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DOE/PNC JOINT PROGRAM ON TRANSPORTATION TECHNOLOGY

M. Kubo, M. Kajitani, M. Seya
Power Reactor and Nuclear Fuel Development Corporation
Tokyo, Japan

H. R. Yoshimura, J. L. Moya, R. A. May
Sandia National Laboratories,*
Albuquerque, New Mexico, USA

M. Huerta, D. R. Stenberg
Southwest Engineering Associates
Albuquerque, New Mexico, USA

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ABSTRACT

This paper summarizes the work performed in a cooperative program on transportation technology between the Department of Energy (DOE) and the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan. This work was performed at Sandia National Laboratories (SNL) in Albuquerque, New Mexico.[1] The joint program emphasized the safety analysis for truck transportation of special nuclear materials (SNM) in Japan. Tasks included structural analyses and testing, thermal testing, leak rate studies and tests, and transportation risk assessments. The purpose of this paper is to present the results of full-scale structural and thermal tests conducted on a PNC developed SNM transport system. Correlation of full-scale impact test results with structural analysis and scale model testing will also be reviewed.

INTRODUCTION

In Japan, nearly all overland transport of nuclear materials, except for spent fuel, is by truck. PNC has developed an SNM highway transport system consisting of a tractor and a trailer carrying up to three shipping casks to transport materials such as mixed-oxide fuel. In this joint program, we assessed the response of the SNM transportation system under impact and fire conditions and performed regulatory drop and puncture tests of a breeder reactor fresh-fuel cask loaded with simulated fuel. The full-scale accident tests included a head-on 90-km/h(56-mph) collision of the cask transport system against a massive concrete barrier, 9-m(30-ft) drop and 1-m(40-in.) puncture tests of the prototype breeder reactor fresh-fuel cask, and 1-h fire testing of the impacted cask transport system.

STRUCTURAL ANALYSIS

Before full-scale testing of the transport system, structural analysis and scale model testing were performed to evaluate the response of the system under the specified impact condition. In the computer evaluation phase of the study, we modeled the system analytically with a one-dimensional, lumped-parameter computer code. In this type of analysis, the system is modeled with a number of mass and spring coupling elements (Figure 1). The force displacement characteristics of the couplings were estimated by using the cross-sectional area and load-deflection characteristics for each load-carrying member of the transport system.

The purpose of the analytical model was to provide estimates of the response of the system to impacts against a rigid barrier. In this type of analysis the lumped masses are given an initial velocity against the rigid barrier, and the computer program solves the associated equations of motion and calculates the response of the system as a function of time. The results included the amount of crushup in the system, the time the system takes to come to rest, and the forces in various system elements, including the tiedowns. It was of primary importance to determine if the cask would impact the target, an event that may cause damage to the cask.

During the lumped-parameter evaluation, we varied several parameters to determine a possible range of behavior. (The precise force-displacement characteristics of the various elements in the system are not known.) For example, the crushup of the cab could only be approximated. The ultimate breaking strength of the fifth-wheel connection is another item that could only be estimated; it was found to be a parameter that significantly affects results.

After completing the evaluation, we concluded that, although the proposed 90-km/h impact test would completely destroy the tractor, it would at worst deform the front end of the trailer only slightly. The results also indicated that the cask would remain attached to the trailer and would not impact the target. Figure 2 shows typical results for the calculated velocity-time history of the cask in an impact of 90 km/h. It was calculated that the cask would come to rest in slightly less than 0.3 s. Displacement results indicated that the cask would move forward with the trailer about 4.5 m(15 ft) after the system impacted the target. These results were later compared to results obtained with scale models and from the full-scale testing described below.

SCALE MODEL TESTS

Using full-scale drawings from PNC, we fabricated two quarter-scale models of the transport system for the head-on impact tests. The purpose of the scale-model tests was to verify calculational results and to study possible system response in greater detail. In designing the scale models, we simplified the full-scale system while retaining pertinent structural features. The models included considerable structural detail and were constructed of materials similar to those of the prototype. Two complete quarter-scale models of the PNC system were designed and fabricated, including a detailed cask, a trailer, and a tractor (Figure 3). Note in Figure 3 that the cask is visible through the sides of the trailer structure. Clear panels were used to allow the cask to be viewed during the impact test. Quarter-scale tiedowns, which had not been defined by PNC, were designed and fabricated. The system was designed to run at a sled-track facility where it would be accelerated by rocket motors.

The first scale-model test consisted of a 90-km/h impact environment, and the second test evaluated the response of a revised tiedown and transportation system. Figure 4 is a sequence of photographs taken during a scale-model impact test. Both model tests indicated that the tractor would be demolished and the trailer crushed slightly. The cask would remain attached to its tiedowns. The model impact lasted approximately 0.07 s, which translated into a full-scale impact duration of 0.28 s (events in the larger prototype take longer by the scale factor). The results from the scale-model tests were used to assist in the development of the analytical model and to provide empirical estimates of the response of the full-scale test. These model tests also served as an aid to confirm the design of tiedowns for the full-scale prototype hardware.

FULL-SCALE IMPACT TEST

The purpose of the full-scale impact test was to verify the adequacy of analytical and physical scale modeling. We designed the test transport system components to provide an adequate model of the prototype transport system. A full-scale transport system was constructed using both existing and new materials. A tractor made available from PNC was modified to match the structural characteristics of the actual unit. A new cab structure was specially designed and constructed to fit on the Japanese chassis. A special enclosed trailer was fabricated from simplified drawings of the prototype. The trailer frame was specially fabricated to model the PNC prototype. Structural I-beams of the correct size and shape formed the main frame of the system. Many types of structural shapes and plating were used to form the trailer system so as to conform closely to the PNC prototype. The trailer superstructure was designed with openings on the sides and top to allow viewing the cask during the test.

As mentioned above, the PNC system was designed to carry up to three shipping casks. Before testing, PNC personnel decided that the full-scale impact test should simulate a fully loaded system. For the full-scale test, the trailer contained three casks: two mass models (to simulate the weight of fully loaded casks) and an actual prototype breeder reactor fresh-fuel cask supplied by PNC. A basket and simulated fuel assembly were also provided by PNC and used in the test.

Before testing, the system was instrumented with many accelerometers and strain gages. The data from these transducers would be sent by telemetry to a recording system at the test site. In the actual test, the system was accelerated to speed at a sled-track facility and allowed to impact a very rigid target. The event was recorded by many high-speed cameras to determine the detailed response of the system.

The full-scale test was conducted at a velocity of 90 km/h. The system, propelled by rocket motors, impacted a 625-metric-ton concrete mass backed by 1580 metric tons of earth. System response was evaluated by examining the posttest hardware, by analyzing the high-speed films, and by assessing the results obtained from onboard instrumentation. Figure 5 includes a series of photographs taken from one of the high-speed films of the test. As predicted from the structural analysis and scale-model tests, the tractor was demolished and the trailer was partially crushed during impact. The front end of the trailer sustained damage well within the predictions. The impact lasted approximately 0.3 s, as predicted. The test cask remained with the trailer; the tiedowns did not fail. Posttest examination of the cask revealed only minor damage to the exterior of the body near the impact end. Leak testing of the cask after the test indicated that the seals were intact. The full-scale test demonstrated that (1) an impact of this magnitude will not damage the cask or cause loss of contents, (2) the cask will remain attached to the trailer while decelerating at approximately 28 g, and (3) the cask contents will not be damaged in this type of impact.

FULL-SCALE DROP AND PUNCTURE TESTS

After the full-scale system test, regulatory drop and puncture tests of the prototype cask were performed to verify its design integrity. Two 9-m drop tests, side and center-of-gravity over corner, onto an unyielding surface verified that the shock absorbing system was adequate. Four 1-m puncture tests (side, pedestal, center-of-gravity over damaged corner, and angled) onto a 15.2-cm(6-in.) mild steel probe evaluated the adequacy of the exterior shell. In the side and center-of-gravity over corner drop tests, peak decelerations measured were approximately 200 g and 140 g, respectively. The series of drop and puncture tests caused local deformation of the cask body but did not threaten its fuel-containment capability. The two drop tests proved more serious than the puncture tests, both tests resulting in deformations and deceleration values much higher than recorded in the puncture tests. The damage did not extend to the inner lid. The cask maintained its leak tightness in all of these tests.

FULL-SCALE FIRE TESTING

The crash-tested trailer with two mass models and the drop- and puncture-tested cask were reassembled on pedestals for fire testing. The tractor and front face of the trailer were not included since they were both severely damaged in the 90-km/h impact test. The trailer and cask were instrumented with approximately 100 thermocouples to monitor temperatures at different locations throughout the test. Four water-cooled instrumentation towers were placed by the system. These towers contained thermocouples and calorimeters to characterize the fire environment.

We exposed the transport system to a nominal 1-h jet fuel (JP-4) fire in a 9- by 18-m(30- by 60-ft) pool. After the fuel was ignited, flames quickly engulfed the system and lasted 72 min, with the system fully engulfed in flame 96% of the time. Figure 6 shows the system after the fire test. The trailer structure was considerably warped. The trailer deck sagged on its sides, allowing the side dummy cask to move down with respect to the center cask. Temperatures on the cask varied from about 815 C to 1093 C(1500 F to 2000 F). In general the top surface of the cask was hotter than the bottom, and the front was hotter than the rear. Thermocouples located along the top of the cask showed average peak temperatures of 925 C(1700 F) and bottom was about 825 C(1525 F). The cask surface came up to temperature quite rapidly, remaining at high temperature for about one hr. The cask performed satisfactorily by maintaining its leak tightness throughout the test. Data from the fire will be used to verify a thermal analysis performed separately by PNC.

CONCLUSIONS

Analyses and tests conducted as part of the joint PNC/DOE program provided information about the response of the system to very severe hypothetical accident environments. The structural analysis work relating to impact of the system onto a rigid barrier (based on analytical and physical scale models) indicated that the vehicular system would be seriously damaged but the cask would remain undamaged on the trailer structure. These results were confirmed by a full-scale impact test demonstrating the usefulness of these analysis techniques to a very satisfactory degree. The full-scale drop and puncture tests indicated that the PNC cask will pass regulatory requirements. The cask survived the 1-hr long fire test by maintaining its containment integrity. In summary, the posttest examinations of the hardware also demonstrated that the cask maintained its leak tightness throughout multiple events in the test series.

References

1. S. Kikuchi, M. Kubo, et al., "Overview of the DOE/PNC Joint Program on Transportation Techology" (New Orleans, LA: Proceedings of the International Symposium on Transportation and Packaging of Radioactive Materials, May 1983).

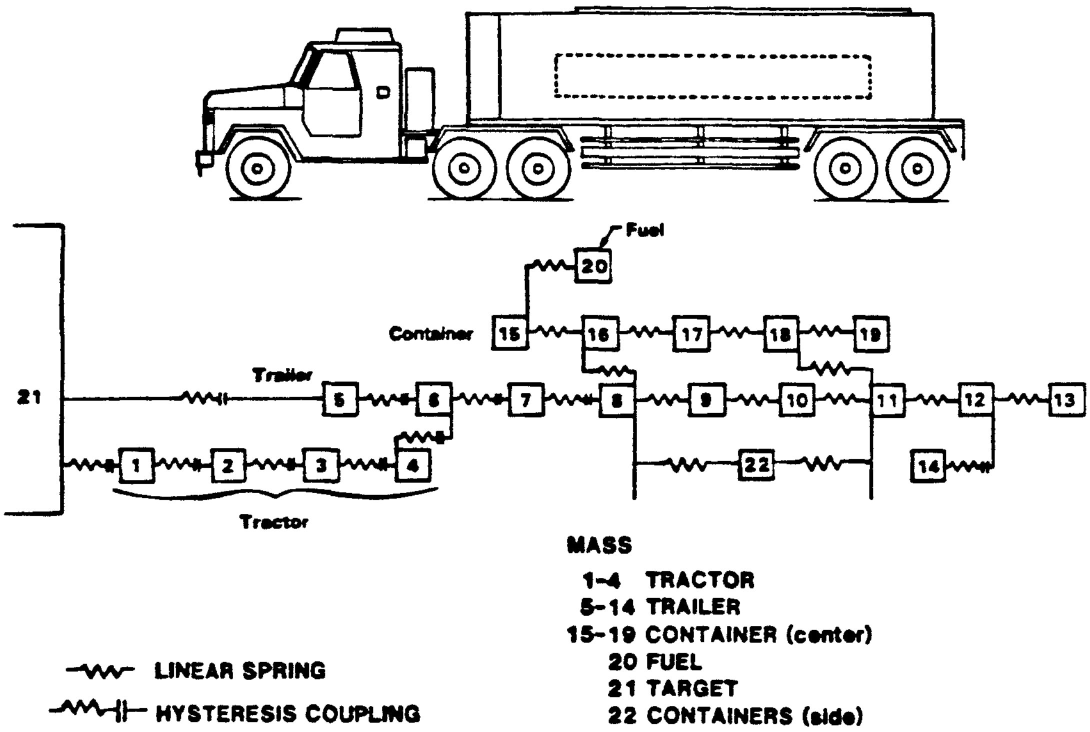

Figure 1. Schematic of the Lumped-Parameter Model

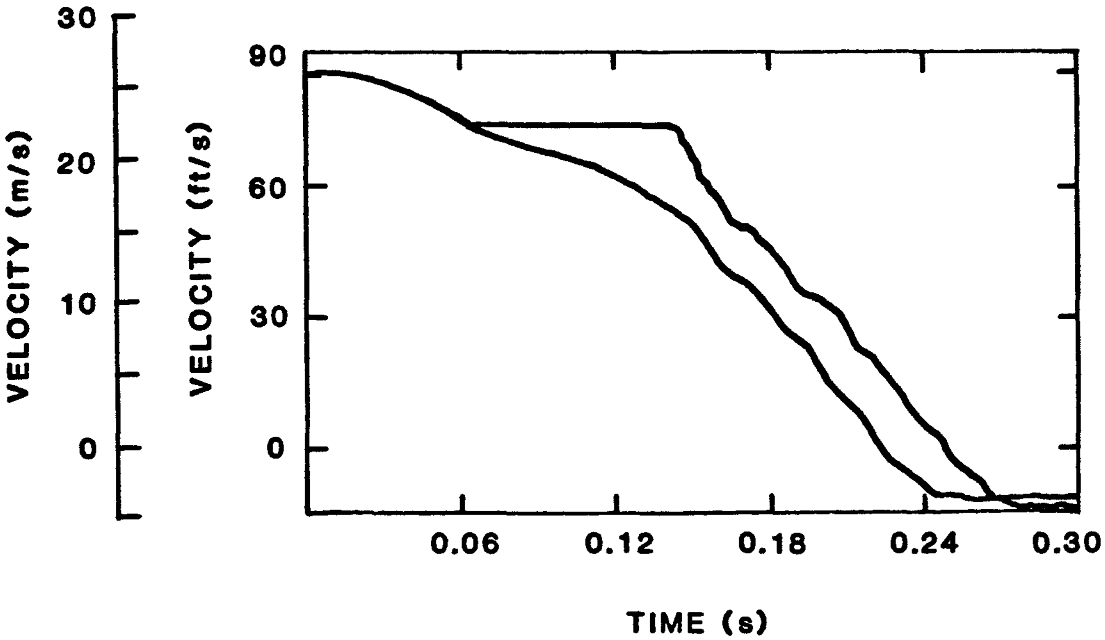

Figure 2. Typical Cask Velocity-Time Results Obtained with the Lumped Parameter Model

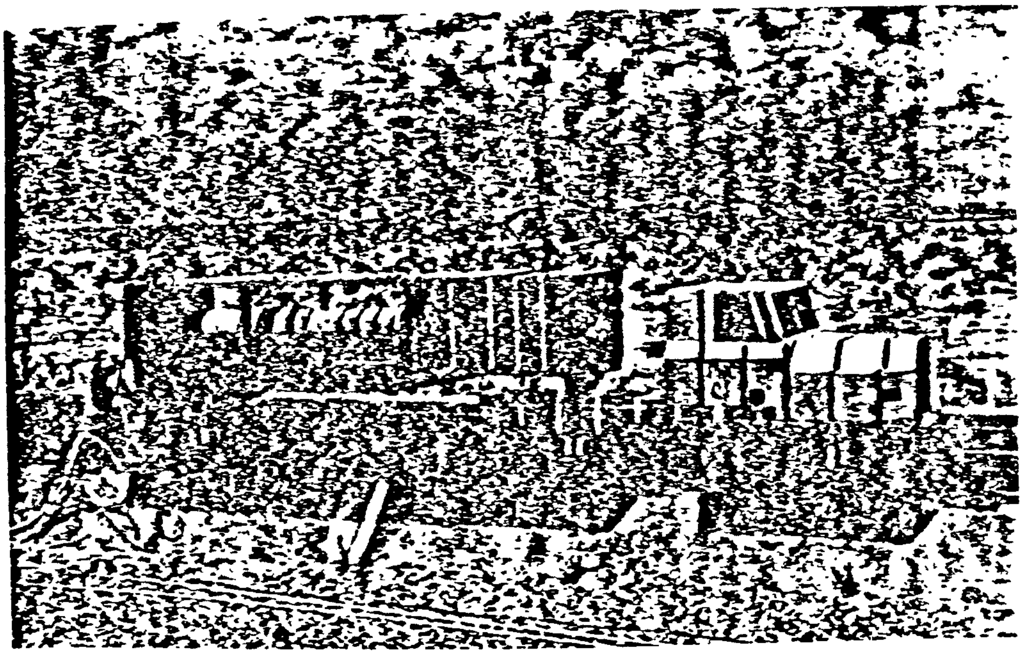

Figure 3. Quarter-Scale Model at the Test Track

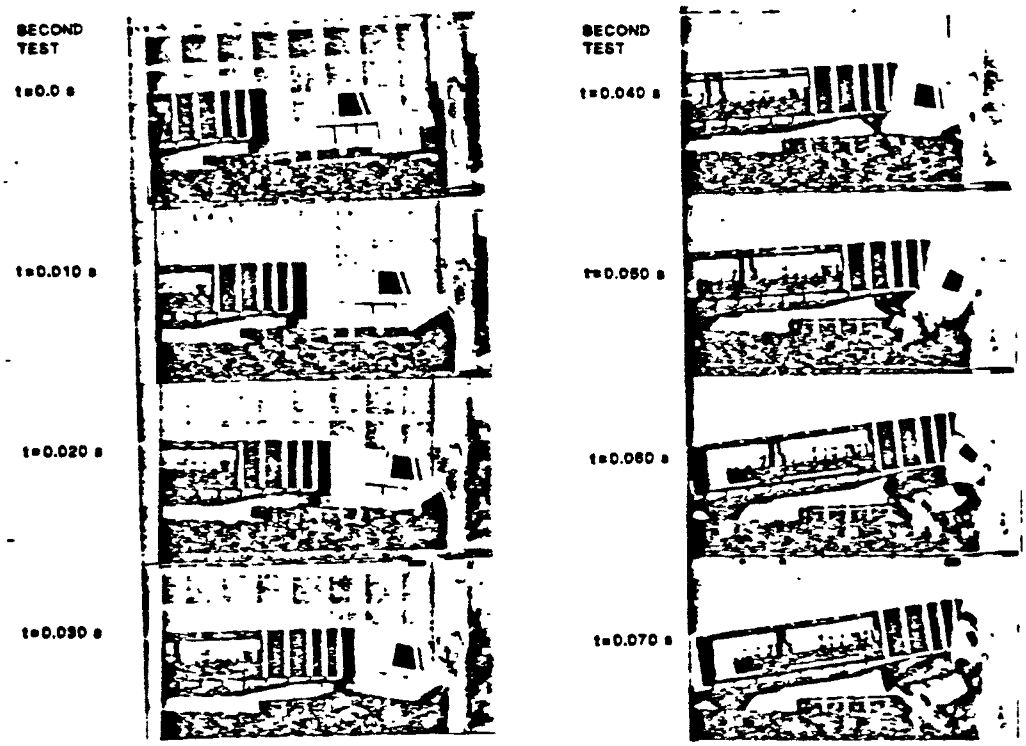

Figure 4. Scale Model Impact Test

Figure 5. Full-Scale Impact Test

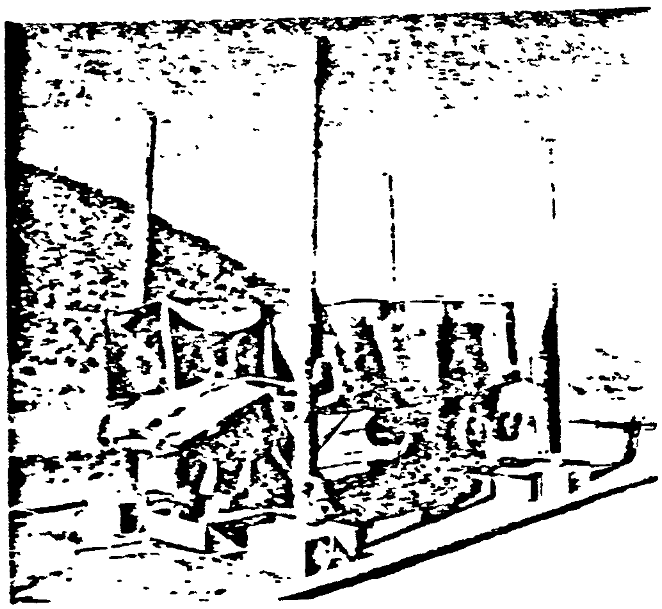

Figure 6. Fire-Tested Cask Transport System