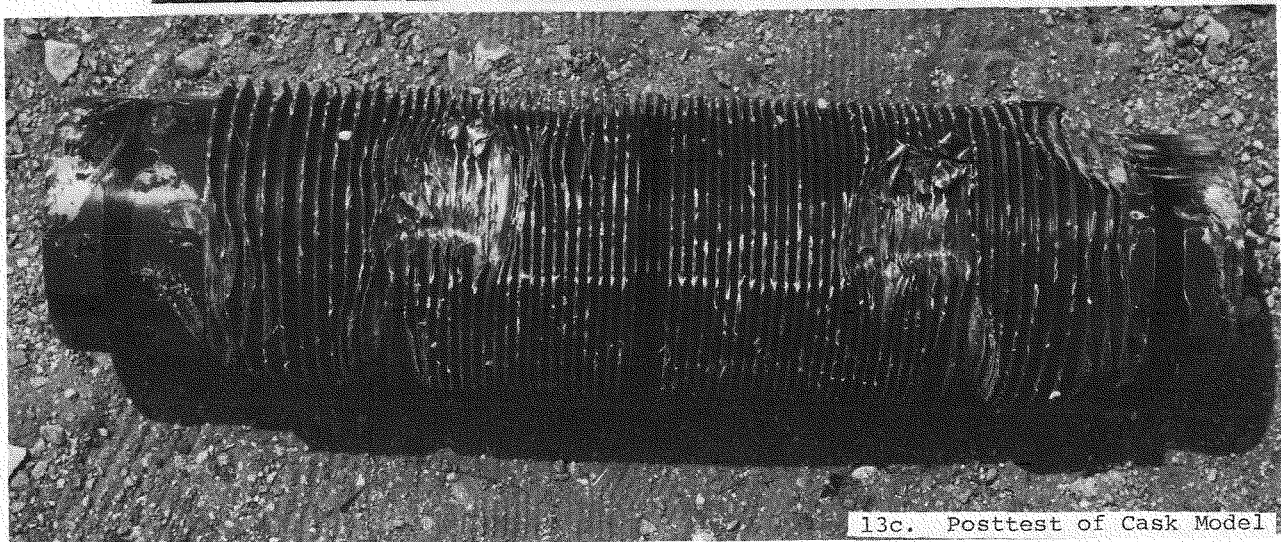
Figure 12.   HONDO model.

13a. Scale Locomotive Model
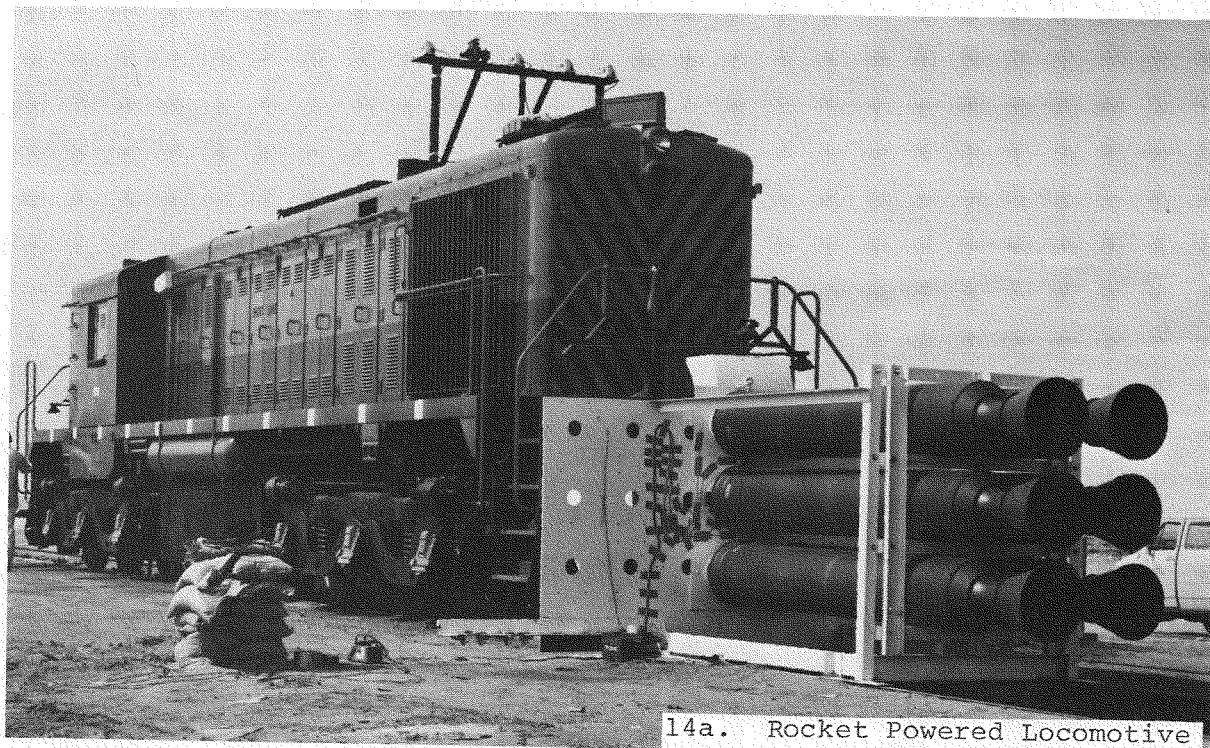

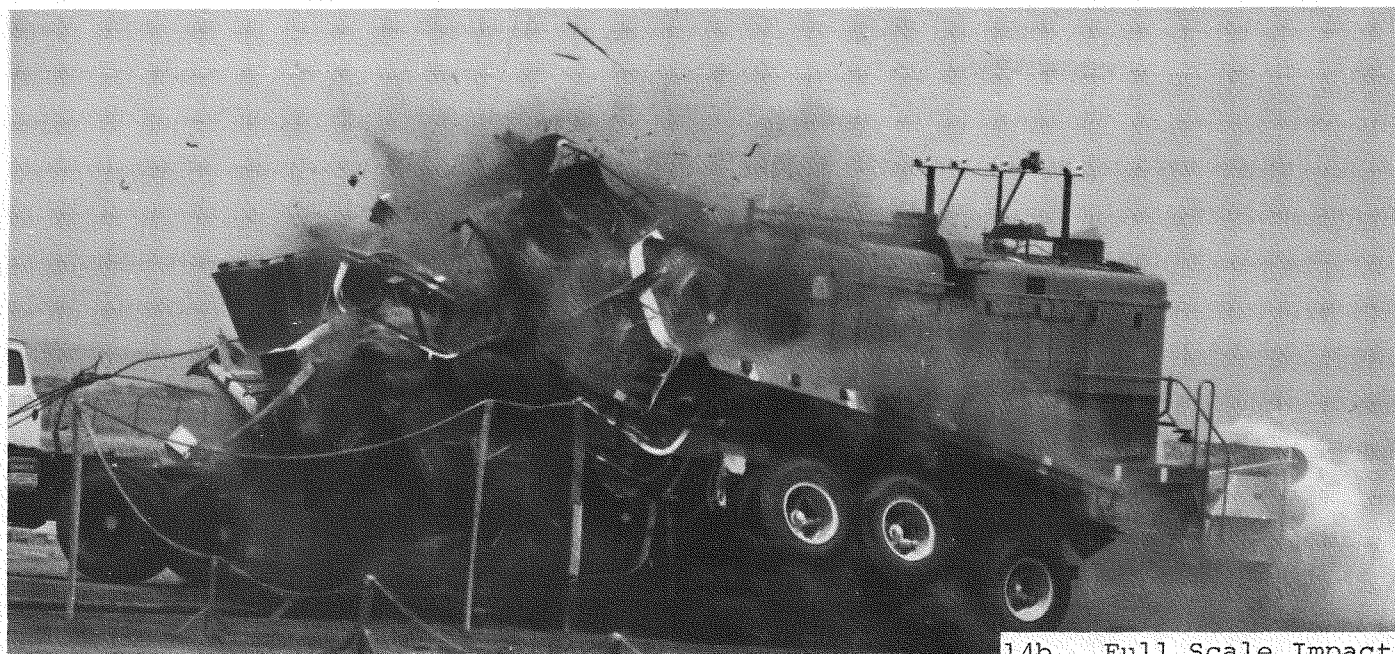13b. Posttest of Locomotive Model

13c. Posttest of Cask Model

Figure 13. Scale test of grade-crossing crash.

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 13b). 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 I-beams (Figure 13c) 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 the 109 metric ton locomotive to test speed (Figure 14a) after which it coasted to an impact at 131 kph. As predicted by pre-test analysis and scale model test results, the frame of the locomotive was crippled forming a ramp, which allowed the cask to rise into the superstructure (Figure 14b). As shown in Figure 14c, failure of the locomotive frame closely resembled that in the model test. After superstructure crush-up, the cask rolled off 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 cause essen-tially no risk to the public. The cask head was removed without
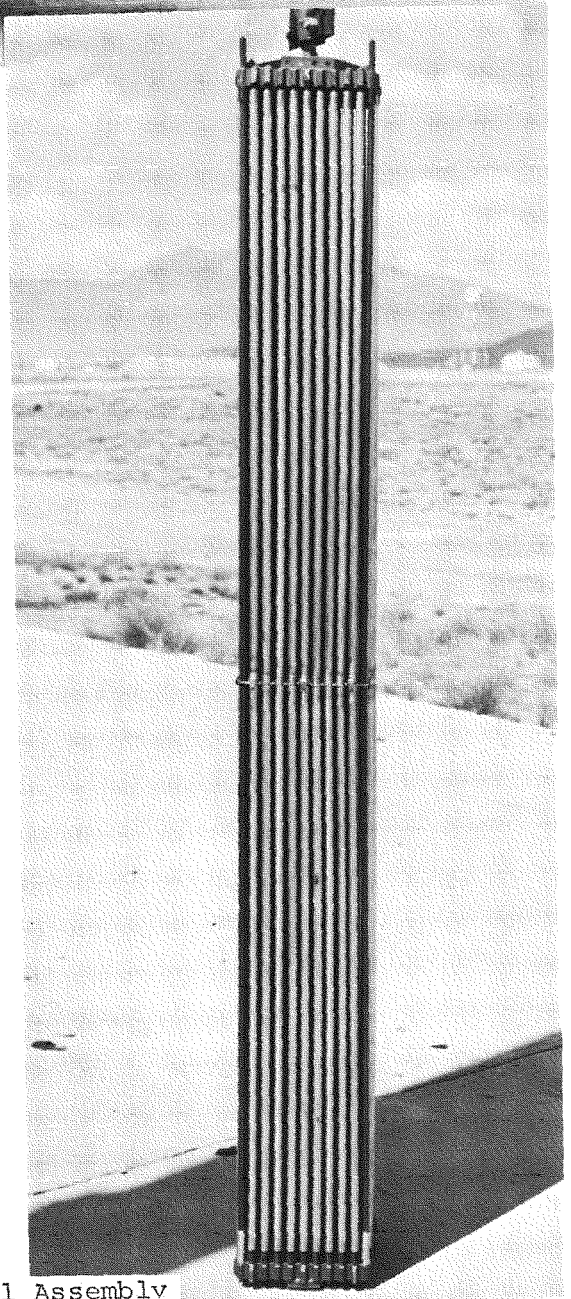
14a. Rocket Powered Locomotive

14b. Full Scale Impact

14c.   Frame Buckling Damage

Figure 14.   Grade-crossing test.

14d.   Posttest Fuel Assembly

difficulty and the fuel assembly was found to be intact. There was some bowing of the fuel pins as shown in Figure 14d; however, no clad failure was detected.

Comparison of the damage to the cask and locomotive 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 "extra severe" or "extreme" categories described in the 1972 Atomic Energy Commission Report (WASH 1238) (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 kph truck impact into a massive barrier is once every 70 years; and for a velocity of 130 kph, approximately once every 1000 years, or no more than once every 1.13 x 10^7 km traveled.

Using the same shipment conditions for the grade-crossing accident, the probability calculations indicate that for a velocity of 130 kph, 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 railcar and cask into a massive concrete barrier followed by a fire, the probability calculations for total shipment distance of 7 million miles indicate that, for a velocity of 115 kph, the probability of occurrence for impact is expected to be approximately once every 5900 years, and for a velocity of 130 kph, 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 while transporting spent fuel the public would not have been exposed to irradiated fuel elements.

Conclusion

The program objectives have been successfully met 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/or scale model

testing.

References

1. C. A. Davidson, J. T. Foley, Transportation Environment Data Bank Index, SAND 75-0248C (updated), Sandia Laboratories, Albuquerque, NM (April 1977).

2. NUREG-0170, Generic Environmental Statement of the Transportation of Radioactive Materials by Air and Other Modes, USNRC, to be issued in 1977.

3. Ivan G. Waddoups, Air Drop Test of Shielded Radioactive Material Containers, SAND 75-0276, Sandia Laboratories, Albuquerque, NM (September 1975).

4. L. B. Shappert, N. C. Bradley, T. H. Evans, M. C. Turgensen, The Obsolete Cask Test Program: Test Number 2, ORNL-TM-1312, Oak Ridge National Laboratory, Oak Ridge, TN (April 1975).

5. V. K. Gabrielson, R. T. Reese, SHOCK Code User's Manual, A Computer Code to Solve the Dynamic Response of Lumped-Mass Systems, SCL-DR-69-98, Sandia Laboratories, Livermore, CA (1969).

6. M. Huerta, H. R. Yoshimura, A. W. Dennis, "Impact Analysis of Spent Nuclear Fuel Shipping Systems," presented at the CUBE Symposium, Albuquerque, NM (October 1976).

7. S. W. Key, HONDO, A Finite Element Computer Program for the Large Deformation Dynamic Response of Axisymmetric Solids, SLA 74-0039, Sandia Laboratories, Albuquerque, NM (January 1974).

8. D. E. McGovern, S. Thunborg, On the Use of Modeling in a Structural Response Problem, SC-RR-70-880, Sandia Laboratories, Albuquerque, NM (1971).

9. T. A. Duffey, Scaling Laws for Fuel Capsules Subjected to Blast, Impact, and Thermal Loading, SC-RR-70-134, Sandia Laboratories, Albuquerque, NM (1970).

10. H. R. Yoshimura and M. Huerta, "Full Scale Tests of Spent Nuclear Fuel Shipping Systems," Transport Packaging for Radioactive Materials, IAEA-SR-10/17, Vienna, Austria (1976).

11. M. Huerta, Analysis, Scale Modeling, and Full Scale Tests of a Truck Spent-Nuclear-Fuel Shipping System in High Velocity Impacts Against a Rigid Barrier, SAND 77-0270, Sandia Laboratories, Albuquerque, NM (1977).

12. A. W. Dennis, <u>Analytical Investigation of a Grade Crossing Accident Between a Rail Train and a Spent Nuclear Fuel Cask</u>, SAND 74-0317, Sandia Laboratories, Albuquerque, NM (January 1975).

13. WASH 1238, <u>Environmental Survey of Transportatiof of Radioactive Materials To and From Nuclear Power Plants</u>, US Atomic Energy Commission, Washington, DC (1972).

Distribution:

William A. Brobst, Chief
Transportation Branch
Environmental Control Technology
U.S. Department of Energy
Washington, DC 20545

Richard B. Chitwood, Acting AD
Transportation
U.S. Department of Energy
Washington, DC 20545

James A. Sisler
Transportation Branch
Environmental Control Technology
U.S. Department of Energy
Washington, DC 20545

5000   A. Narath
5100   J. K. Galt
5200   E. H. Beckner
5300   O. E. Jones
5400   A. W. Snyder
5410   D. J. McCloskey
5420   J. V. Walker
5430   R. M. Jefferson (50)
5431   W. A. Von Riesemann
5432   R. E. Luna
5433   R. B. Pope (25)
5433   H. R. Yoshimura (75)
5450   J. A. Reuscher
5700   J. H. Scott
5800   R. S. Claassen

3141   C. A. Pepmueller (Actg) (5)
3151   W. L. Garner (3)
       For: DOE/TIC (Unlimited Release)
8266   E. A. Aas
3172-3 R. P. Campbell (25)
        For: DOE/TIC (Unlimited Release)