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A Crash Test of a Nuclear Spent Fuel Cask and Truck Transport System

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A CRASH TEST OF A NUCLEAR SPENT FUEL CASK
AND TRUCK TRANSPORT SYSTEM

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ABSTRACT

Sandia Laboratories has conducted a 96 kph (60 mph) full scale truck impact test for ERDA's Environmental Control Technology Division. Rockets propelled a 20,500-kg (22-ton) cask mounted on its shipping trailer, coupled to a conventional cab-over tractor, into a massive, heavily reinforced concrete target. This summary report describes and compares the results of the computer analysis, scale model, and full scale tests.

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A CRASH TEST OF A NUCLEAR SPENT FUEL CASK AND TRUCK TRANSPORT SYSTEM

Introduction

Sandia Laboratories is conducting a series of full scale impact tests involving nuclear spent fuel "transport systems" for the Environmental Control Technology Division of the United States Energy Research and Development Administration (ERDA). A transport system consists of a shipping cask with its associated tiedown hardware and the vehicle on which it is transported, such as a truck/trailer or a railcar. The test series includes three different basic accident scenarios:

1. Impact test of a truck transport system and nuclear spent fuel shipping cask head-on into a solid concrete barrier.
2. Locomotive grade crossing impact with a truck-tractor trailer system carrying a nuclear spent fuel shipping cask.
3. Impact into a solid concrete barrier and fire test of a special railcar carrying a nuclear spent fuel shipping cask.

These tests provide conditions which have a very low probability of occurring. Statistically, a head-on truck crash into a massive target similar to the one used in the full scale test is so unlikely that a velocity of 96 kph (60 mph) it can be expected to occur no more often than about once in 65 years. If the velocity were increased to 120 kph (80 mph) or more, the predicted frequency of occurrence is somewhat less than once in every 1,000 years (these calculations are based on the assumptions that 3,500 - 2,000 mile shipments per year are made). In fact, no accidents of such severity involving spent nuclear fuel transport systems have ever occurred. Velocities in all of the tests are in the 96 to 129 kph (60 to 80 mph) range.

The test series has two main purposes: (1) is to assess the validity and utility of analytical and scale modeling techniques for predicting the response of these shipping systems subjected to severe accidents environments, and (2) to gain quantitative knowledge of the extreme accident environment by measuring the response of representative full scale casks and associated transportation vehicles under actual crash conditions.

These tests are not intended to prove or disprove the validity of the present regulatory standards.

This report summarizes the results of the first full scale test in which a 32,000 kg (70,000 lb) tractor-trailer cask system impacted head-on at 98 kph (61 mph) into a rigid barrier. Analyses completed before the test, including mathematical and scale modeling of the system are described. Results from the full scale test are compared to the pretest analyses.

Analysis

The basic dynamics and response of the truck-tractor test were investigated by means of a mathematical lumped parameter model. In this type of modeling, the structure is separated into discrete masses and couplings. The coupling definitions are based on analytical estimates of their load-displacement behavior. After the model was formulated, an existing computer program, SHOCK, was used to solve the associated system of equations¹.

Figure 1 is a schematic of the lumped parameter model devised for this test. Here the system, including the target, is modeled with eight discrete masses and ten couplings. Mass 1, the target, is fixed and the remaining masses are given initial velocities equal to the impact velocity. Computational results from this model provide estimates of expected deformations as well as displacement-time and velocity-time histories for the components.

Figure 1. Schematic of the Lumped Parameter Model

Because of the uncertainties which exist in the used, out-of-service, hardware evaluated in this test (and which to a lesser extent also can exist in new hardware), parameters in the model were varied to obtain information regarding a possible range of system response. In particular, the strength of the container tiedown system was varied. Results from this parametric study provided definitions of "favorable" and "unfavorable" responses. These can best be depicted by the calculated range of the velocity-time histories illustrated in Figure 2, which were computed with the lumped parameter model.

Figure 2. Velocity-Time History for the Container
Calculated with the Lump Parameter Model

In the unfavorable case, it was calculated that the container would break free from the trailer structure very early in the impact after only a small reduction in velocity and would impact the wall at a relatively high velocity. The resulting velocity change at target impact would be large and rapid. In the favorable case, the container would remain attached to the trailer and would be continuously slowed as the front end of the trailer structure crashed. As a result, it would impact the wall at a much lower velocity (see Figure 2). Detailed dynamic response of the container was investigated for the worst case, in which the container impacts the wall at the higher velocity.

If the lumped parameter model predicts impacts and forces sufficient to deform the cask, a more detailed finite element computer program, HONDO, is used to obtain information regarding permanent deformations which the cask sustains².

Using results from the finite-element model, only very slight deformations to the cask would be expected even for the worst condition (i. e., the unfavorable case). These deformations were not expected to violate the containment capability of the cask. Scale model tests, which are described in more detail in the following section, were performed to verify this analysis.

Scale Model Test

Scale model testing can be used to either verify analytical methods or to directly evaluate structural response in accident conditions. Therefore, as part of the overall program, scale model impact tests of the tractor-trailer system were conducted (subsequent to the mathematical modeling) at the Sandia Laboratories' sled track facility. All scale models were constructed with a scale factor of 8 (linear dimensions were 1/8 as large as the prototype). Figure 3 is a photograph of one of the models at the track facility. In each test, a small rocket sled accelerated the model to a velocity slightly higher than the intended impact velocity, the sled was separated from the model, and the model coasted into a scaled target.

Figure 3. Photograph of the Scale Model at the Track Facility

The scale model system included a tractor, trailer, cask, tiedowns, and impact limiter. Its total weight was 60 kg (132 pounds). The model cask was a machined stainless steel structure and included lead shielding cast into the annular region between the inner and the outer shells. The cask body, as well as the head and its bolting, were closely scaled approximations of the full scale hardware. An impact limiter, which was incorporated into the full scale test, was included on the model cask. The tractor-trailer model structures were designed with emphasis placed on the major masses and structural elements. Only those elements expected to contribute significantly to the cask dynamics were included. The models, therefore, adequately simulated the major dynamics and resultant damage to be expected in the full scale test. One of the scale model impacts was conducted at the exact velocity of the full scale test described in this report. Subsequent discussions of scale model results will pertain to this test.

The model test results agreed closely with analytical predictions. In this test, the tractor crushed completely; the front end of the trailer structure separated from the fifth wheel and plowed into the cab, solidly impacting the wall; and a good portion of the front end of the trailer was crushed. The model cask remained nearly horizontal as the vehicular structure crushed; it moved forward through the cab area and impacted the wall in nearly an end-on orientation with the crushed cab in between; the impact limiter was only partially compacted. Figure 4 is a photograph of the model cask and trailer system taken after one of the tests. All of the front end of the trailer deformed and buckled up along the vertical face of the target, the cask suffered negligible damage.

Figure 4. Scale Model after the 98 kph (61 mph) Impact Test

From the scale model test results, it was predicted that: (1) complete destruction of the tractor, and gross deformation to the front end of the trailer would occur in the 96 kph (60 mph) full scale tests; (2) the cask would remain nearly horizontal during crushing of the vehicular structures and would rotate only after impacting the wall; (3) only partial crush of the impact limiter would result; and (4) only minimal damage to external features of the container could be expected in the first full scale test.

Full Scale Test

The first tractor-trailer cask test was conducted on January 18, 1977. This test involved a 20,500 kg (45,000 pounds) out-of-service shipping cask mounted head-forward on the same trailer that actually transported it during its time in service. The cask was loaded with a single fresh LWR fuel assembly (PWR) and with 157 kg (346 pounds) of water as coolant. The trailer

was coupled to an out-of-service commercial tractor. A rocket-powered sled accelerated the system which was guided by rails. upon separation from the power sled, the system coasted into the target. Extensive photo coverage and onboard instrumentation were provided for the test. Figure 5 is a photograph of the system early in the acceleration phase. Figure 6 is a photograph of the massive and heavily reinforced concrete target, which is comprised of 6.27×10^5 kg (690 tons) of heavily reinforced concrete backed with 1.58×10^6 kg (1740 tons) of earth. The target was designed to be very massive and rigid with respect to the cask impact; that is to say, for all practical purposes considering the masses and velocities involved in the test, the target is essentially unyielding. An object of this size and weight is rarely, if ever, found along normal truck routes.

Figure 5. Full Scale System being Accelerated to Impact Velocity

Figure 6. Concrete Target for Full-Scale Test

The full scale system impacted at 98 kph (61 mph). As both analytical and scale model results predicted, the tractor was completely destroyed in the crash; the trailer moved forward through the cab and impacted the wall; and the front end of the trailer crushed and buckled up along the target face. The cask tiedowns almost broke loose from the trailer frame. The cask remained essentially horizontal during the crush-up of the vehicular structure. It was stopped by the wall, with rubble from the tractor and trailer in between. The cask velocity just as the impact limiter reached the wall was approximately 43 kph (27 mph). The limiter was partially crushed in the axial direction in the final stages of the impact. Following the main impact, the cask and trailer rotated to a maximum angle of approximately 30 degrees relative to horizontal (see Figure 7), and then returned to the roadbed in front of the target. Figure 8, taken immediately after the test, illustrates the condition of the system. The cask remained intact and sustained only minor damage to external cooling fins and piping, and came to rest on the trailer. Instrumentation on the cask body indicated strains were below the yield point of the material. The cask cover was removed without difficulty and the fuel subassembly was found to be intact and undamaged.

Figure 7. Transport System 1/2 Seconds after Contacting Target

Figure 8. Transport System Subsequent to Impact

Comparison of Analysis to Full Scale Results

The overall response of the full scale system agreed well with the predictions from analytical and scale model results. For example, the fifth wheel connection between the tractor and trailer failed early in the impact allowing the trailer to move forward crushing the cab. The trailer plowed through the cab solidly hitting the wall and buckling upwards (see Figures 4 and 8). The cask rotated only slightly prior to the impact with the target. Partial crush of the impact limiter on the front end of the cask occurred but the cask body was undeformed. These responses were observed in the analysis of the scale model test.

A more quantitative comparison of analysis, scale model, and full scale test results is provided by Figure 9, which illustrates velocity-time histories for the cask from each of these three sources. The full scale results closely paralleled the analytical model predictions using a favorable tiedown response. The scale model velocity-time predictions were also in excellent agreement with full scale test results as can be seen in this figure. Thus, both mathematical analysis and scale model testing generally approximated the container velocity-time history, an important parameter in predicting damage to the shipping container.

Figure 9. Velocity-Time History for the Cask in the Full Scale Test and from Analysis

Conclusions

The pretest analysis predicted the full scale test results well. The results showed that a lumped parameter model separated into discrete masses and couplings can yield reasonably accurate indications of the behavior of a system, such as the one tested, even when involved in a violent impact producing gross deformations to peripheral structures. It was demonstrated that a simplified scale model can adequately predict the basic structural behavior in this kind of environment. The scale model response, including times, deformations, and dynamics of the system accurately simulated the behavior of a full scale system.

Although the intent of the full scale vehicle testing program was not to prove or disprove the validity of the present regulatory standards, several observations can be made from the first test. The final impact of the cask into the wall was approximately 43 kph (27 mph). This compares to 48 kph (30 mph) in a standard regulatory 9-meter drop test into an essentially unyielding surface. The reason for this low final velocity is that part of the kinetic energy of the 98 kph full-scale impact test was dissipated in crush-up of the vehicle structure and breaking of the tiedowns. Sufficient energy was absorbed in the structure to reduce the cask velocity to

less than the impact velocity of the regulatory drop test. Further, additional cushioning was provided by the deformed structure of the tractor and trailer caught between the cask and target while the regulatory drop test requires an essentially unyielding surface. On this basis, it appears that the standards regulatory drop test into an essentially unyielding surface is a more severe standard environment than what the cask was subjected to in this low probability of occurrence full scale test.

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