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Chemical Technology Division

DROP TESTS OF THE THREE MILE ISLAND KNOCKOUT CANISTER

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ABSTRACT

A type of Three Mile Island Unit 2 (TMI-2) defueling canister, called a "knockout" canister, was subjected to a series of drop tests at the Oak Ridge National Laboratory's Drop Test Facility. These tests were designed to confirm the structural integrity of internal fixed neutron poisons in support of a request for NRC licensing of this type of canister for the shipment of TMI-2 reactor fuel debris to the Idaho National Engineering Laboratory (INEL) for the Core Examination R&D Program.

Work conducted at the Oak Ridge National Laboratory included (1) precise physical measurements of the internal poison rod configuration before assembly, (2) canister assembly and welding, (3) nondestructive examination (an initial hydrostatic pressure test and an X-ray profile of the internals before and after each drop test), (4) addition of a simulated fuel load, (5) instrumentation of the canister for each drop test, (6) fabrication of a cask simulation vessel with a developed and tested foam impact limiter, (7) use of refrigeration facilities to cool the canister to well below freezing prior to three of the drops, (8) recording the drop test with still, high-speed, and normal-speed photography, (9) recording the accelerometer measurements during impact, (10) disassembly and post-test examination with precise physical measurements, and (11) preparation of the final report.

This report presents the data generated and the results obtained from a series of four drop tests that included two drops with the test assembly in the vertical position and two drops with the assembly in the horizontal position.

1. INTRODUCTION

Drop tests were conducted at the Drop Test Facility of Oak Ridge National Laboratory (ORNL) on the TMI-2 knockout canister, which is a

type of defueling canister designed to transport damaged irradiated fuel from TMI-2 to Idaho National Engineering Laboratory (INEL). These drop tests were designed to demonstrate that the internal poison rods in the canister would not be displaced beyond values used in criticality calculations for hypothetical drop accident conditions postulated in 10 CFR 71.

The knockout canister was loaded with a mixture of water and lead shot to simulate the fuel to be transported and was drop tested four times from a height of 9 m (30 ft). Three of the four drops were performed with the canister temperature reduced to approximately -12°C (10°F) before release. This temperature reduction ensured that the mass of simulated fuel was located in the canister so as to impart maximum loads to the internals in each drop orientation. Each of the four drops was made with the canister placed inside a cask simulation vessel (CSV) that had foam impact limiters attached to the point of impact. These limiters were designed to reduce the impact loads realized by the canister while it was in the CSV during drop-accident conditions.

Vertical drops were conducted to test each end of the canister, and two drops were conducted with the canister in the horizontal position. Accelerometer data, photographic records, and X-ray profiles of the internal assembly were obtained for all phases of the drop tests and are presented in this report.

Precise physical measurements of the internal poison rods were taken before the canister was assembled and again when the drops were completed and the canister had been disassembled. The two sets of measurements were then compared to determine the permanent deformation in the poison rods from the forces experienced in the drop tests.

2. DESCRIPTION OF KNOCKOUT CANISTER

2.1 PHYSICAL DESCRIPTION

The knockout canister (Fig. 2.1) is one of three types of defueling canisters that have been designed to implement the removal and storage of fuel debris from the damaged TMI-2 reactor. The three canisters, called the fuel, knockout, and filter canisters, all use a 35.6-cm-O.D. (14-in.-O.D.), 0.64-cm-wall (0.250-in.-wall) pipe made of 304L stainless steel as the outer shell. In each type, the lower head is a reversed dish made of 0.45-cm (0.375-in.)-thick 304L stainless steel. The upper head of the knockout canister is a flat plate closure that is welded to the shell. The thick, metal plate upper heads are made of 10.1-cm (4-in.)-thick 304L stainless and contain penetrations for hydraulic loading and dewatering. The head has a recess machined into the center for interfacing with the handling grapple. The penetrations in the upper head are fitted with quick-disconnect couplings using a nuclear-grade pipe sealant during attachment to the top head. A skirt on the upper head extends 10.1 cm (4 in.) beyond the top to protect the disconnect fittings. The total length of the knockout canister is 380 cm (149.75 in.).

The internal assembly (Fig. 2.2) is supported from a 3.175-cm (1.25-in.)-thick lower support plate and is positioned at the top of the canister by welded chock blocks at the upper support plate. An absorber array of four outer rods around a central rod is located in the canister for criticality control. The outer rods are 3.34 cm (1.315 in.) in

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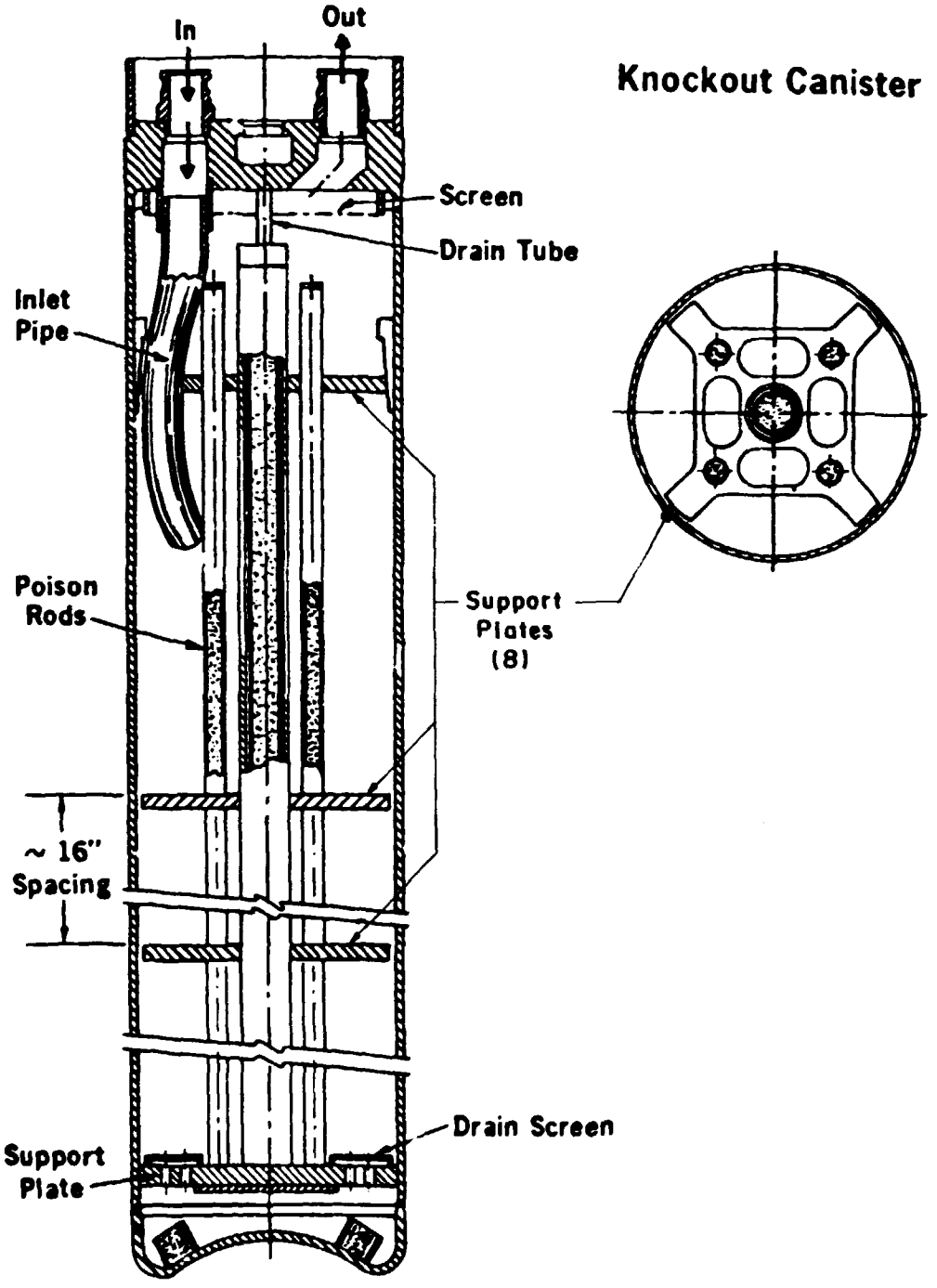


Fig. 2.1. Knockout defueling canister.

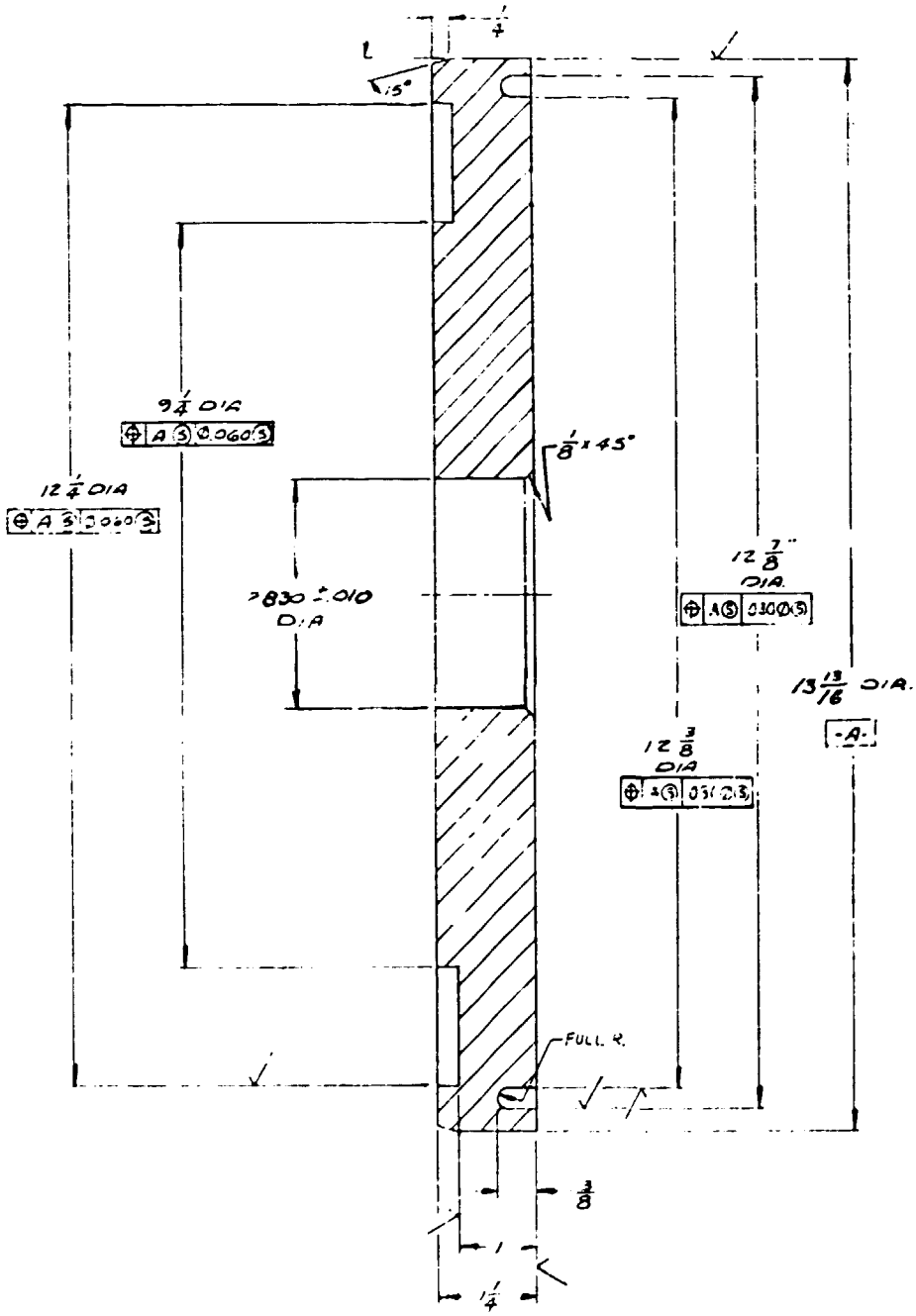


Fig. 2.2. Lower support plate for internal poison rod assembly. Source: Engineering drawing No. 1150950E, Babcock & Wilcox, Lynchburg, Virginia, 1984.

diameter and have a 6.0-mm (0.25-in.) wall tube filled with neutron-absorbing B4C pellets. The central absorber rod is comprised of a 7.30-cm (2.875-in.)-diam strong-back tube with a 7.9-mm (0.312-in.) wall. Inside this tube is a 5.39-cm (2.125-in.) rod with a 1.6-mm (0.063-in.) wall filled with the B4C pellets. Seven intermediate support plates cradle the rods along their lengths and have a 3.0-mm (0.125-in.) radial clearance to the shell (Fig. 2.3). All support parts are constructed of 304L stainless steel, whereas the tubes containing the B4C pellets are made of 316L stainless steel.

The absorber rods are held in place mechanically by a seal plate that is attached to the bottom of the lower support plate of the internal assembly by a 6.0-mm (0.25-in.) fillet weld. The lower support plate is welded to the outer shell with a 6.0-mm (0.25-in.) fillet weld.

Catalysts, in the form of small pellets and spheres, are provided to boost the recombination of any radiolytically generated hydrogen and oxygen gases into water. The catalysts are in specially prepared pockets that are located in the top and bottom heads. This arrangement allows half of the catalysts to be above the midplane in all canister orientations (see Fig. 2.4).

2.2 DESCRIPTION OF LOADING OPERATIONS DURING DEFUELING

The knockout canister was designed to be loaded with fuel debris ranging up to about 12 mm (0.5 in.) in diameter, including whole fuel pellets. The debris will be vacuumed into the canister using a Fines/Debris Vacuum System (F/DVS); the effluent will be returned to the reactor vessel.

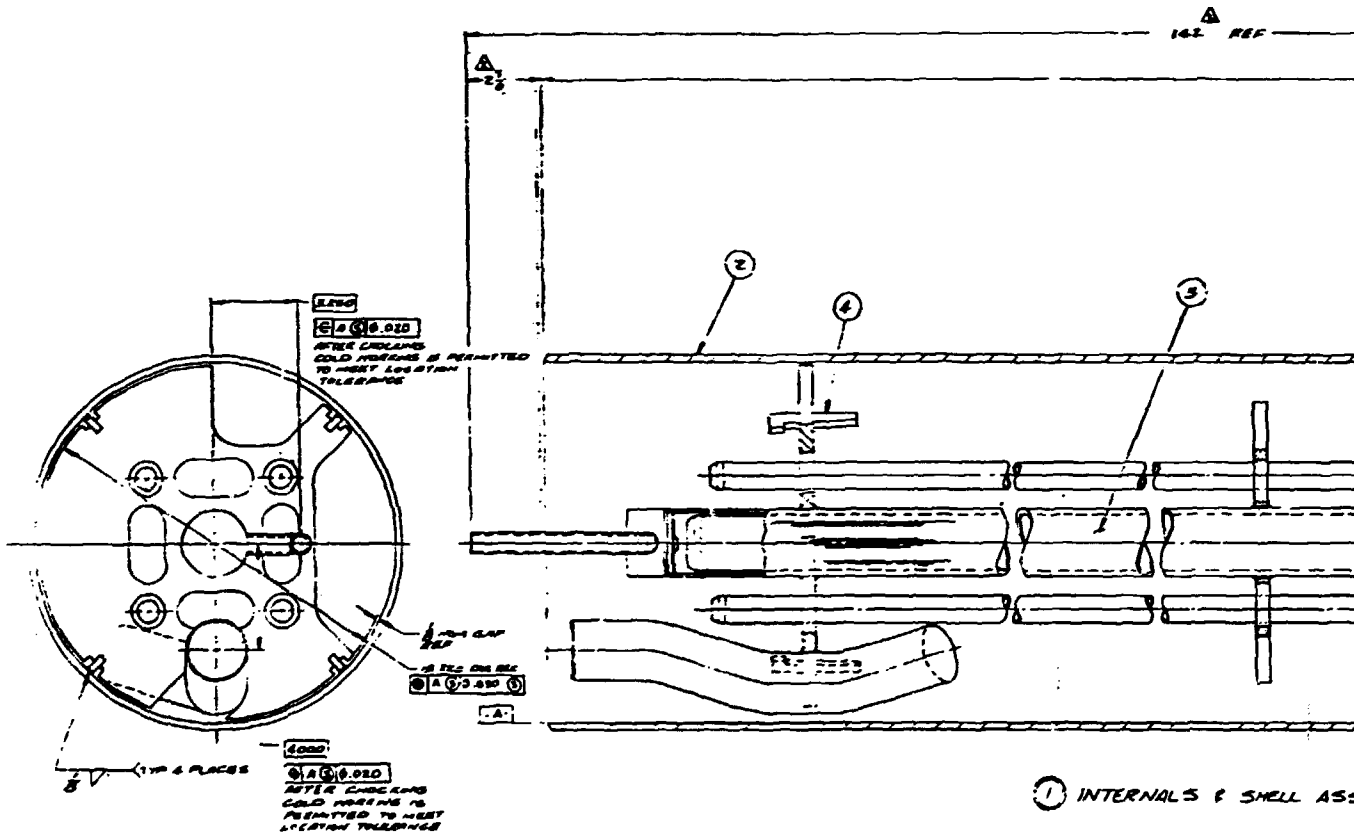
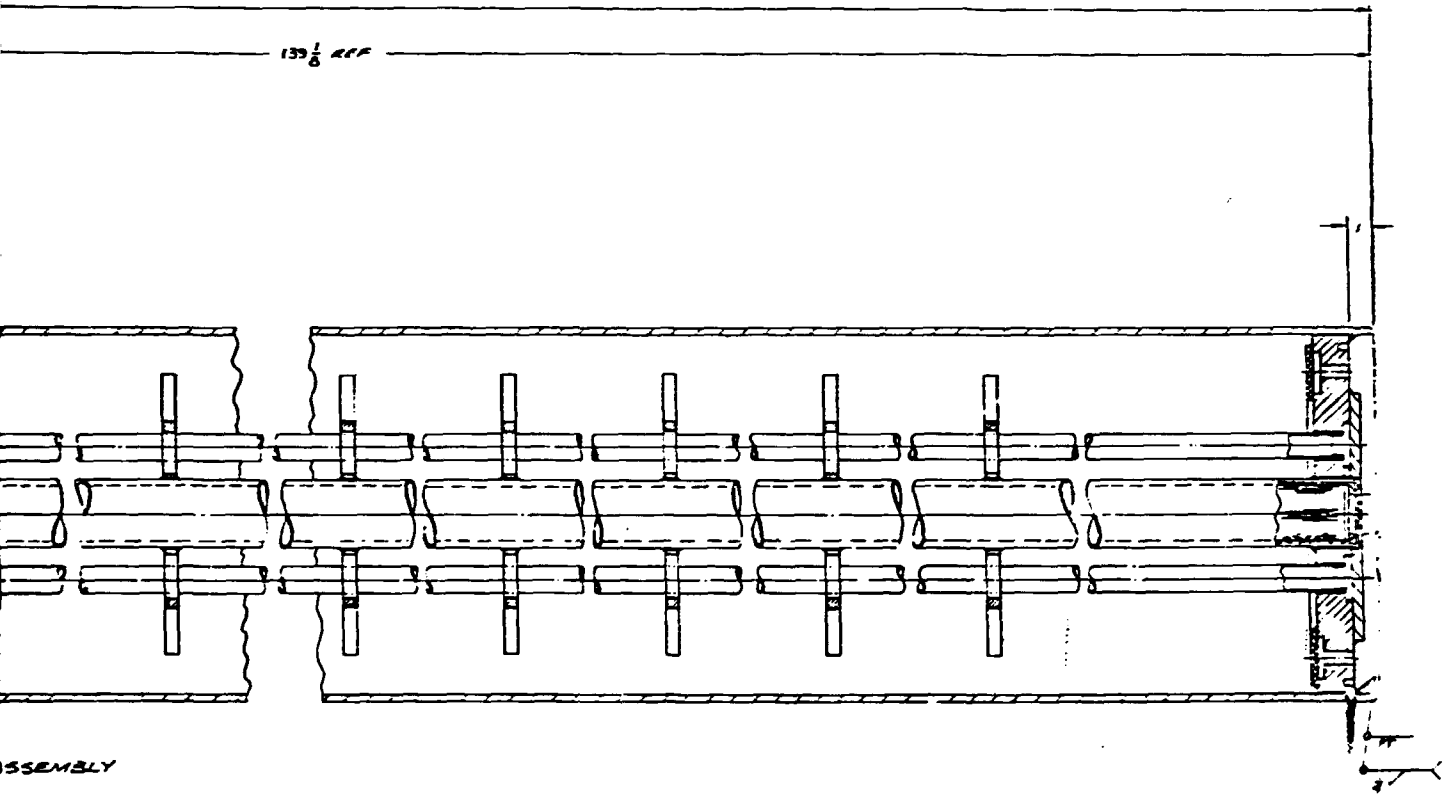


Fig. 2.3. Central absorber ro
canister. Source: Engineering dra
Lynchburg, Virginia, 1984.



rod array for knockout defueling
drawing No. 1154034F, Babcock & Wilcox,

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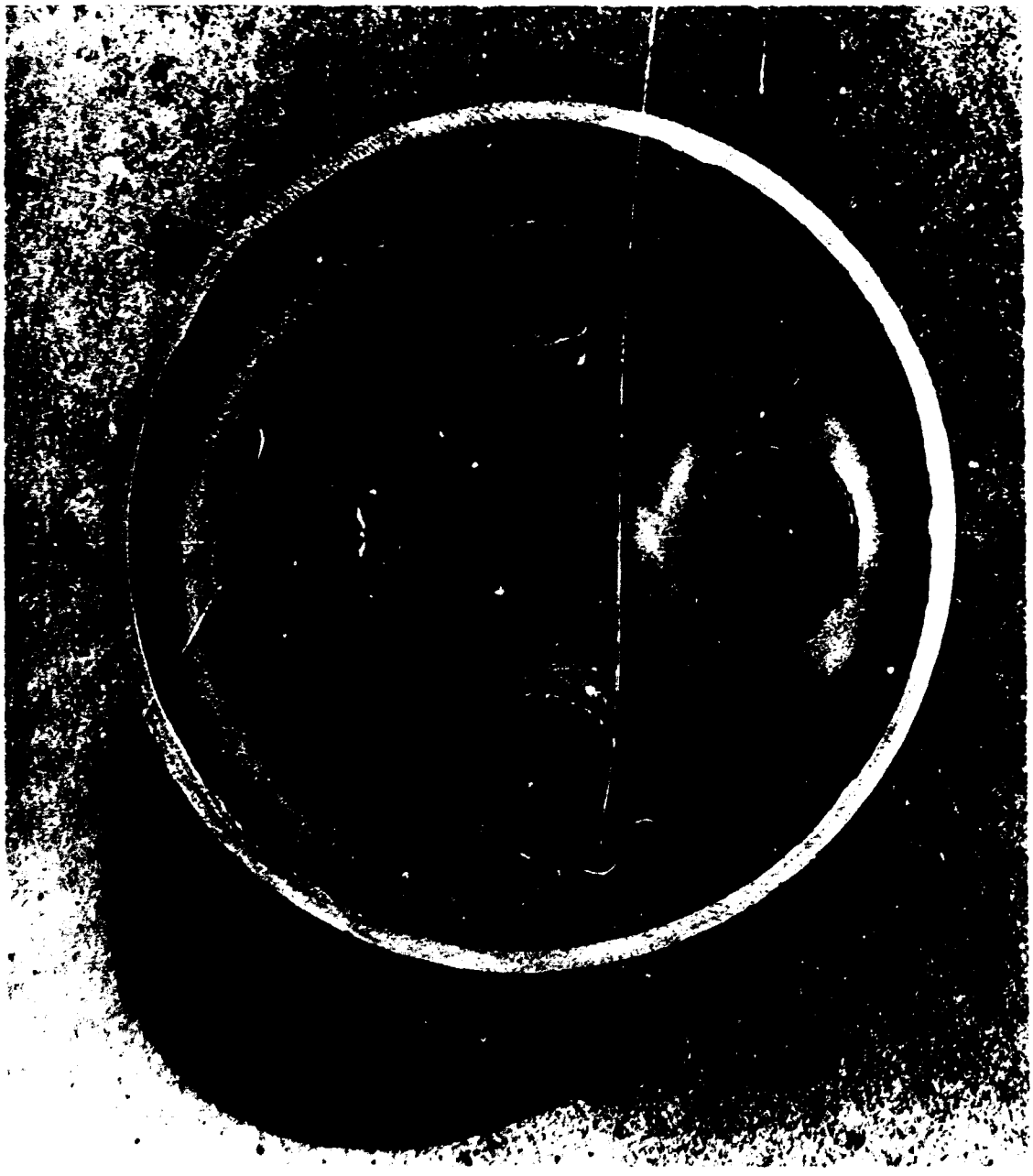

Fig. 2.4. Catalyst packets in lower head.

The fuel-water slurry will enter the canister through a 5.1-cm (2-in.) fitting in the upper head. This fitting is attached to an inlet pipe that xtends ~61 cm (24 in.) into the canister. The pipe is curved to give the slurry a radial velocity as it exits into the canister cavity. The heavier pieces of debris will fall out of the slurry and settle to the bottom of the canister. Water will flow up out of the canister and be filtered through a 20-mesh screen that is welded to the bottom support plate. This screen prevents particles >840 μm (>0.03 in.) from passing through the canister.

When the canister is filled, excess water will be removed by pressurizing the internal cavity with argon through the vent fitting. The water will be forced into the bottom sump, up through the drain line connected to the top head, and out of the canister by means of fittings that allow remote connection of the vent and dewatering lines to the canister.

2.3 KNOCKOUT CANISTER SHIPMENT

In preparation for shipment, the canister will be pressurized to 207 kPa, absolute, (30 psia) with argon, weighed to verify water removal and weight limitations, and loaded into one of the tubes of a NuPac 125-B rail shipping cask. Seven canisters will be transported to INEL in this cask for eventual storage in a nonborated water pool.

The shipping cask is designed to limit the deceleration forces on the canister to 981 m/s^2 (100 g) laterally and to 392 m/s^2 (40 g) axially under hypothetical drop-accident conditions. Scale-model

testing has shown that these forces are greater than will be experienced by the canister in the hypothetical drop-accident conditions used in the Nuclear Regulatory Commission (NRC) regulations.

3. TEST FACILITY AND EQUIPMENT

The ORNL Drop Test Facility was constructed in 1978, incorporating the unique capabilities located at the Tower Shielding Facility (TSF) complex. The Drop Test Facility is located about 8 km (5 miles) southeast of the main ORNL area, on a ridge adjacent to the Melton Hill Dam. The facility consists of four towers — each 96 m (315 ft) high — set in a 30-m (100-ft) × 60-m (200-ft) rectangular array (Fig. 3.1). Each of the towers is guyed with two pairs of 5-cm (2-in.)-diam cables. A cabling system connected to the top of two towers is used to lift the test pieces for the drop test. The safety factors assumed for the lifting system of the facility exceed 6, and safety factors are comparable for other components of the facility. An engineering assessment of these capabilities is shown in a graph of drop height vs cask weight (Fig. 3.2).

The impact pad (Fig. 3.3) was constructed of 600 metric tons (t) of 5-cm (2-in.) rebar-reinforced concrete in a stepped-pyramid arrangement with a large base and a 70-t armor plate surface that is 51 cm (20 in.) thick. The impact surface is 6.1 m (20 ft) long and 2.5 m (8 ft) wide.

The ancillary equipment available for drop testing includes (1) still, normal, and high-speed photographic equipment; (2) video recording equipment; (3) an accelerometer and strain gage recording devices; and

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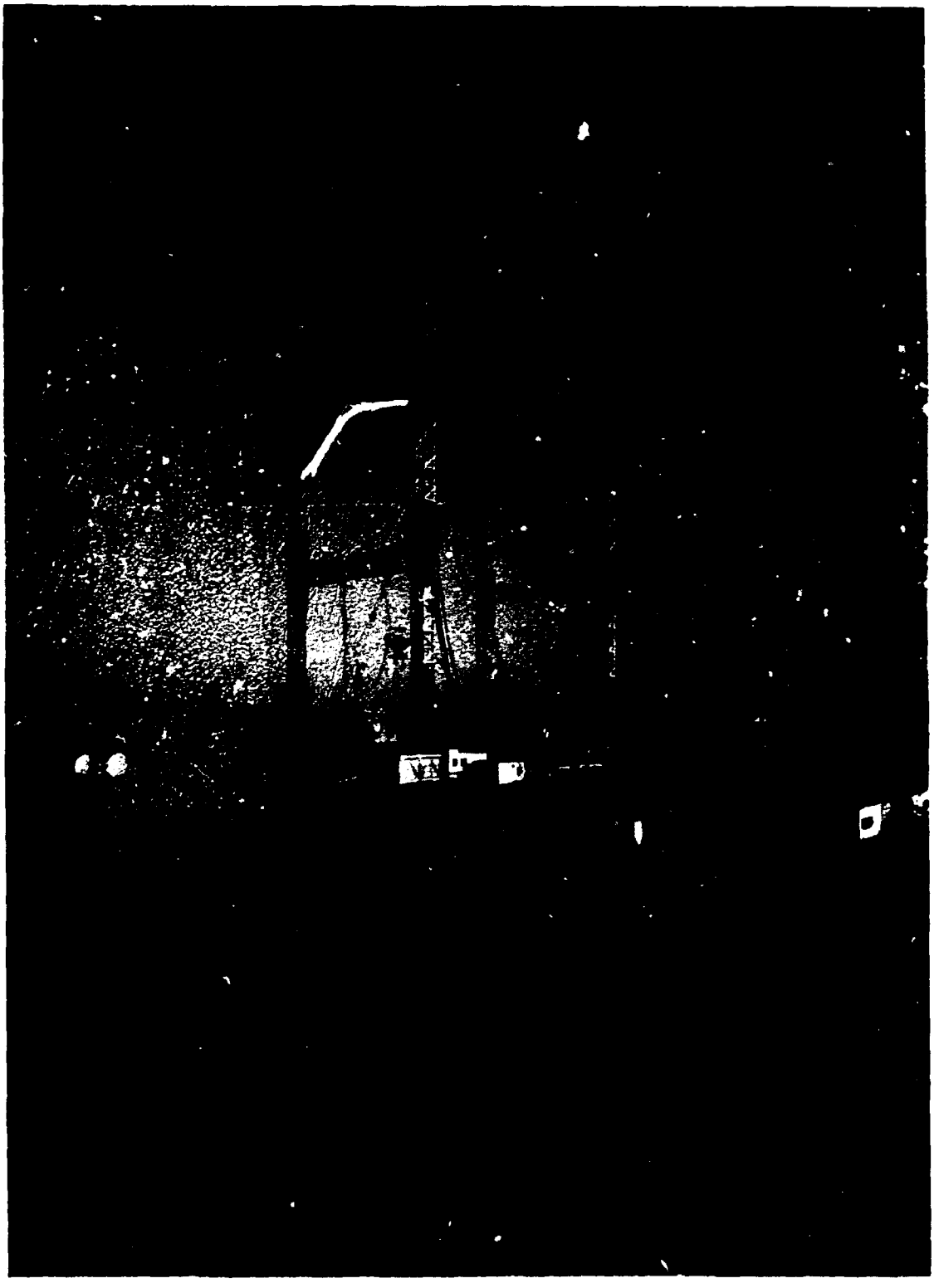

Fig. 3.1. ORNL Drop Test Facility.

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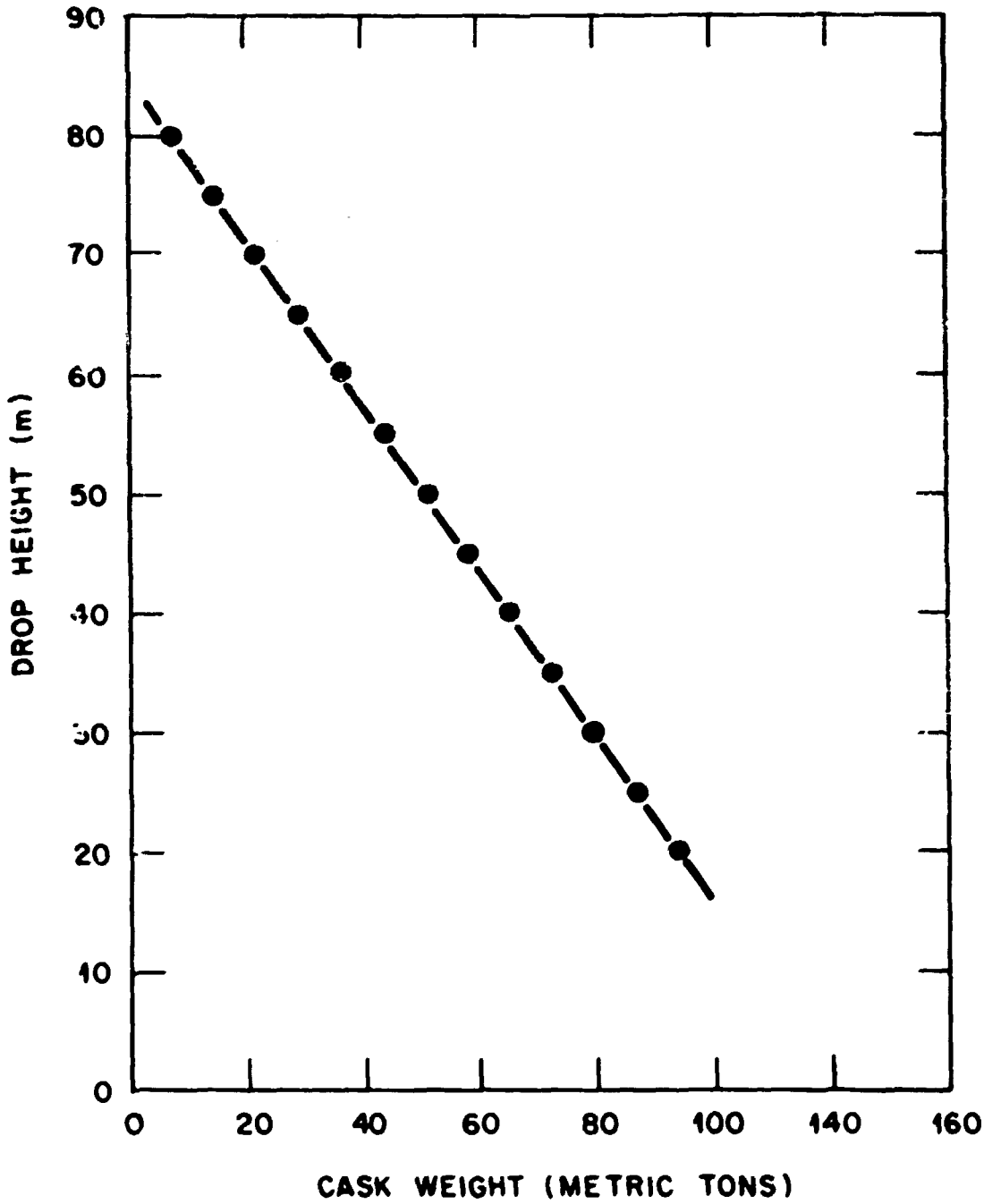

Fig. 3.2. Engineering assessment data for cask weight vs drop height at the ORNL Drop Test Facility.

ORNL PHOTO 5821-77

Fig. 3.3. Impact pad of the ORNL Drop Test Facility.

(4) a computerized drop test timing sequencer that automatically turns on and tests each electrical component of the drop test equipment. This sequencer receives a feedback message that stops the program if predetermined signals are not received from each component. When all systems are functional, the computer advances the program and automatically fires the release mechanism that drops the test specimen. The sequencer also tests the firing circuits of the explosive release fixtures for continuity before the computer advances to the next step.

4. PRETEST MEASUREMENTS AND PREPARATIONS

4.1 PHYSICAL MEASUREMENTS

Prior to our tests, the Metrology Department of the ORNL Plant and Equipment Division placed the internal assembly of the knockout canister on a certified flat surface and made precise measurements of the location of the poison rods, the support plates, and the strong-back tube to which the support plates were welded. These measurements were recorded and retained for comparison with measurements to be taken after the last drop test. A summary of the measurement data taken before and after the drop tests is presented in Sect. 13.

4.2 CANISTER ASSEMBLY

When the physical measurements were completed, the canister pieces were taken to the shop area, and the subassembly was placed into the outer shell. A fillet weld on the bottom of the lower support plate attached the internal assembly to the stainless steel shell. The prescribed wedges were placed between the upper support plate and the shell and welded to hold the internal assembly in the desired location.

The weld between the lower support plate and the shell was checked with dye-penetrant and found to be sound.

The lower head was welded to the shell, dye-penetrant tested, and found to be sound. The weld was then inspected using X-ray radiography techniques. The films revealed that, when the fillet weld was made between the lower support plate and the shell, the shell had been slightly reduced in diameter; because the shell was smaller than the head, slightly less than total fusion existed at the root of the weld. This small defect did not affect the soundness of the weld, and representatives of EG&G, Idaho; B&W; Bechtel; and Martin Marietta Energy Systems, Inc., all formally agreed that this weld nonconformance would be acceptable for the drop tests.

The top head was welded to the canister, and the weld was dye-penetrant tested and X-rayed for weld integrity. The welds passed both of these tests, and the canister was transferred to the Inspection Engineering Department for further testing.

4.3 CANISTER INSPECTION

The canister was subjected to a hydrostatic pressure test by filling it with water and pressurizing to 1.55×10^3 kPa, gauge (225 psig), by means of a hydraulic hand pump. The canister was allowed to remain at this pressure for 30 min and then examined for signs of leakage. At the end of this time, the pressure remained at 1.55×10^3 kPa, gauge (225 psig), and no evidence of leakage was found.

A complete X-ray profile of the canister internals, showing the position of the poison rods, was taken for comparative purposes so that

it could be determined whether the rods were permanently displaced after each drop test. More than 70 radiographic films were taken after each drop to complete the required profile for the comparisons.

4.4 PREPARATION OF CASK SIMULATION VESSEL

The shipping cask that has been developed to transport the canisters to INEL is designed to hold seven of the individual canisters. This cask affords considerable protection to the canisters in the event of an accident. In order to simulate this protection, several CSVs (mild steel pipes) were prepared with lifting ears so they could be picked up in either the vertical or the horizontal position. These CSVs were equal in diameter and length to the inner vessel of the shipping cask. Each pipe was equipped with an energy absorber designed to limit the deceleration force, seen by the canister during the drop tests.

The shipping cask (Fig. 4.1) has impact limiters of urethane foam on each end to afford protection to the cask and canisters. The CSVs were prepared with foam impact limiters of similar crush strength and density (Figs. 4.2 and 4.3) to duplicate this protection. Tests were conducted on small sections of the foam, to make certain that the properties were within the range of the values calculated to limit the deceleration forces to those specified in the test plan.

An impact limiter was designed and constructed for each of the drop tests. The required area and thickness of foam needed to restrict the impact loads on the canister were calculated using an in-house program on an IBM personal computer. Since the area of impact would be much

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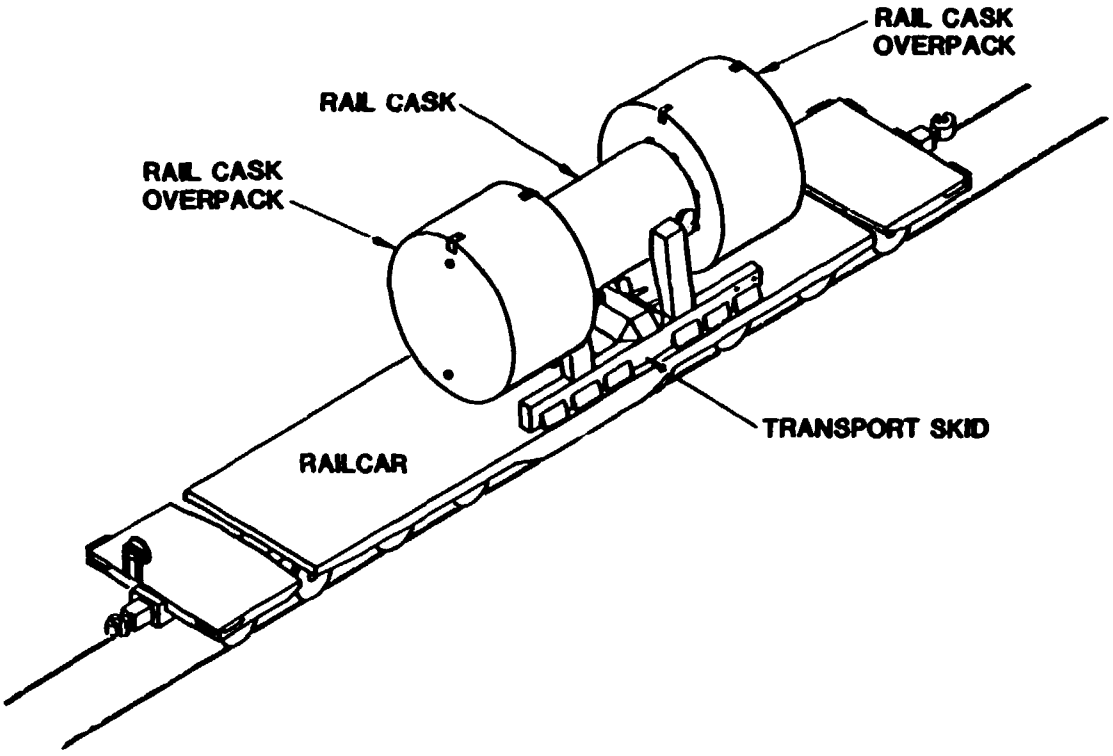

Fig. 4.1. NuPac 125-B rail shipping cask on transport skid.

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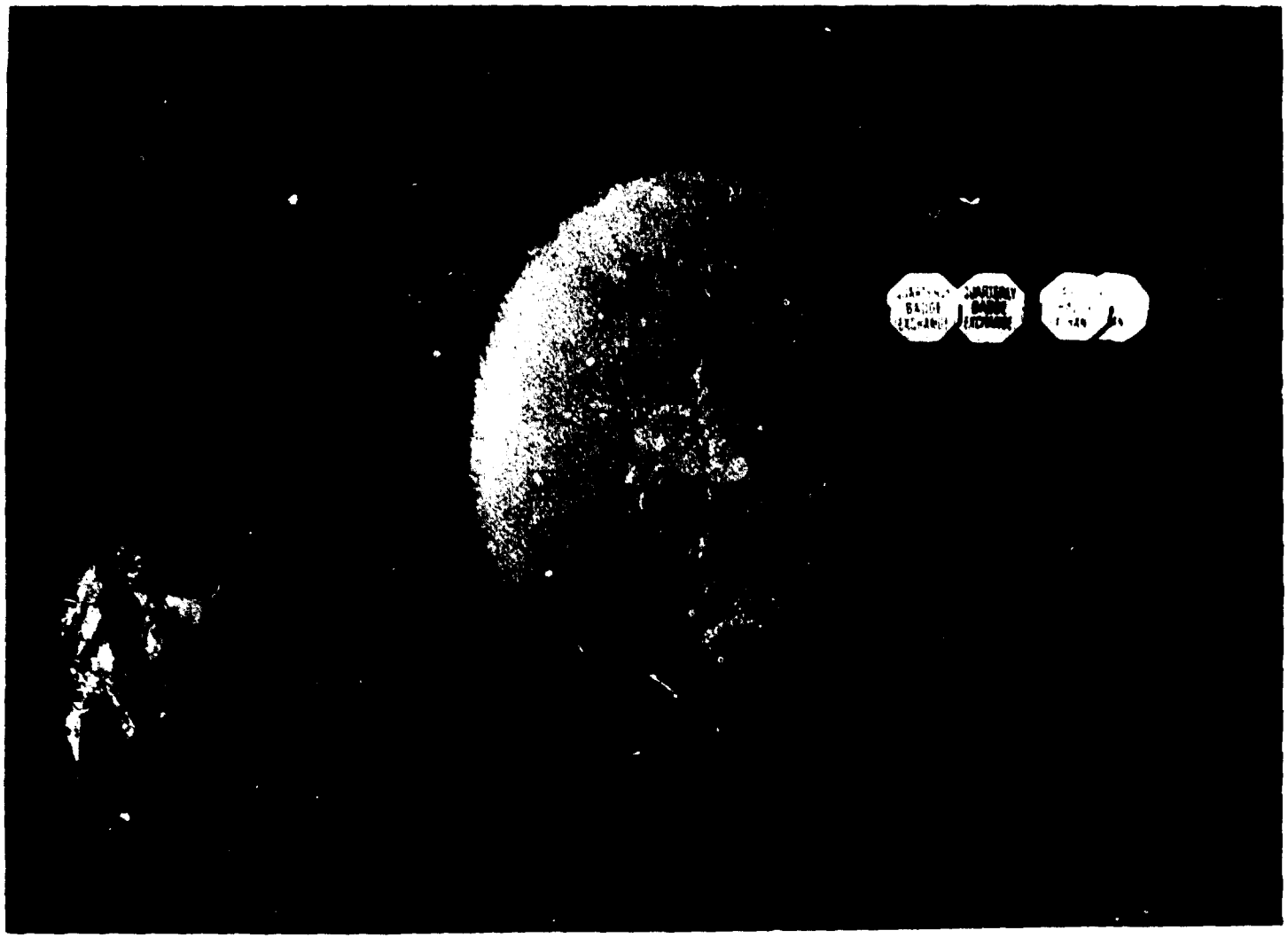

Fig. 4.2. Impact limiter of high density foam on cask simulation vessel.

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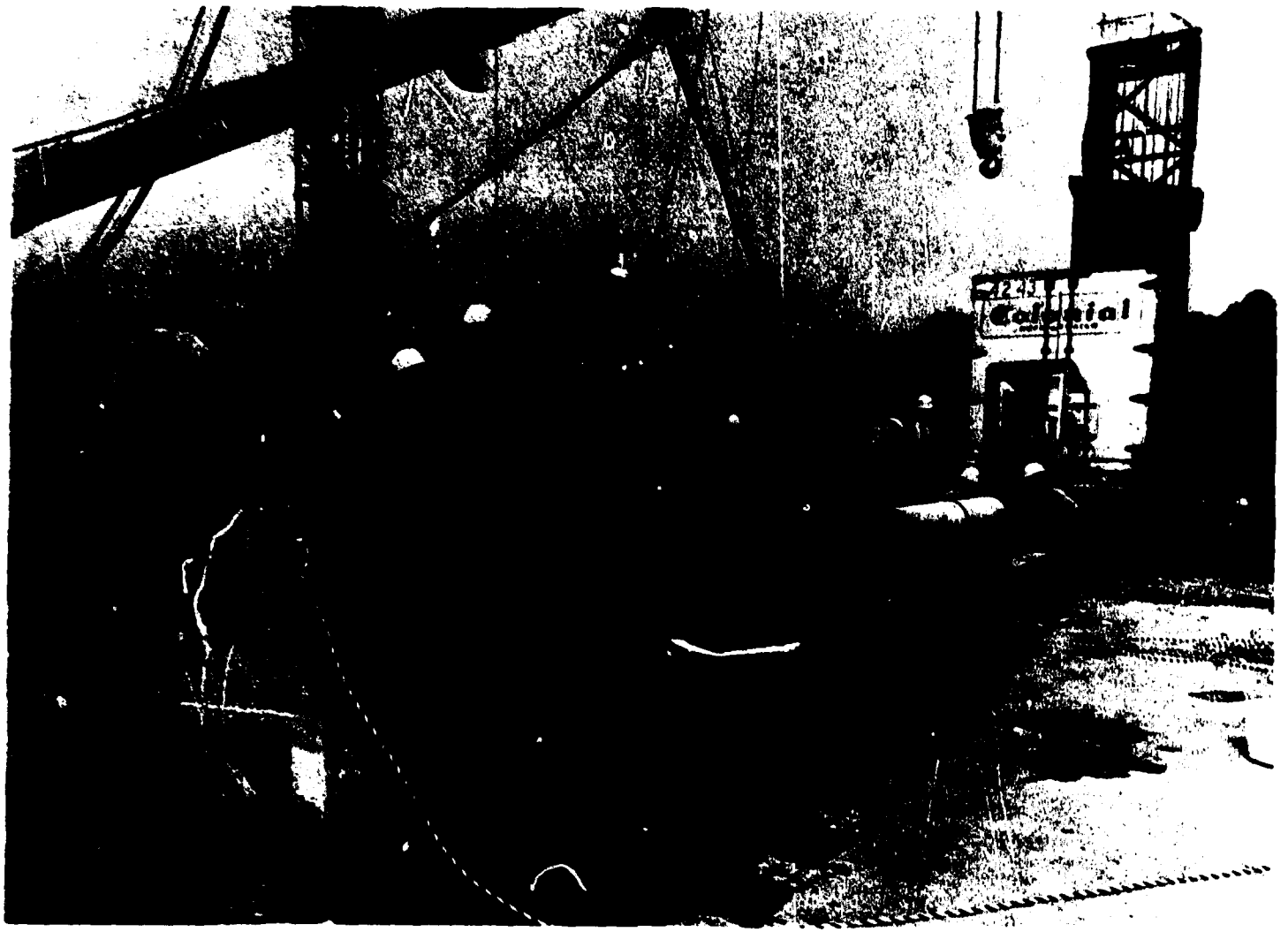

Fig. 4.3. Impact limiter of high density foam for horizontal drop test on cask simulation vessel.

larger in a horizontal drop test than in a vertical drop test, it was decided to divide the limiter into four equal sections distributed evenly along the CSV's horizontal surface (shown in Figs. 4.4 and 4.5).

4.5 ATTACHMENT OF ACCELEROMETERS

Figure 4.6 is a diagram of the general instrumentation scheme used in all drop tests in this series. Signals from the six accelerometers were routed through an umbilical cable attached to the CSV. The other end of this cable terminated in an external junction box located at ground level approximately 12.2 m (40 ft) from the drop pad. The signals were then transmitted through permanently installed cabling to an internal junction box in the underground control room and from there to Model SGA-20, signal-conditioning amplifiers, then recorded on a Bell & Howell Model CPR-4010, multichannel, frequency-modulated (FM) tape recorder.

In addition to the six accelerometers installed on the canister, a type-K thermocouple was mounted in a well along the central axis of the canister, through the top head, to measure the canister temperature. Temperatures were recorded on a Minneapolis-Honeywell strip-chart recorder.

Both positive and negative calibrations of the accelerometers were performed just prior to each drop, by automatically shunting appropriate legs of each accelerometer bridge with fixed-precision resistors. Deflections produced by this procedure were recorded on the FM tape and later used in the data-reduction process.

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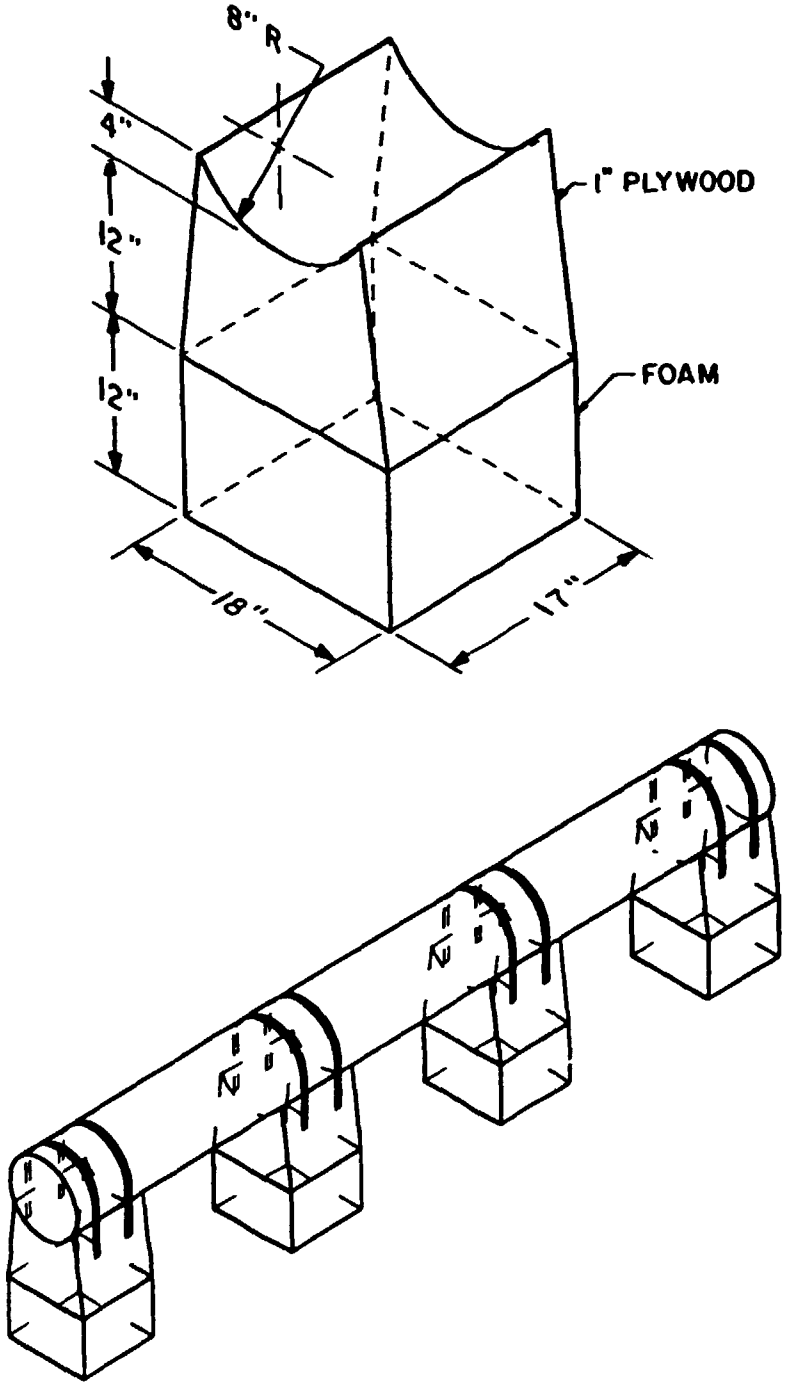

Fig. 4.4. Schematic of impact limiters for various horizontal drop tests.

ORNL PHOTO 7862-85

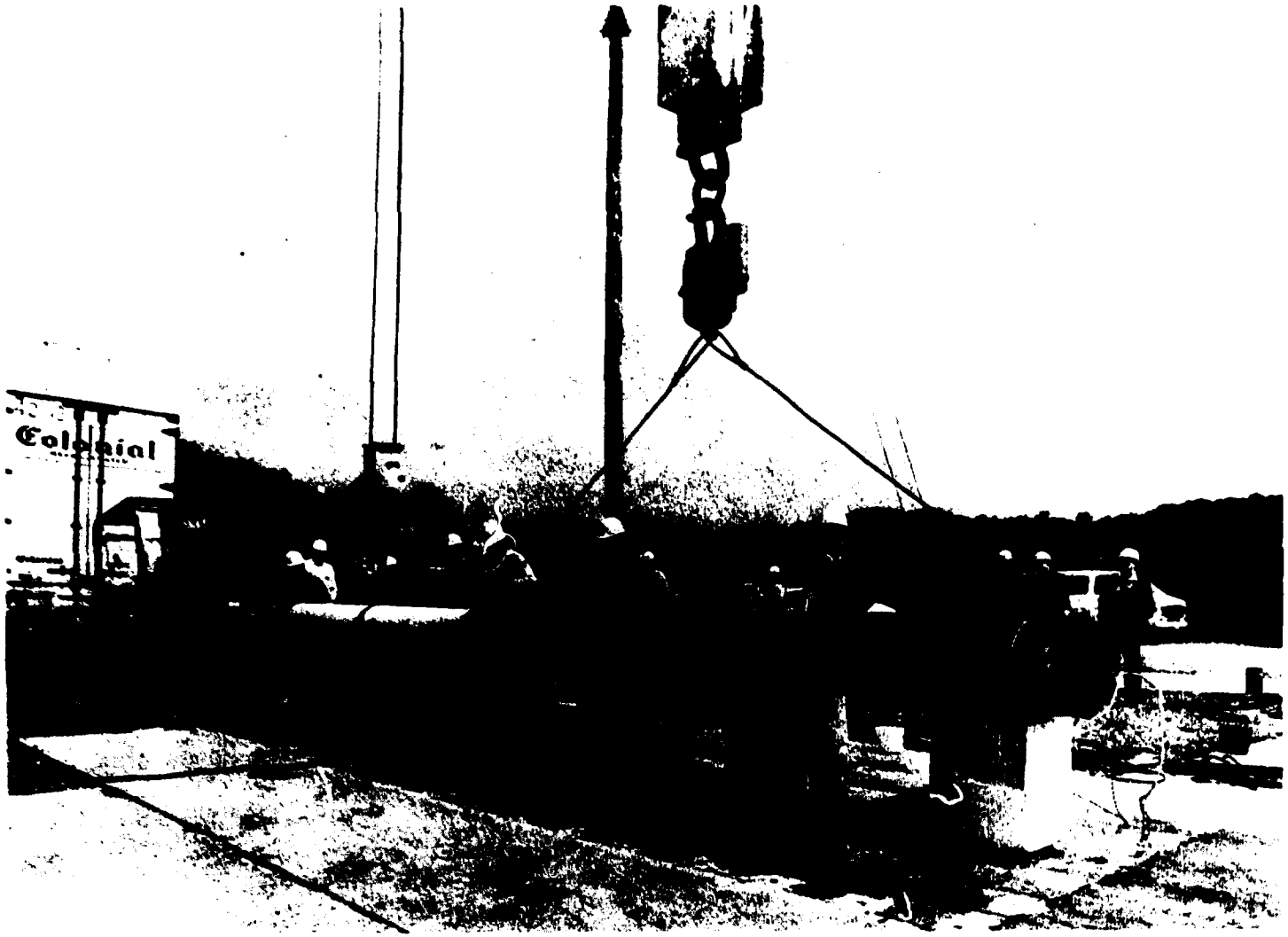

Fig. 4.5. Cask simulation vessel with impact limiters spaced equally along horizontal length.

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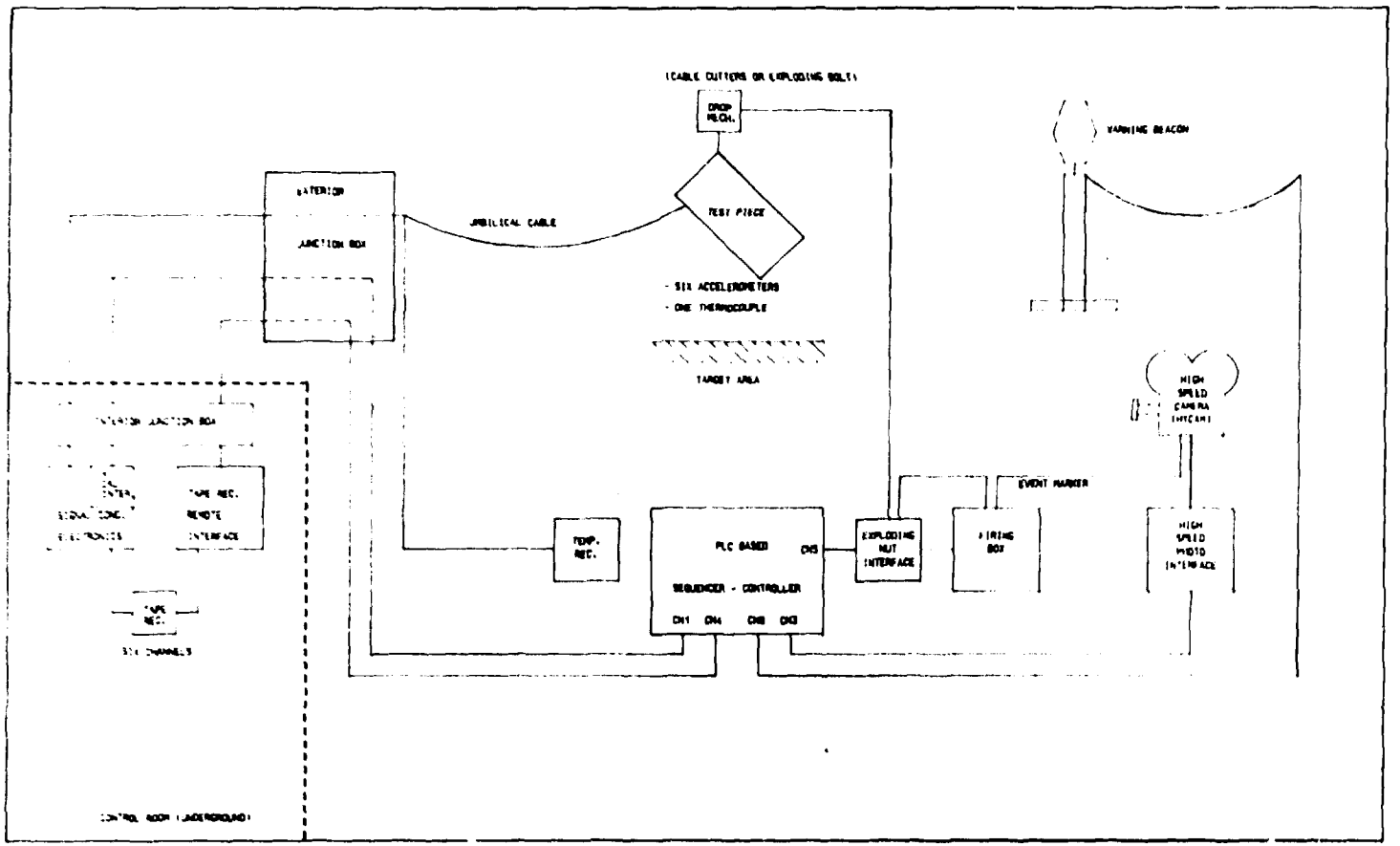

Fig. 4.6. Schematic of instrumentation for TMI-2 drop tests.

The test data were filtered, digitized, and recorded on digital tapes, which were processed on a PDP-11 computer to convert to engineering units. Software routines were used to correct for built-in variations in accelerometer range and sensitivity (factory-supplied data), individual differences in calibration, and, in some cases (the two horizontal drops), calculated corrections for angular deviations of the accelerometers from vertical.

Mounting blocks were welded or epoxied to the top and bottom heads, and the accelerometers were attached to the canister in the appropriate positions for each of the drop tests. Each set was positioned to give recordings in the x, y, and z axes. Accelerometer signals were transferred to the recording equipment through an umbilical cable connected from the top of the CSV to a junction box located at the base of the drop pad. Permanent wiring transferred the signals to a bank of recorders in an underground control room at the facility.

4.6 ADDITION OF SIMULATED FUEL

The knockout canister was loaded with 818 kg (1800 lb) of lead shot to yield the same weight as that of the reactor fuel debris. A volume of water sufficient to cover the lead shot was added to the canister. This water-lead mixture produced a density of 6808 kg/m^3 (421 lb/ft^3) and resulted in a canister weight of 1371 kg (3016 lb).

4.7 REDUCTION OF TEMPERATURE

During a transportation accident, the orientation of the fuel cask, canister, and contents may be such that the fuel mass is above the internal poison structures of the canister at the moment of impact, thus

resulting in maximum forces on the poison structures. To achieve this same condition, the simulated fuel was frozen and the canister rotated to place the bulk of the material above the internal poison rods during the drop tests.

Prior to these drop tests, the canister containing the simulated fuel mixture was placed inside a refrigerator truck capable of reducing the internal trailer temperature to ~−29°C (~−20°F), which was rented and positioned at the Drop Test Facility. The diesel-powered refrigeration system was designed to operate continuously for several days so the canister could be placed in the truck ~24 h before the scheduled drop test to ensure complete freezing of the simulated fuel-water mixture. A thermocouple was installed to monitor the internal temperature of the canister.

5. VERTICAL DROP ON BOTTOM HEAD

5.1 CANISTER PREPARATION

The canister was placed into the refrigerated truck 24 h before the first drop test was scheduled to ensure that the simulated fuel remained completely frozen during the time required for the canister to be removed from the truck and placed into the CSV for the drop test. For the vertical drop test, the simulated fuel was frozen around the "B" leg of the support plate shown in Fig. 5.1.

The impact limiter was attached to the end of the CSV to prepare for the vertical drop. At the end of the 24-h freezing period, the canister was taken out of the truck and inserted into the CSV. The accelerometers were bolted to the mounting plates and connected to the data transmission cable. The canister was pressurized to 207 kPa,

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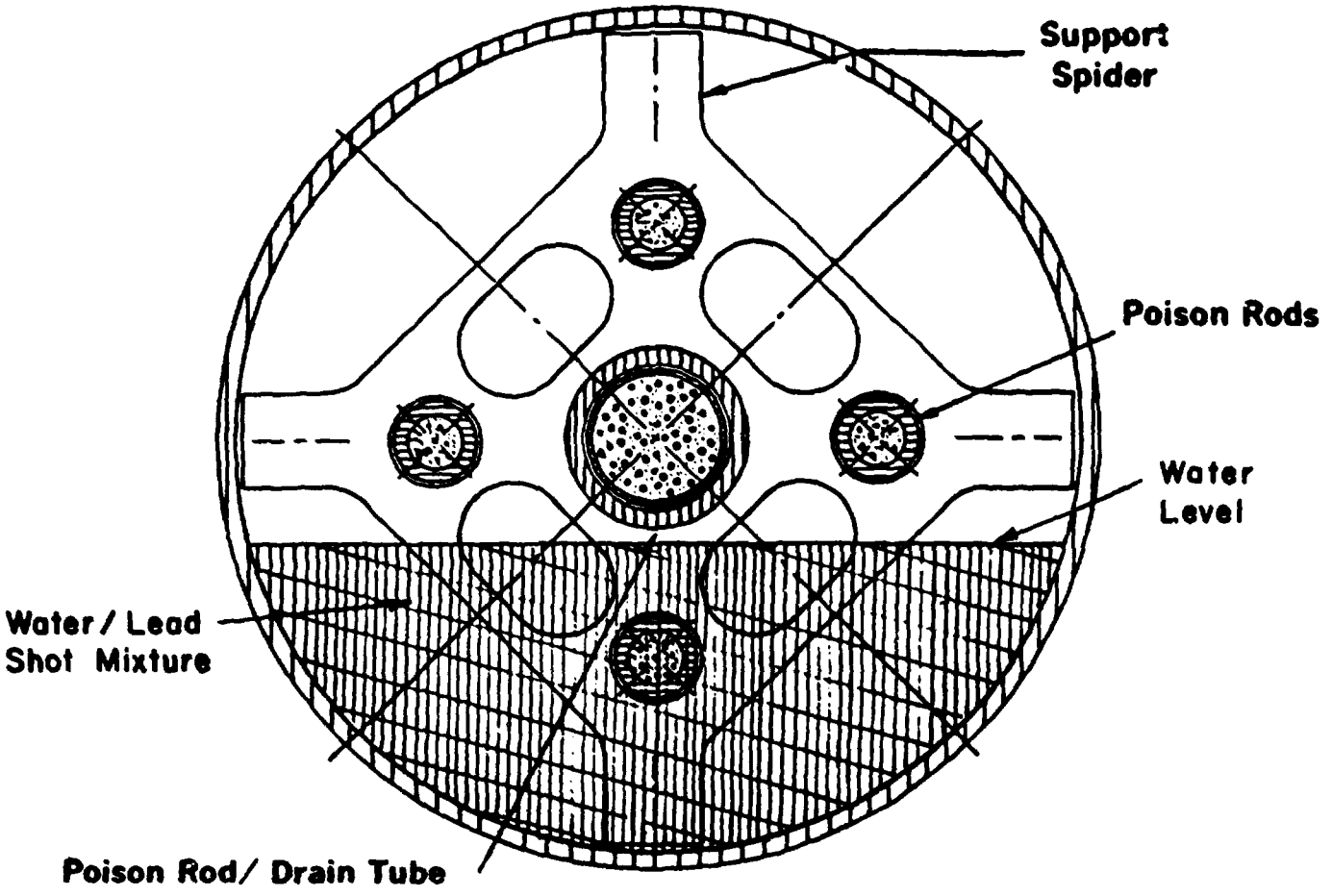

Fig. 5.1. Cross-section of knockout canister at mid-plane.

absolute (30 psia), with argon, and the entire assembly was lifted to position the bottom of the canister 9 m (30 ft) above the impact pad. The computer sequencing program was initiated, and the drop test progressed as planned. Cables attached from the top of the CSV to the bottom of the lifting hook prevented the CSV and canister from falling over after impact, without interfering with the free-fall (see Fig. 5.2).

5.2 DROP TEST SEQUENCING PROGRAM

When the computer sequencing program is initiated, the first programmed action is to switch on the instruments that record signals from the accelerometers. When these instruments are operating, a feedback signal to the computer activates a check light and allows the program to advance to the next step.

The next programmed events in the sequence are a flashing light and an audio alarm signal that alert personnel in the drop test area. The feedback from these systems turns on the appropriate computer lights and permits the program to advance to the next level. At a predetermined time, the high-speed movie cameras are started so that they will be fully operational when the drop occurs. The feedback signal activates the respective computer light and allows the normal-speed cameras to begin filming.

When all systems are functioning, a small electrical signal is sent over the firing system to determine whether there is continuity in all legs of the explosive release devices and connecting wiring. If continuity exists in all systems, the feedback signal allows the computer to deliver a 5-A current to the explosive devices that release the CSV

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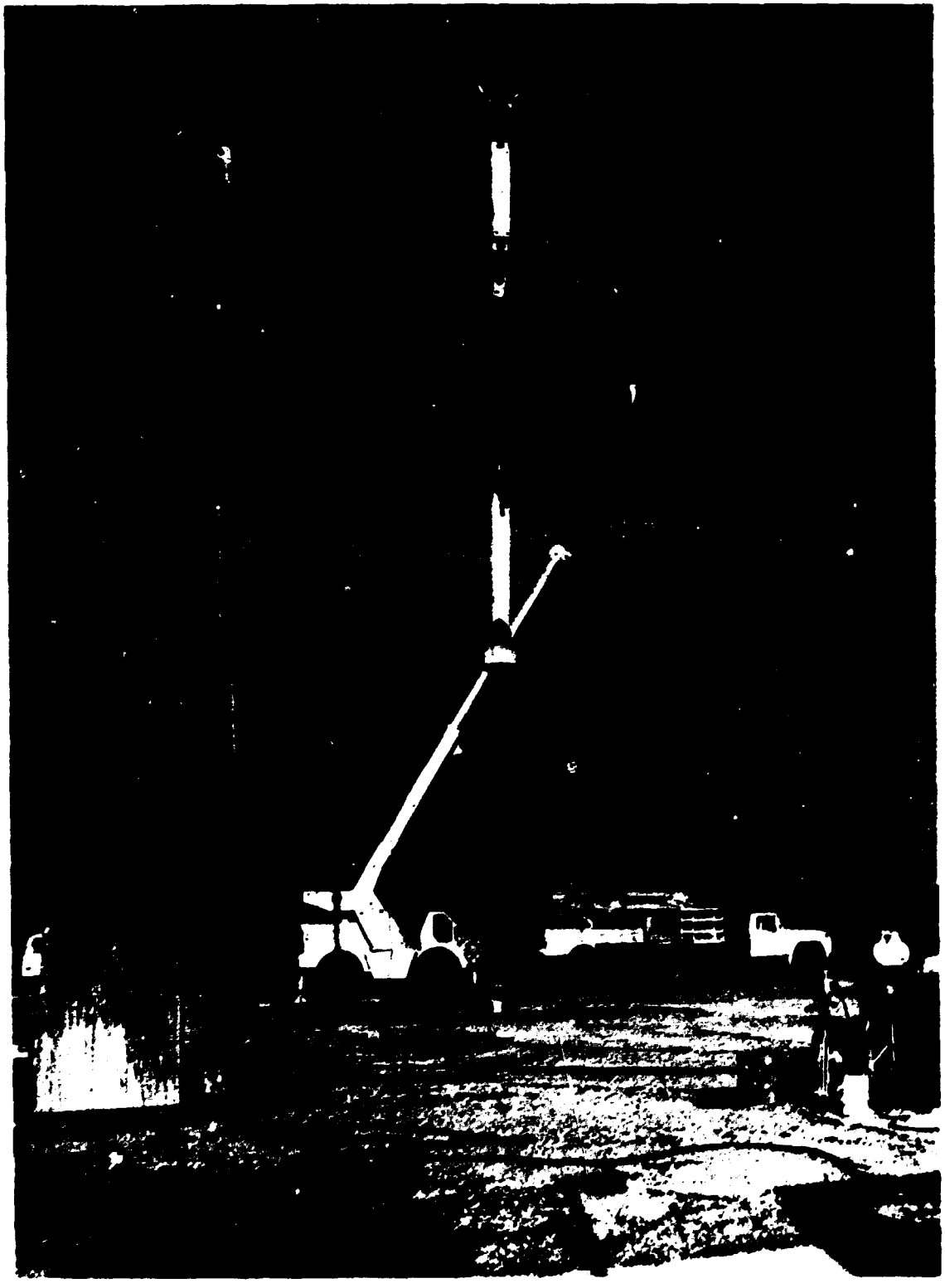

Fig. 5.2. Vertical drop testing of the knockout defueling canister.

and canister. When sufficient time has elapsed to allow all data to be recorded, the program shuts down all systems and returns to the beginning for another drop.

5.3 VISUAL EXAMINATION

A visual examination of the canister after it was removed from the CSV following the vertical drop test indicated that no external damage resulted from the test (see Figs. 5.3 and 5.4). One of the caps placed on each of the fittings prior to the test fell off during the impact, but, even with this cap removed, no leakage from the fittings was detected. A canister pressure reading of 214 kPa, absolute (31 psia), was taken by means of the inlet plug. This higher internal pressure was attributed to the increase in temperature inside the canister, which resulted from its exposure in ambient air at a temperature of ~21°C (~70°F).

After visual examination, the canister was placed on a flatbed truck and transported to the Radiography Facility of the ORNL Inspection Engineering Department. The canister was allowed to stand for a period of 8 h to reach equilibrium with ambient temperature in the laboratory.

When the canister had reached ambient temperature, the diameter of the canister was measured at five equidistant positions along the length and at five positions 90° around the circumference from the first set. These measurements showed evidence that the canister had not been flattened by the drop test.

5.4 X-RAY PROFILE OF INTERNAL ASSEMBLY

The canister was subjected to a series of X-ray examinations so that a complete profile of the internal assembly was recorded on film.

ORNL PHOTO 6429-85

Fig. 5.3. Knockout defueling canister after first vertical drop test.

ORNO PHOTO 6468-85

Fig. 5.4. Impact end of knockout defueling canister after first vertical drop test.

A comparison of the X-ray films taken after the drop test with those taken prior to the test revealed that the force of the vertical impact on the end of the canister had driven the central poison rod downward within the strong-back tube with enough force to form a dimple ~10 mm (0.4 in.) deep in the center of the cover plate welded to the bottom of the lower support. This plate was designed to hold the poison rods in position. Even though the force of the impact was sufficient to deform the plate, the welds throughout the canister were still sound, and the poison rods remained in the correct positions to prevent criticality. No cracked pellets were found inside the poison rods, but a 10-mm (0.4-in.) gap was discovered between two of the pellets located in poison rod C.

5.5 INSTRUMENTATION DATA

The canister was equipped with six, Endevco, piezoresistive accelerometers mounted on two triaxial blocks which were attached to the top of the canister with 5-min epoxy. Accelerometers installed in the horizontal planes (x and y) were Endevco Model 2262A-100, with a rated range of -100 to +100 g and a typical mounted natural frequency of 5000 Hz. Accelerometers installed in the vertical (z) plane were Endevco Model 2262A-200, with a rated range of -200 to +200 g and a typical mounted natural frequency of 7000 Hz. The locations and orientations of these accelerometers are shown in Fig. 5.5.

Accelerometer plots were generated from the data recorded on the FM tapes by passing the demodulated analog signals through an adjustable anti-biasing filter to an A/D converter and then to a digital tape

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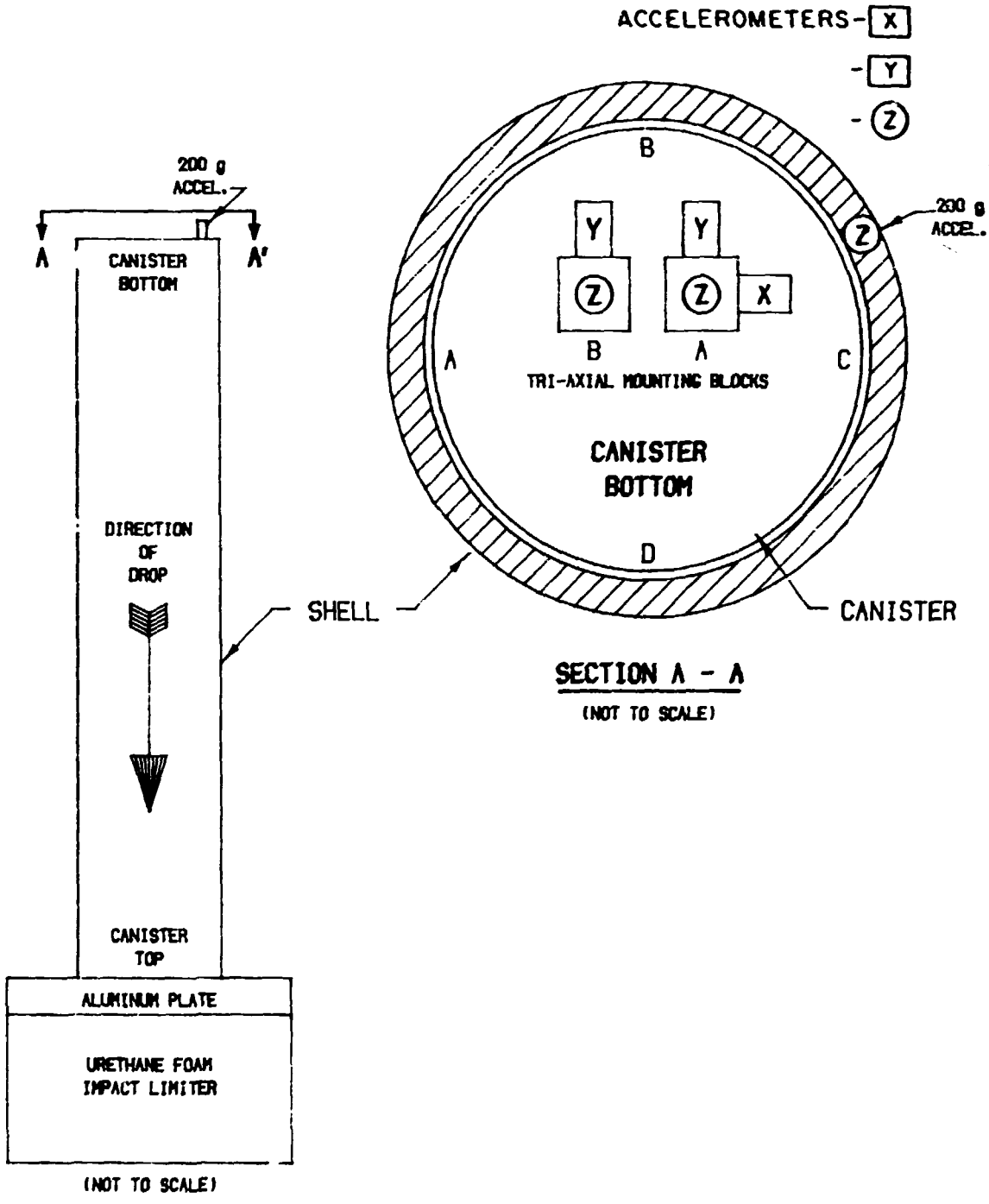

Fig. 5.5. Schematic diagram of knockout canister showing locations and orientation of accelerometers. Horizontal accelerometers mounted at X and Y; vertical accelerometer at Z.

recorder. The variable filter was adjusted to function also as a low-pass filter, with a pass band of 0 to 200 Hz, to eliminate high-frequency (low-energy) noise spikes.

Figure 5.6 is a plot of output from the z (vertical) accelerometer mounted on Block "B." Note that acceleration is plotted on the ordinate vs time in seconds on the abscissa. Time zero is ground impact.

Plots generated from data collected by the other accelerometers may be found in Appendix B of this document. Note that the scale of the ordinate varies among plots because of automatic scaling by the software.

In ORNL DWG 86-529 (in Appendix B), note that the tops of the positive peaks in the data plot are flattened, which indicates that the range of this accelerometer was exceeded. However, these data were from a low-range (-100 to +100 g) accelerometer that was added to the shell when the Z accelerometer on Block A (see Fig. 5.5) was determined to be defective.

6. PREPARATION FOR HORIZONTAL DROP

6.1 IMPACT LIMITER PREPARATION

The second drop test in the program required the canister to be horizontal during impact, with the simulated fuel load frozen and held at the top of the canister. This configuration applied downward forces to the poison rods during the impact, creating the maximum horizontal loads to the rods that could occur during a horizontal-drop type of accident.

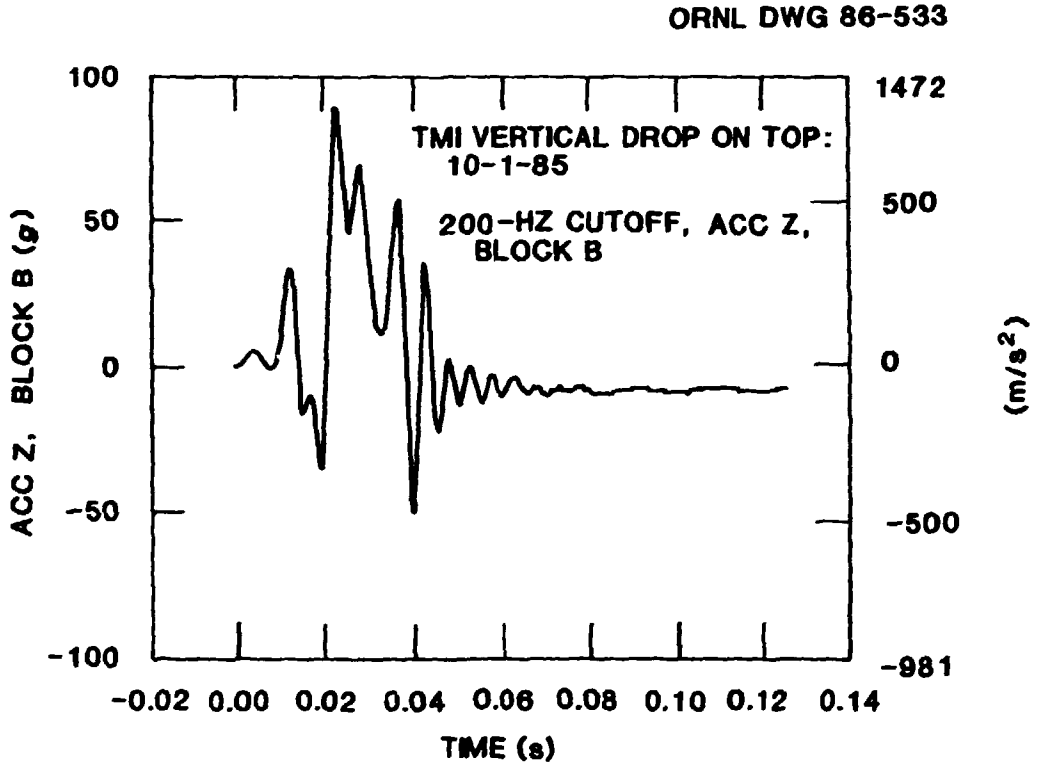

Fig. 5.6. Plot of output from vertical accelerometer mounted on block B in knockout defueling canister during vertical drop test.

As in the vertical drop, protection simulating that provided by the shipping cask was required during the impact. The computer determined that the quantity of foam necessary to limit the impact of the canister to between 981 and 1177 m/s^2 (100 and 120 g) was 7900 cm^2 (1229 $in.^2$) and 20 cm (8 in.) thick.

The size of the impact limiter which was calculated to give the desired loadings was shorter than the total length of the CSV; therefore, to distribute the load of the canister over the foam equally, it was decided to divide the foam into four sections and to place these sections along the CSV at equal distances apart. Solid wooden saddles were fashioned from plywood to conform precisely to the curve of the CSV, and the foam impact-limiting material was cast onto the bottom of the saddles. The CSV was then placed into the saddles, and metal strapping was pulled over the top and nailed to each side of the plywood (see Fig. 4.4). Crush-strength and density measurements of this foam indicated that the physical attributes were sufficient to limit the impact to the range prescribed in the procedures.

6.2 ATTACHMENT OF ACCELEROMETERS

In the horizontal drop test, two sets of accelerometers were mounted at opposite ends of the canister. One set was mounted on the plate that was used in the first drop; the other set, located at the top head, was secured to a mounting plate which was epoxied to the top head. The umbilical cable was divided so that one leg collected the signal from one set of accelerometers, and the other leg collected from the second set.

6.3 TEMPERATURE REDUCTION

The temperature of the knockout canister was reduced for this test by placing the assembly in the refrigerated truck for 24 h before the scheduled drop test. To freeze the simulated fuel in the desired location, the canister was positioned horizontally in the truck, with the simulated fuel mixture of lead shot and water surrounding the rod C of the support spiders (configuration B in Fig. 6.1). This rod was chosen because it was not covered by the frozen simulated fuel in the first test. Any damage to leg B of the spider in the first drop test would be compounded in the second drop, if the frozen material impacted on the same leg again.

The canister was removed from the refrigerator truck, placed into the CSV, and chocked with wedges so that the simulated fuel was above the internal assembly. The accelerometers were attached to the mounting plates, and the internal pressure was raised to 207 kPa, absolute (30 psia). The system was then raised to a height of 9 m (30 ft), and the drop sequence was begun (Fig. 6.2). The temperature of the canister's internals was -13°C (6°F) at the time of the drop.

7. RESULTS OF HORIZONTAL DROP TEST

7.1 VISUAL EXAMINATION

After landing on the foam impact limiters, the CSV–canister system fell over onto the side of the CSV. The drop caused no visible damage to the canister, and all of the caps remained in place during the test. The pressure inside the canister was 214 kPa, absolute (31 psia); again, this increase was due to the increase of the internal temperature of the canister.

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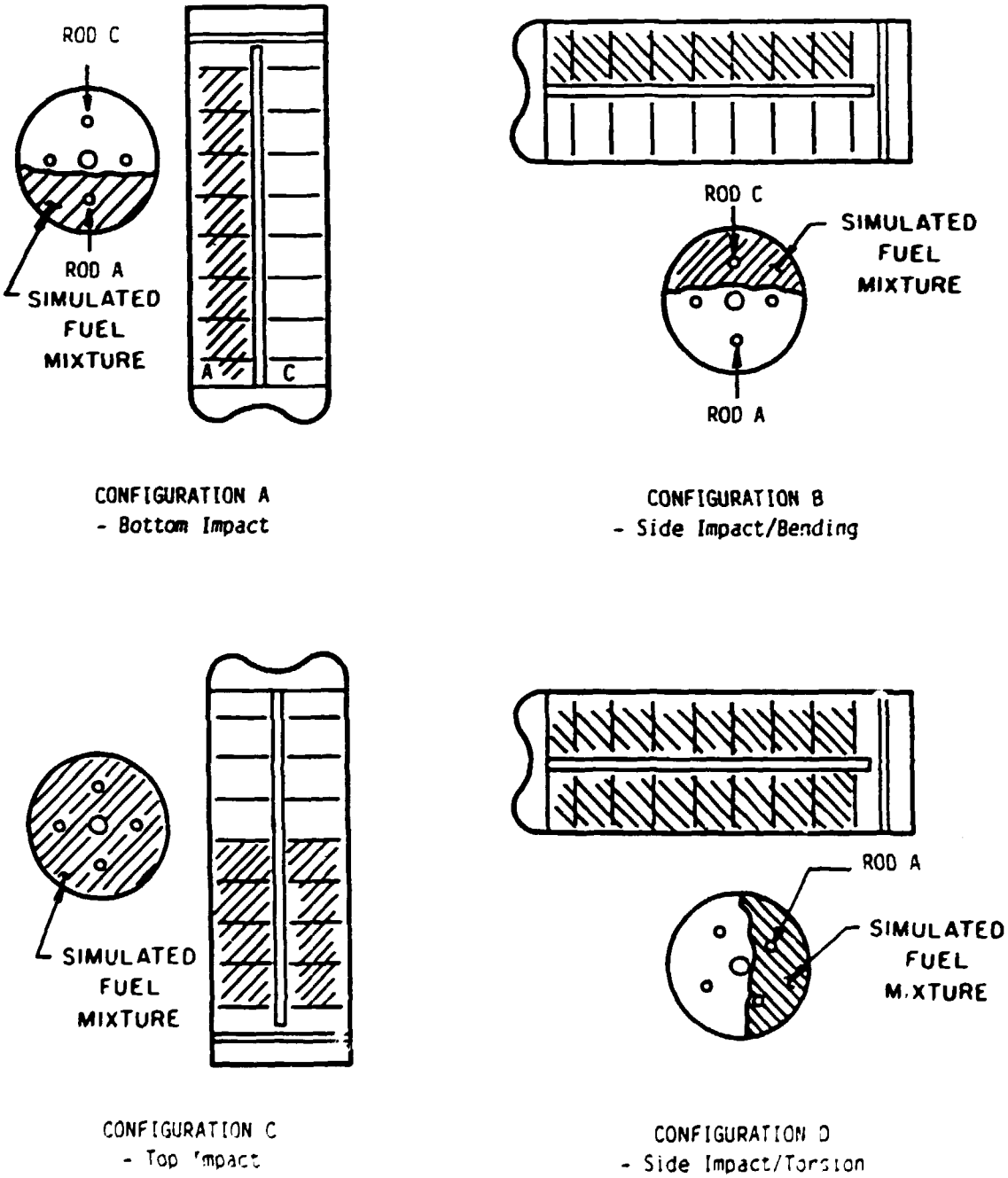

Fig. 6.1. Drop test configurations.

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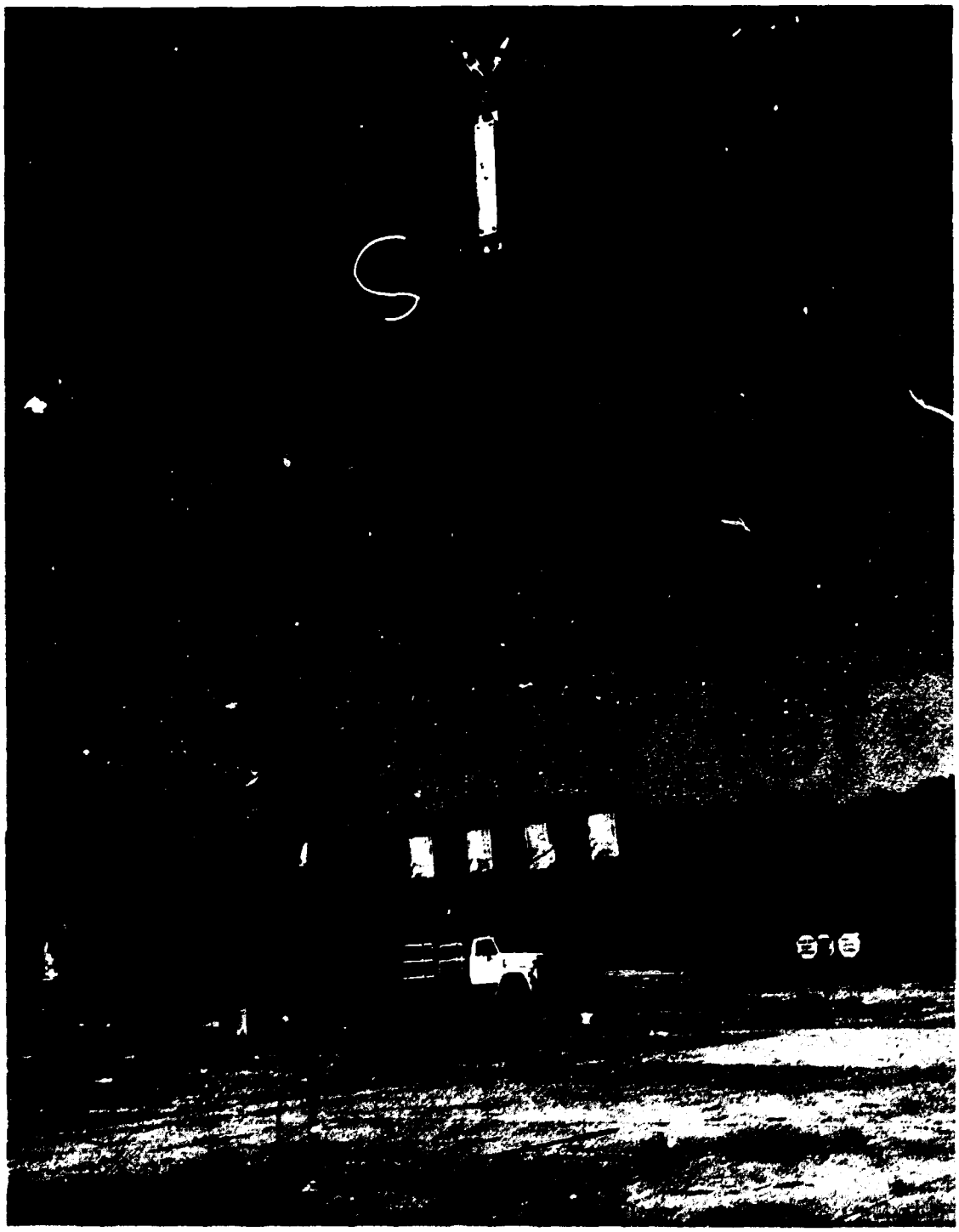


Fig. 6.2. Horizontal drop test of knockout defueling canister.

The canister was taken to the radiography laboratory and allowed to reach ambient temperature. While waiting, measurements of the diameter of the canister were recorded and compared to those obtained after the vertical drop test. The two sets of measurements showed no significant differences.

7.2 X-RAY PROFILE OF INTERNAL ASSEMBLY

The canister was subjected to a complete X-ray profile, and detailed examination of the photographic films revealed very little damage to the poison rods and the support plates. Rod C was within 3 mm (0.1 in.) of its original placement. Two of the individual pellets of the poison material had a 10-mm (0.4-in.) spacing between them in rod A. Rod C had a 10-mm (0.4-in.) gap between two pellets and a 3-mm (0.1-in.) gap between two others. Most of the pellets remained packed closely together and did not appear to have cracks (Fig. 7.1).

7.3 INSTRUMENTATION

Instrumentation installed for the first horizontal drops included six accelerometers mounted on triaxial blocks located at the ends of the canister, as shown in Fig. 7.2. The block located at the bottom of the canister was attached by bolts to a plate welded to the canister bottom, and the block located at the top was attached by bolts to a plate epoxied to the top of the canister. The ranges of the vertical (y) accelerometers used in this drop were -200 to +200 g, and the ranges of those installed in the horizontal (x and z) axes were -100 to +100 g. The general instrumentation scheme was the same as depicted in Fig. 4.6 for the vertical drop test.

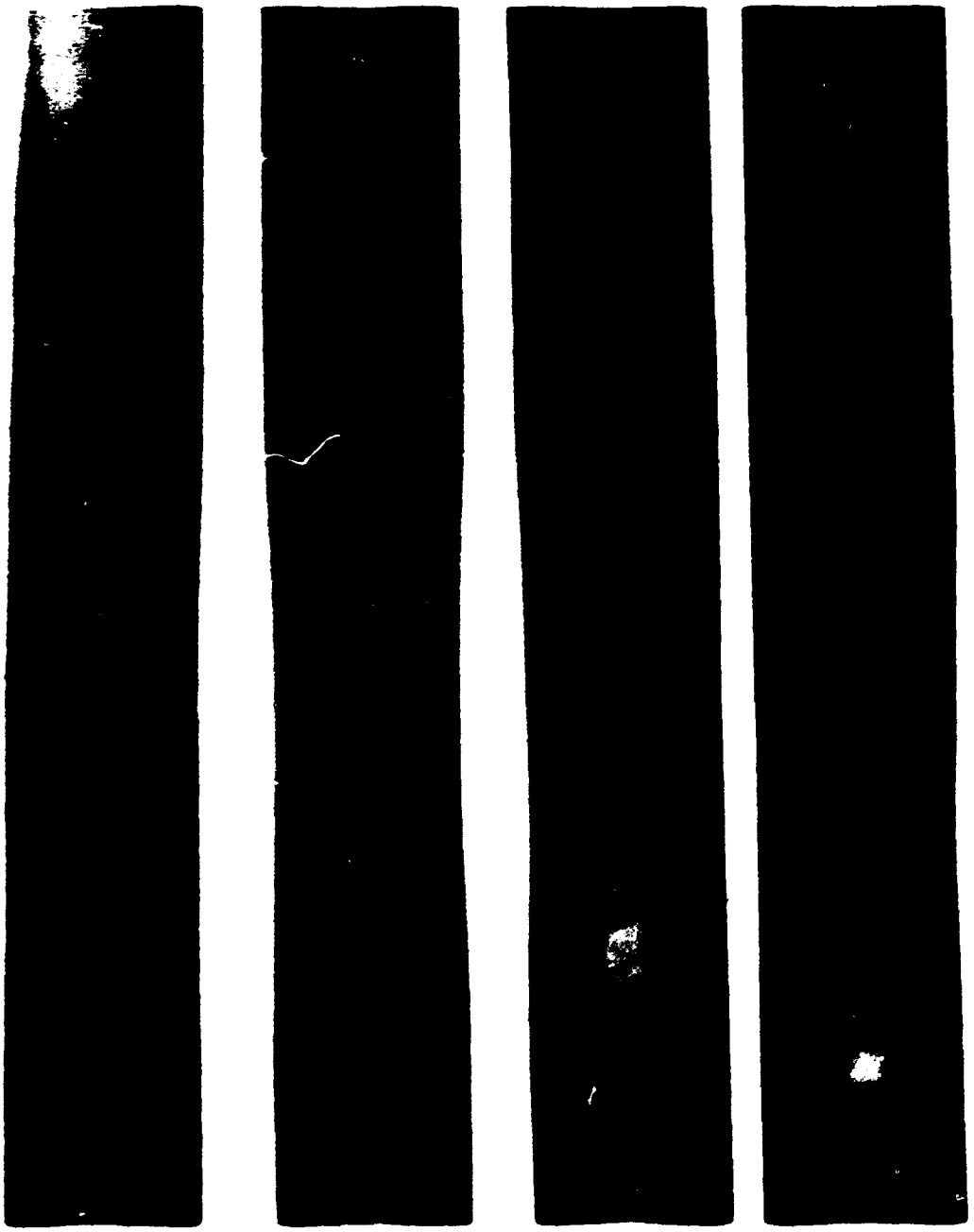
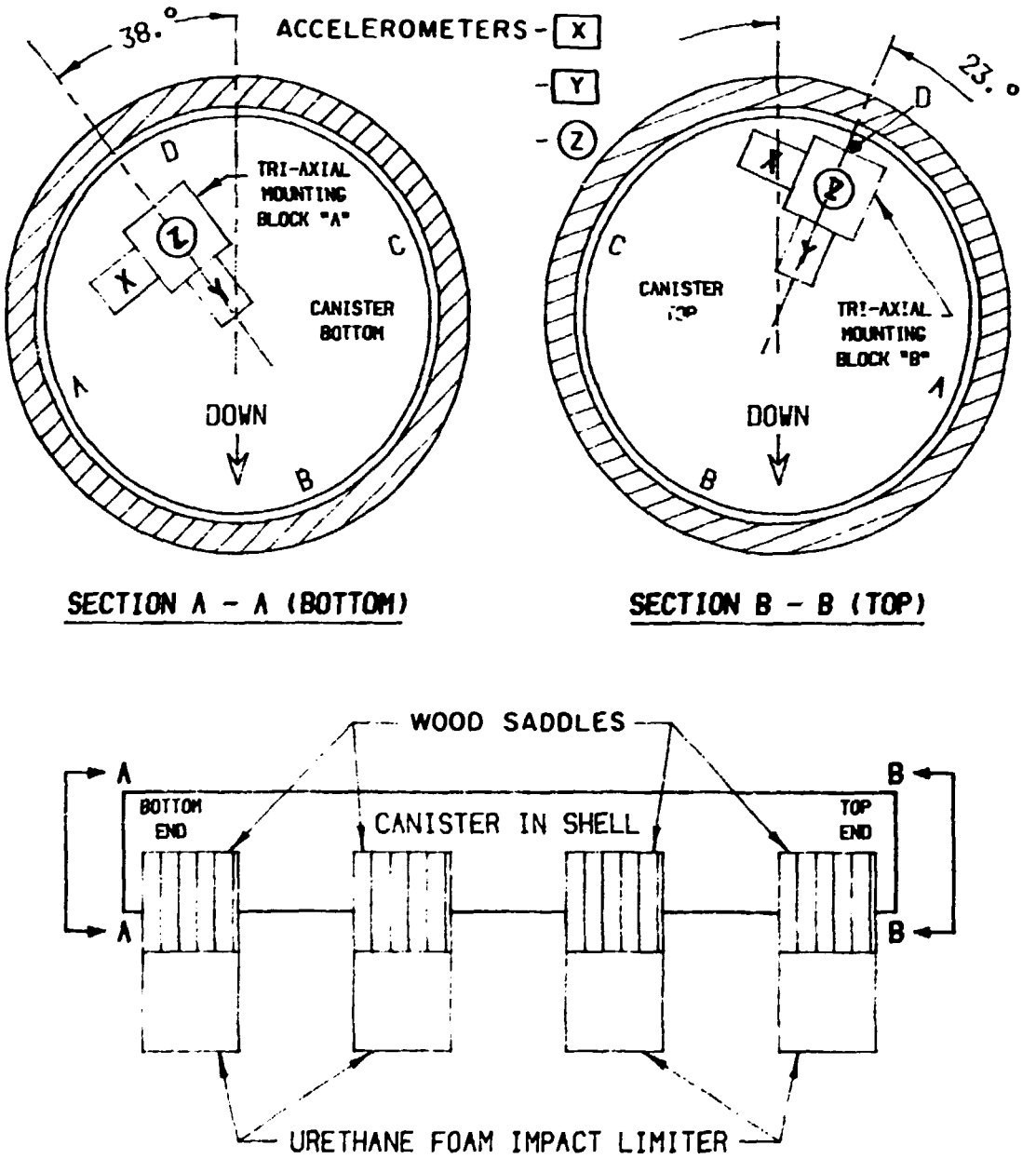


Fig. 7.1. X-ray photograph of absorber rods showing the individual pellets of the boron carbide poison material.

ORNL DWG 86-447R



NOTE: THIS DRAWING IS NOT TO SCALE.

Fig. 7.2. Schematic diagram of knockout canister showing location and orientation of accelerometers.

Measurement of the vertical component of acceleration during this drop was complicated by the fact that the triaxial mounting blocks were not vertically aligned because of rotation of the canister during its insertion in the shell. A computer program was written to vectorially combine the instantaneous vertical components of the x and y accelerometers. A plot of the vertical acceleration calculated by this method from the accelerometers located on Block A (canister bottom) is shown in Fig. 7.3.

Plots from other accelerometers used in this drop are presented in Appendix B of this document.

8. PREPARATION FOR VERTICAL DROP ON TOP HEAD

This test was intended to place a maximum tension load on the weld holding the internal assembly to the lower support plate. Therefore, the water/lead shot mixture was not frozen, and, during assembly, the openings in the upper support spider were closed with thin pieces of metal plate which were tack-welded into place. These plates and a silicone sealant around the circumference of the upper spider permitted the internal assembly to carry the weight of all the simulated debris at impact.

The drop was performed at ambient temperature (16°C, 60°F). Since the canister had been pressurized to 207 kPa, absolute (30 psia), for the previous (frozen) tests and no leakage had occurred, it was necessary to vent the canister, which was now warm, from an absolute pressure of 241 kPa (35 psia) to 207 kPa (30 psia) to meet test requirements.

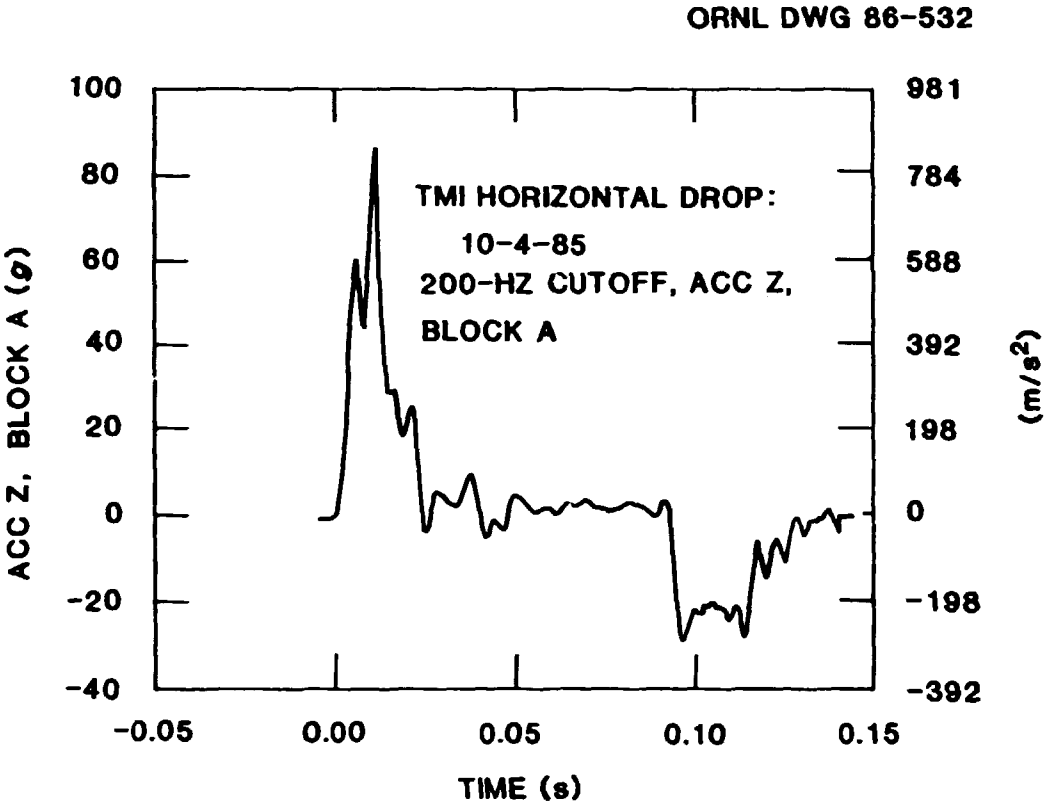


Fig. 7.3. Plot of output from vertical accelerometer mounted on bottom of knockout defueling canister during horizontal drop test.

8.1 IMPACT LIMITER PREPARATION

The test assembly for this drop was the same as that used for the first vertical drop [a 30-cm (12-in.)-thick by 76-cm (30-in.)-diam impact limiter foamed onto the 10-cm (4-in.)-thick by 76-cm (30-in.)-diam aluminum foundation that was bolted to the CSV].

The foam was prepared one day prior to the drop and at a lower ambient temperature [13°C (55°F)], which delayed the initiation of the foaming reaction but did not otherwise affect the product. The foam was allowed to cure overnight, and a sample was taken to obtain compressive strength and density measurements.

8.2 ATTACHMENT OF ACCELEROMETERS

Two mounting blocks for the triaxial sets of accelerometers were attached to the bottom head of the canister; one was tack-welded, and the other was epoxied in place. Unfortunately, the orientation of one of the mounting blocks resulted in a physical obstruction that prevented the installation of the second x-oriented accelerometer. This accelerometer was mounted instead on the CSV in the z (vertical) direction; therefore, this test was conducted with one x accelerometer, two y accelerometers, and two z accelerometers on the canister and a third z accelerometer on the CSV.

9. VERTICAL DROP ON TOP HEAD

After the impact limiter was attached to the CSV and the canister was inserted, the assembly was raised to a height so that the top head was 9 m (30 ft) above the drop pad. The assembly was then dropped using the explosive bolt mechanism.

9.1 VISUAL EXAMINATION

This drop caused no visible damage to the exterior of the canister. As in the first drop, the Hanson cap came off the 1.9-cm (0.75-in.) pressurization fitting on the head. The internal pressure of the canister was measured as 207 kPa, absolute (30 psia). A recheck several hours later also found the pressure to be 207 kPa, absolute (30 psia), indicating that no leaks had developed as a result of the drop.

9.2 X-RAY PROFILE OF INTERNAL ASSEMBLY

The canister was transferred to the radiography facility for X-ray profiling, and the resulting radiographs were compared to those taken prior to this test to assess any damage that had occurred. Bending of the two support plates nearest the upper head assembly was readily apparent. Some slight movement in the position of one of the poison rods was revealed, but no evidence of any significant permanent damage was discovered. The other rods appeared to be unchanged.

The radiographs also revealed that several poison pellets had suffered some damage. Fractured pellets were observed near the bottom end of rods B, C, and D. In each case, the fractured pieces were well-defined, and no powdering could be detected. It was also noted that several pellets shifted, producing a 6-mm (0.25-in.) gap between adjacent pellets in one rod.

In the interest of expediting the testing schedule, all parties agreed not to produce a full set of radiographs of the canister after this test. Complete profiles were taken of the top and bottom areas of the canister, and only a cursory examination was performed on the mid-section of the canister.

9.3 INSTRUMENTATION DATA

As previously stated, instrumentation for the third drop (vertical, on top head) included six accelerometers; however, because of limited space between the triaxial mounting blocks, one of the x accelerometers was eliminated, and an extra z accelerometer was mounted on the shell (see Fig. 9.1). One of the triaxial mounting blocks was bolted to a plate welded to the canister bottom (this block was previously used in the first horizontal drop), and the other block was bolted to a plate epoxied to the bottom of the canister. Ranges of the three z (vertical) accelerometers were −200 to +200 g, and ranges of the x and y (horizontal) accelerometers were both −100 to +100 g. The general instrumentation scheme was as described in Sect. 4.5 of this document, except that the type K thermocouple was not used in this vertical drop, because it took place at ambient temperature.

A plot of data from the z (vertical) accelerometer is shown in Fig. 9.2. Other plots are included in Appendix B of this document.

10. PREPARATION FOR HORIZONTAL DROP WITH INTERNAL TORQUE

This test was designed to produce a torque loading on the internal assembly of the canister. The torque was achieved by dropping the canister in a horizontal orientation with the frozen mass on the sidewall.

10.1 IMPACT LIMITER PREPARATION

The impact limiters for this test were constructed in a manner similar to that described in Sect. 6.1. Four foam pads were prepared,

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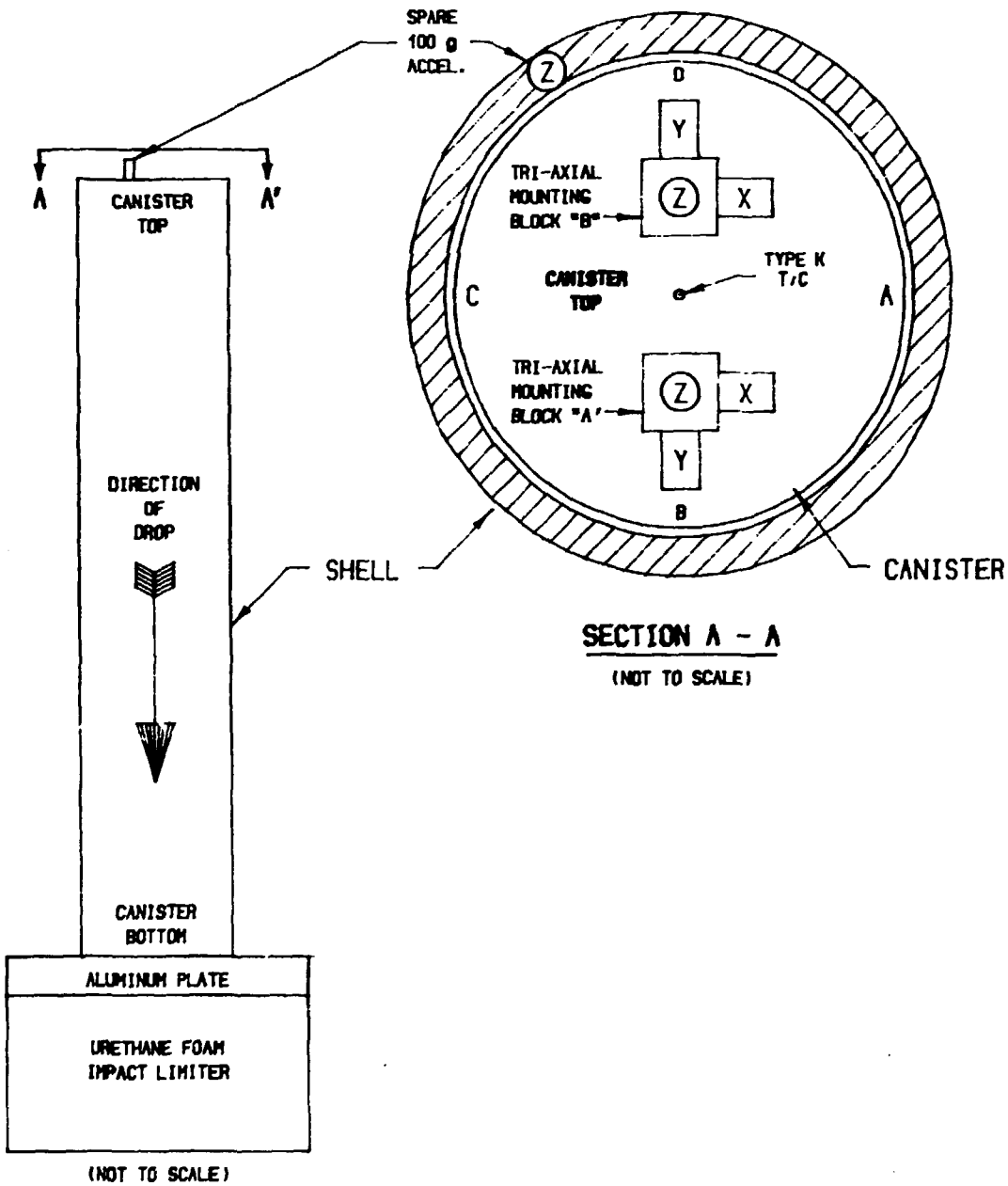

Fig. 9.1. Schematic of knockout defueling canister bottom showing the vertical (z), and horizontal (x,y) accelerometers locations.

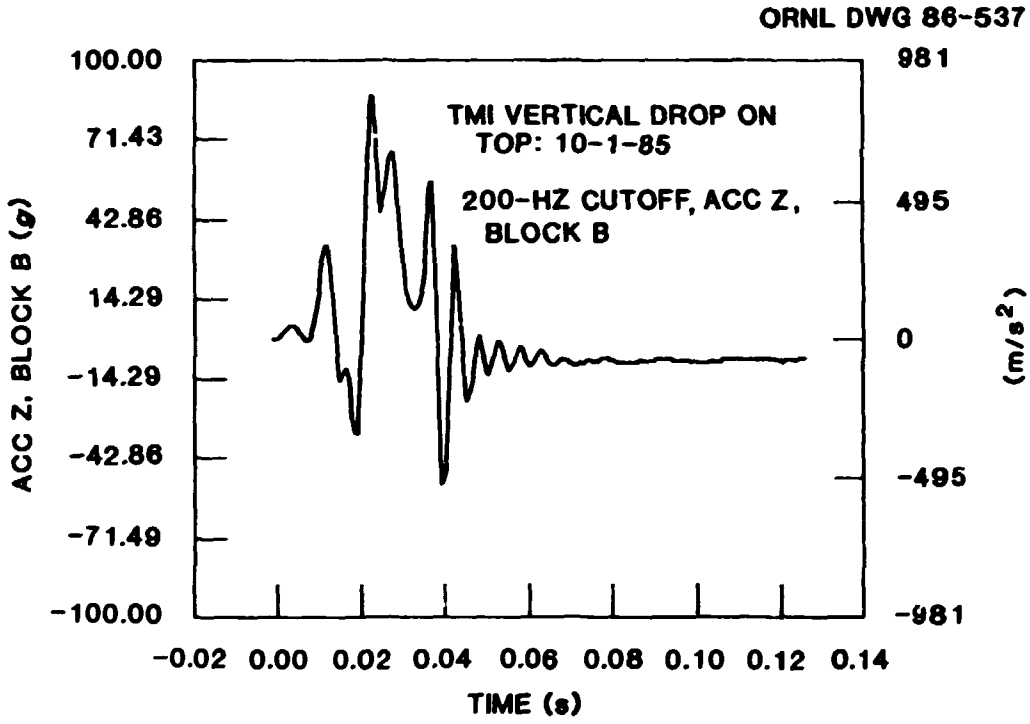

Fig. 9.2. Plot of output from vertical accelerometer mounted in the knockout defueling canister during the vertical drop test.

samples were cut from each pad, and compression strengths of 1999, 1861, 2123, and 2206 kPa (290, 270, 308, and 320 psi) were obtained. The measured densities and compressive strenghts indicated that the pads would provide the desired impact limitation. The impact limiters, along with the wooden saddles, were attached to the CSV with steel straps.

10.2 ATTACHMENT OF ACCELEROMETERS

The accelerometer blocks were attached to the top and bottom heads of the canister in a manner similar to that used for the previous horizontal drop test. The block on the bottom head was tack-welded in place; epoxy was used to attach the one on the top head adjacent to the protective skirt. The accelerometers and umbilical cable were attached after the temperature-reduction step.

10.3 TEMPERATURE REDUCTION

The temperature of the canister was again reduced by placing it in the refrigerated truck for 24 h prior to the scheduled drop. Dry ice was stacked along the length of the canister to expedite cooling, producing a lower ultimate temperature for the same refrigeration period. This was done to provide the extended working time needed to install the canister in the CSV, attach the accelerometers, and rig the assembly for the drop before the internal temperature rose above freezing. For the same reason, the canister, at ambient temperature, was pressurized to 241 kPa, absolute (35 psia), to yield a final pressure that required minimal adjustment after freezing to obtain 207 kPa, absolute (30 psia), for the drop.

11. HORIZONTAL DROP WITH INTERNAL TORQUE

This final test was designed to exert torque on the internal assembly upon impact. This was accomplished by freezing the simulated fuel mixture of lead-shot and water so that it completely encased tube A and partially encased tube B. Any damage to tube B from the first three drops would be compounded from the impact of the simulated fuel debris and the torsional load imposed on the B rod during this drop test. After freezing, the canister was inserted into the CSV, which was oriented 90° from the drop direction. The canister was wedged in the CSV to maintain this orientation, and the assembly was placed upright, putting the frozen mass on the sidewall of the assembly. The unbalanced loading produced a slight tilt from vertical in the assembly, which could not be corrected without interfering with the free fall. It was decided that the slight tilt would not seriously affect the intended loading mechanism for this test and that, upon impact, the shifting load would still apply a significant torque to the internal poison rod assembly. The accelerometers were attached to the canister, and the internal pressure was measured. At the time of the drop, the internal temperature was -2°C (29°F), and the pressure was 210 kPa, absolute (30.5 psia).

11.1 VISIBLE DAMAGE

During the 9-m (30-ft) fall, the test assembly rotated slightly toward the side and impacted at a 22° angle from vertical. Upon impact, the foam impact limiters were only partially effective, since they crushed on the corner and then sheared at an angle of ~45°. The unbalanced test assembly then fell over on its side, with the CSV

striking the armor plate impact pad. No visible damage to the canister was detected following this test. The canister pressure was measured at 217 kPa absolute, (31.5 psia), with the increase again resulting from warming of the canister during and after the drop.

11.2 ACCELEROMETER DATA

Instrumentation of the second horizontal drop included six accelerometers as in previous drops. Three accelerometers were mounted on each of two triaxial blocks, one located at the top and the other at the bottom of the canister, as shown in Fig. 11.1. The triaxial block located at the bottom of the canister was bolted to a plate which was welded to the canister, whereas the triaxial block located at the top was bolted to a mounting plate that was epoxied to the canister. As in the first horizontal drop, the ranges of the vertical (y) accelerometers were -200 to +200 g and the ranges of the horizontal (x and z) accelerometers were -100 to +100 g.

During its descent, the canister rotated about its horizontal axis through an angle of approximately 22°. The plot of the vertical acceleration data (Fig. 11.2) has been corrected for this rotation. Plots of the horizontal components of acceleration for this drop test (found in Appendix B) have not been corrected for this rotation.

12. DISASSEMBLY OF CANISTER

After the drop tests were completed, the simulated fuel was allowed to reach ambient conditions and was then poured out of the canister. Following this, the canister was taken to the machine shop, where both

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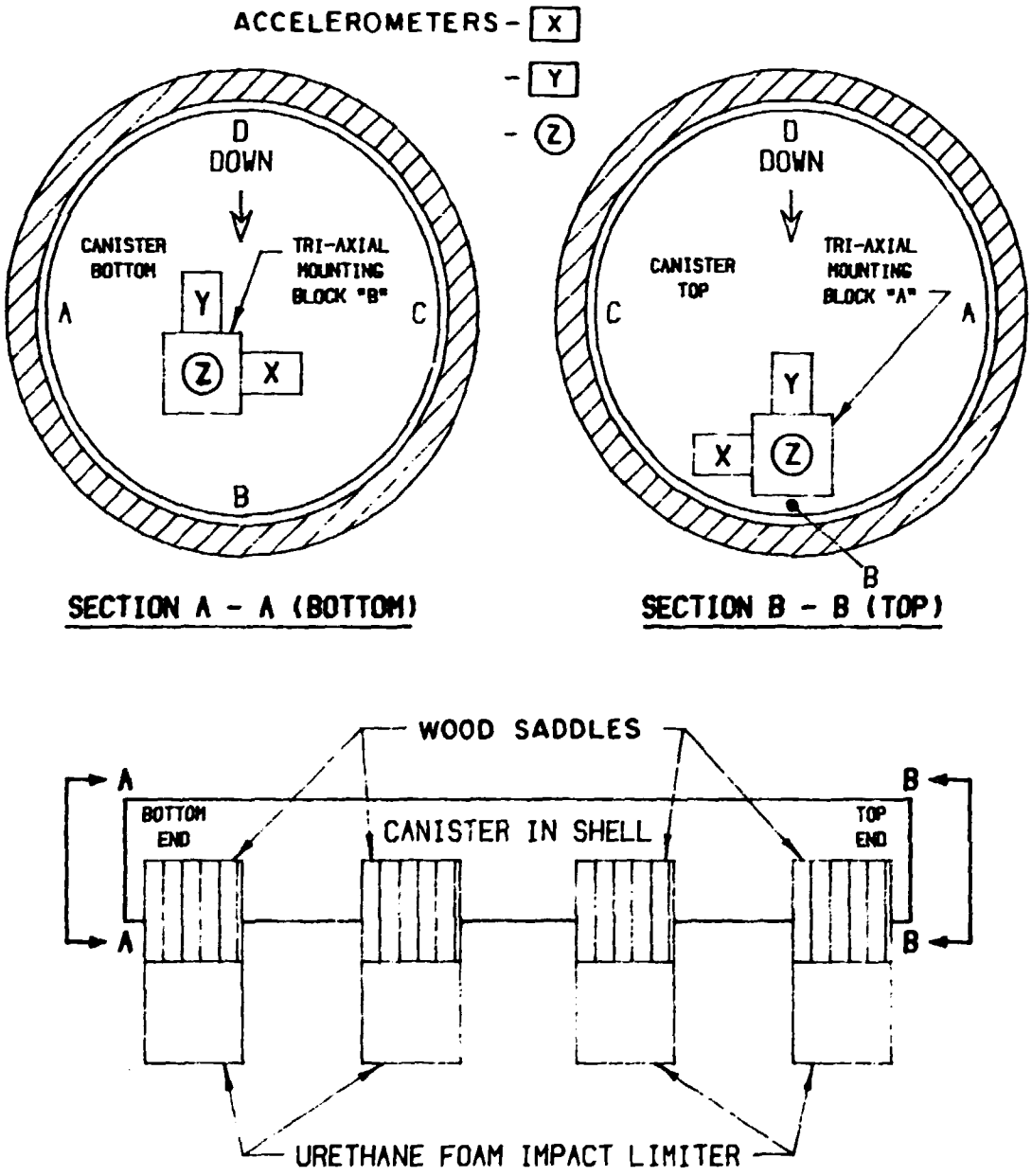

NOTE: THIS DRAWING IS NOT TO SCALE.

Fig. 11.1. Schematic of knockout defueling canister showing locations of accelerometers during the horizontal drop test with internal torque.

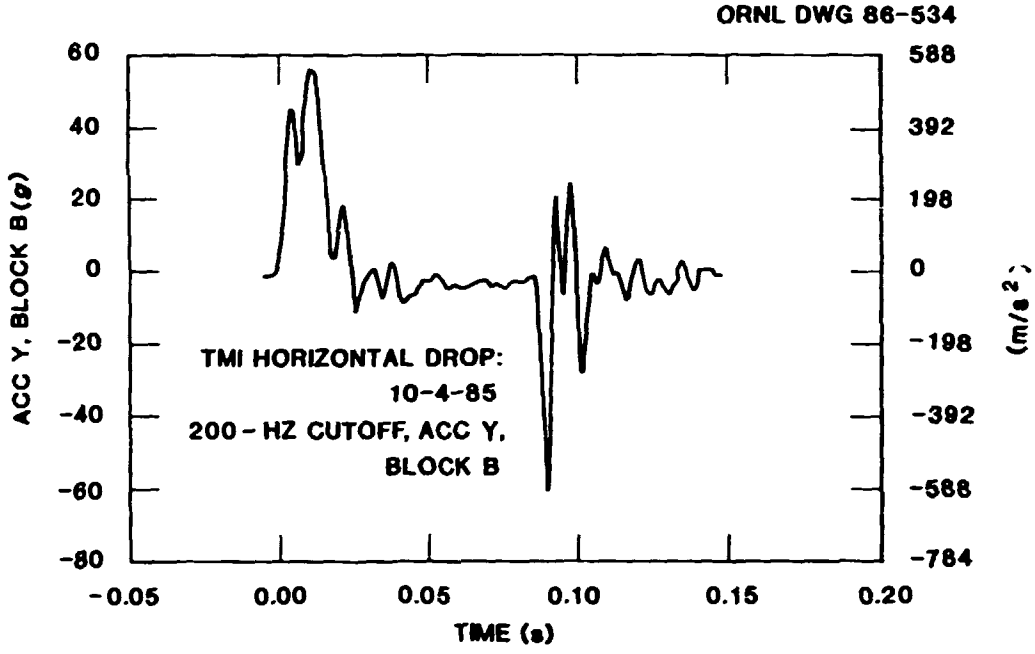

Fig. 11.2. Plot of output for vertical accelerometer of knockout defueling canister during a horizontal drop test. Data has been corrected for a 22° angle of rotation during drop.

the bottom head and the top head were cut from the shell (Figs. 12.1 and 12.2, respectively). The next step in the disassembly was to cut a section from the shell's circumference, ~5 cm (~2 in.) above the bottom of the support plate (Fig. 12.3) and remove the inner assembly (Fig. 12.4). The entire assembly was easily extracted from the outer shell, indicating no significant permanent damage to any of the poison rods or support plates had occurred.

12.1 VISUAL EXAMINATION

The stainless steel screens covering the recombiner pellets were removed to allow examination of the pellets (see Figs. 12.5 and 12.6). This inspection revealed that the recombiner material was undamaged and that the screens adequately contained the pellets within the designed containers in both the bottom and top heads.

The visual inspection of the internal poison assembly indicated that the poison rods had not been displaced (Fig. 12.7). The tips of two of the support spiders had been bent ~12 mm (~0.5 in.) toward the top head (Fig. 12.8) as a result of the third drop. The poison rods in the bent spiders remained straight, since the diameter of the passageways was 3.0 mm (0.13 in.) larger than that of the rods.

The only other visually evident damage to the canister that resulted from the drop tests occurred during the final horizontal drop at the canister location where the simulated fuel had been frozen around rods A and B. The frozen material was positioned on the side where torsion was applied to the two rods and, thus, to the inner assembly. This damage was observable in the form of some bending of the wedges that

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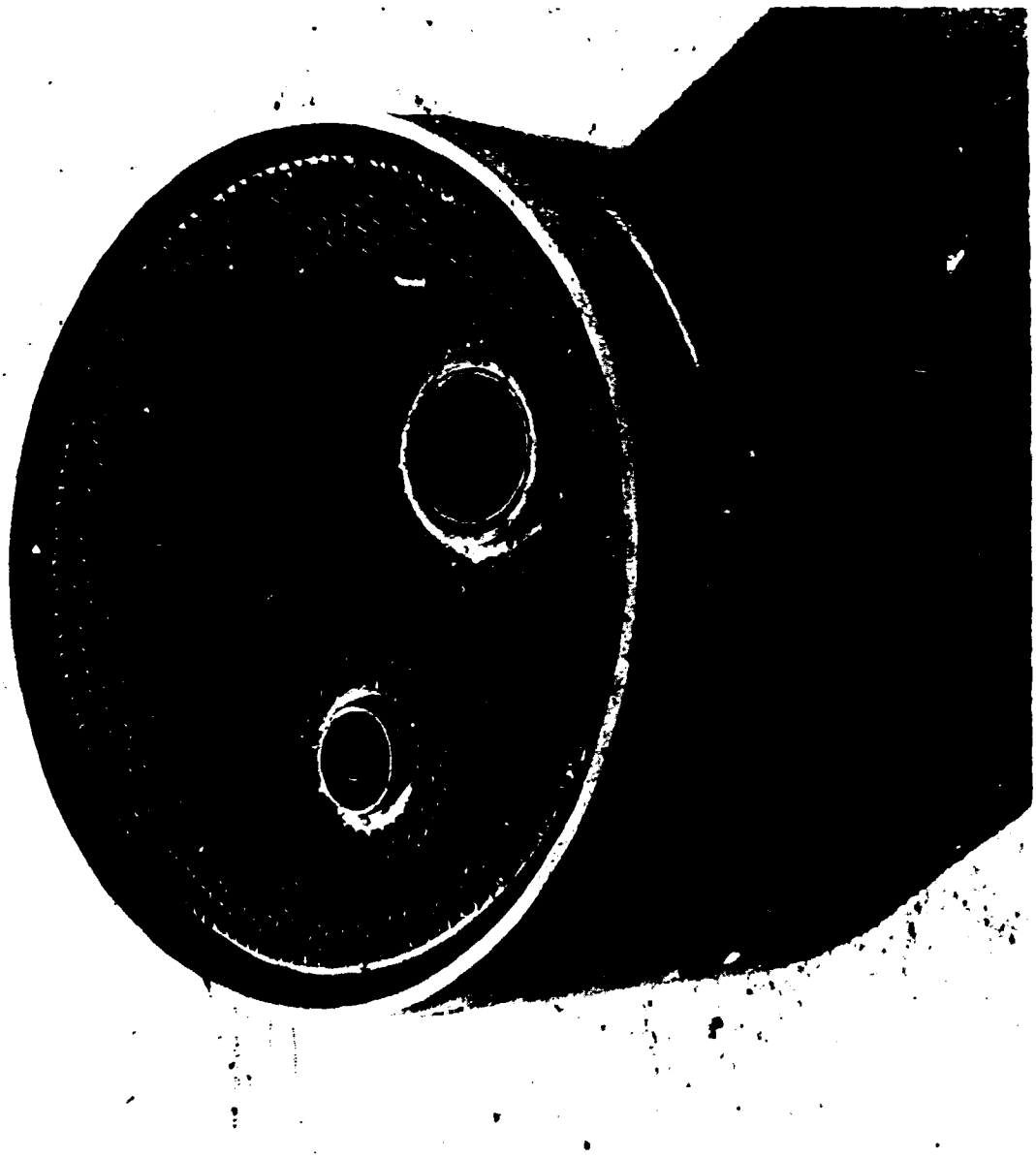

Fig. 12.1. Top head of the knockout defueling canister after all of drop tests.

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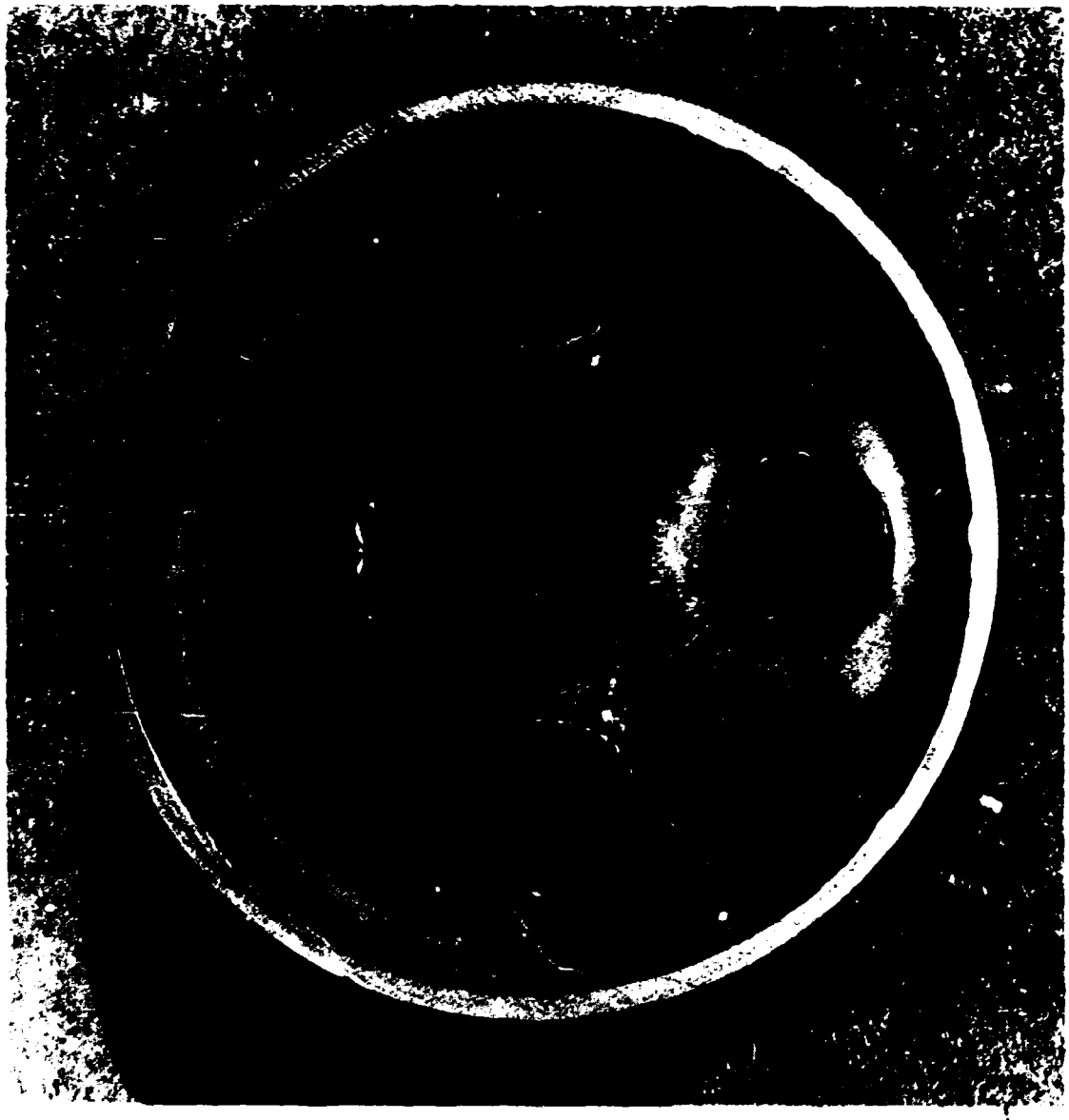

Fig. 12.2. Bottom head of the knockout defueling canister after all of the drop tests.

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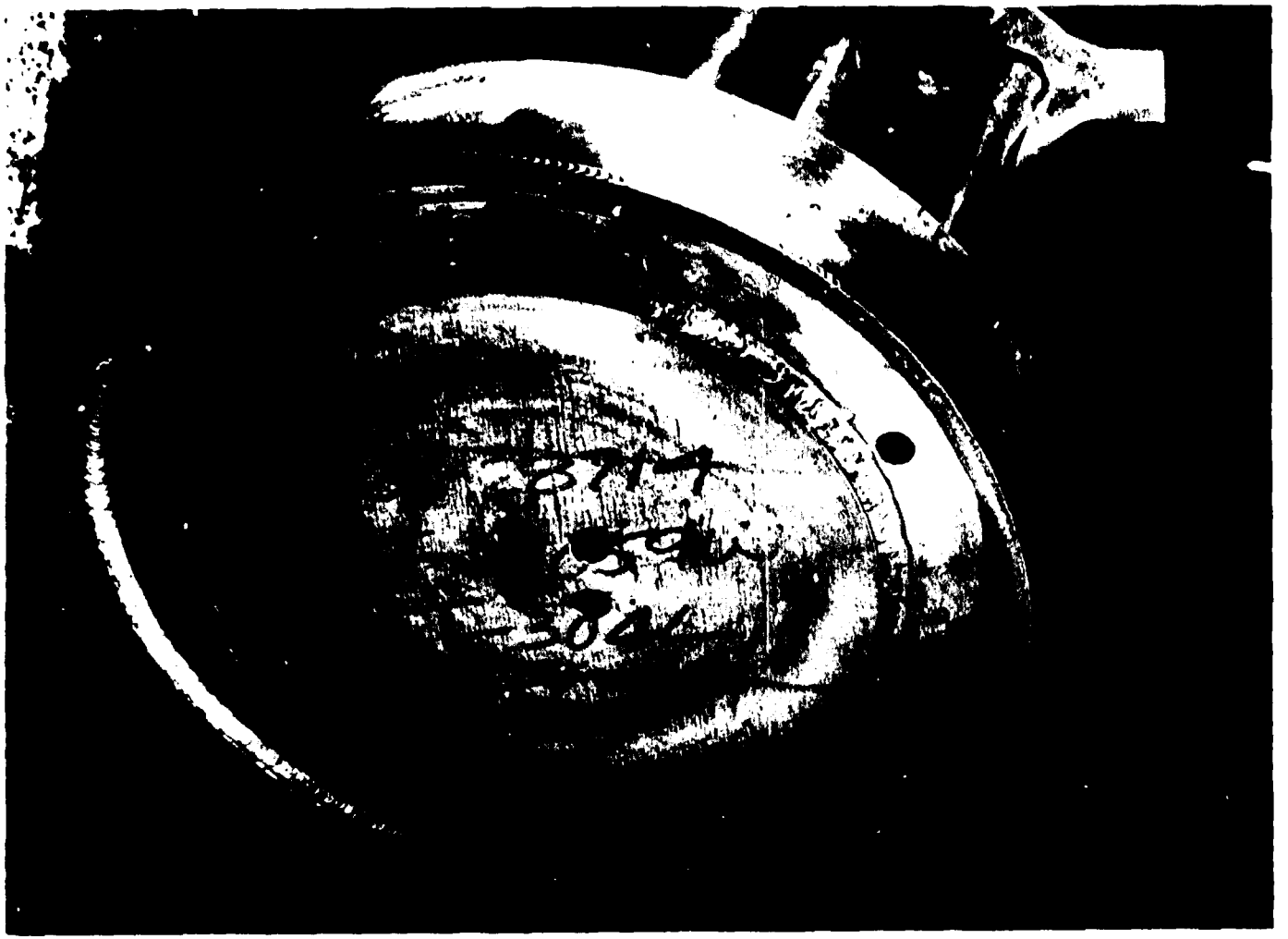

Fig. 12.3. Cross section removed from the knockout defueling canister showing the lower support plate that holds absorber rod in position.

ORNL PHOTO 7879-85

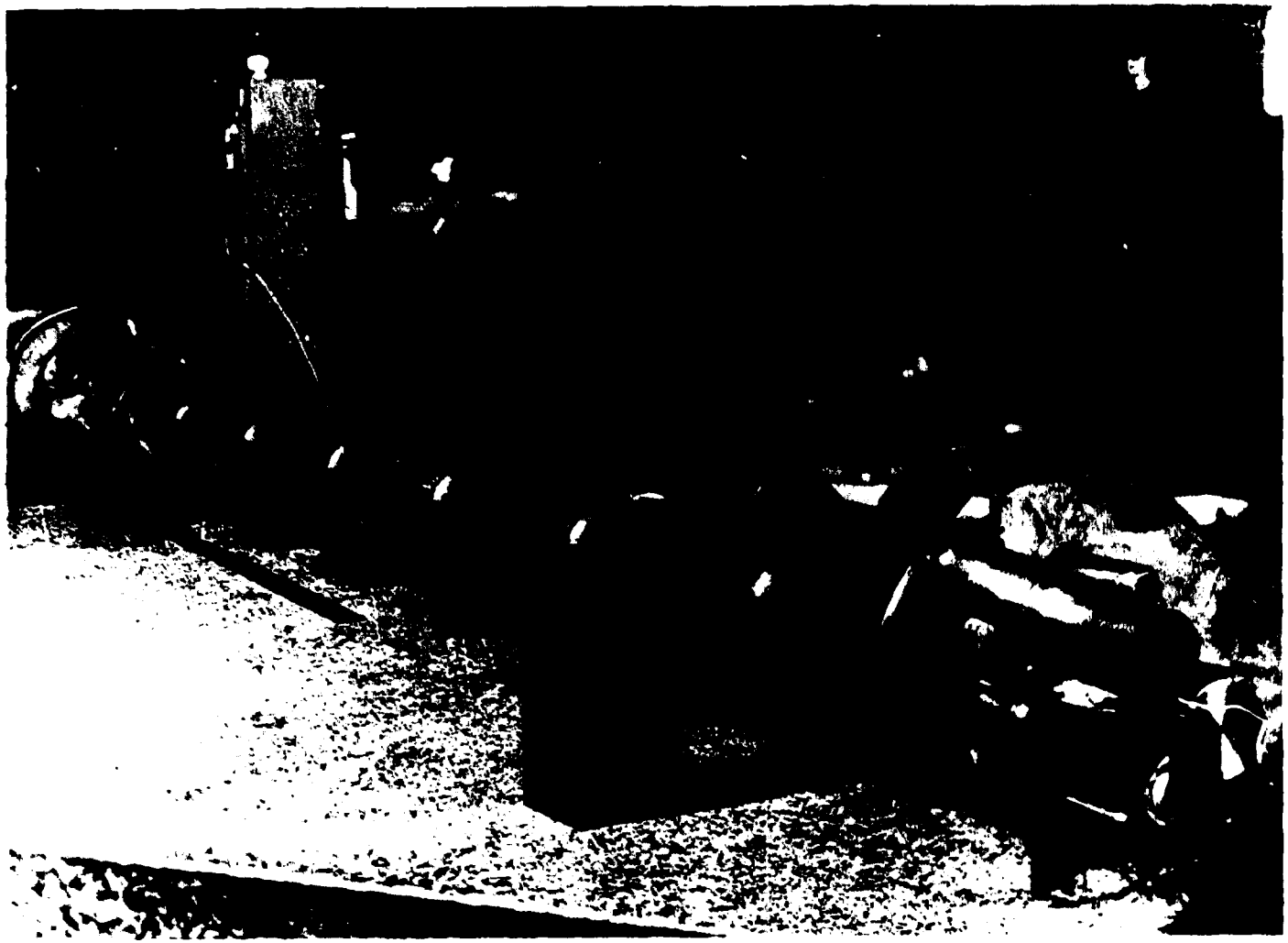

Fig. 12.4. Internal assembly from the knockout defueling canister after completion of all drop tests.

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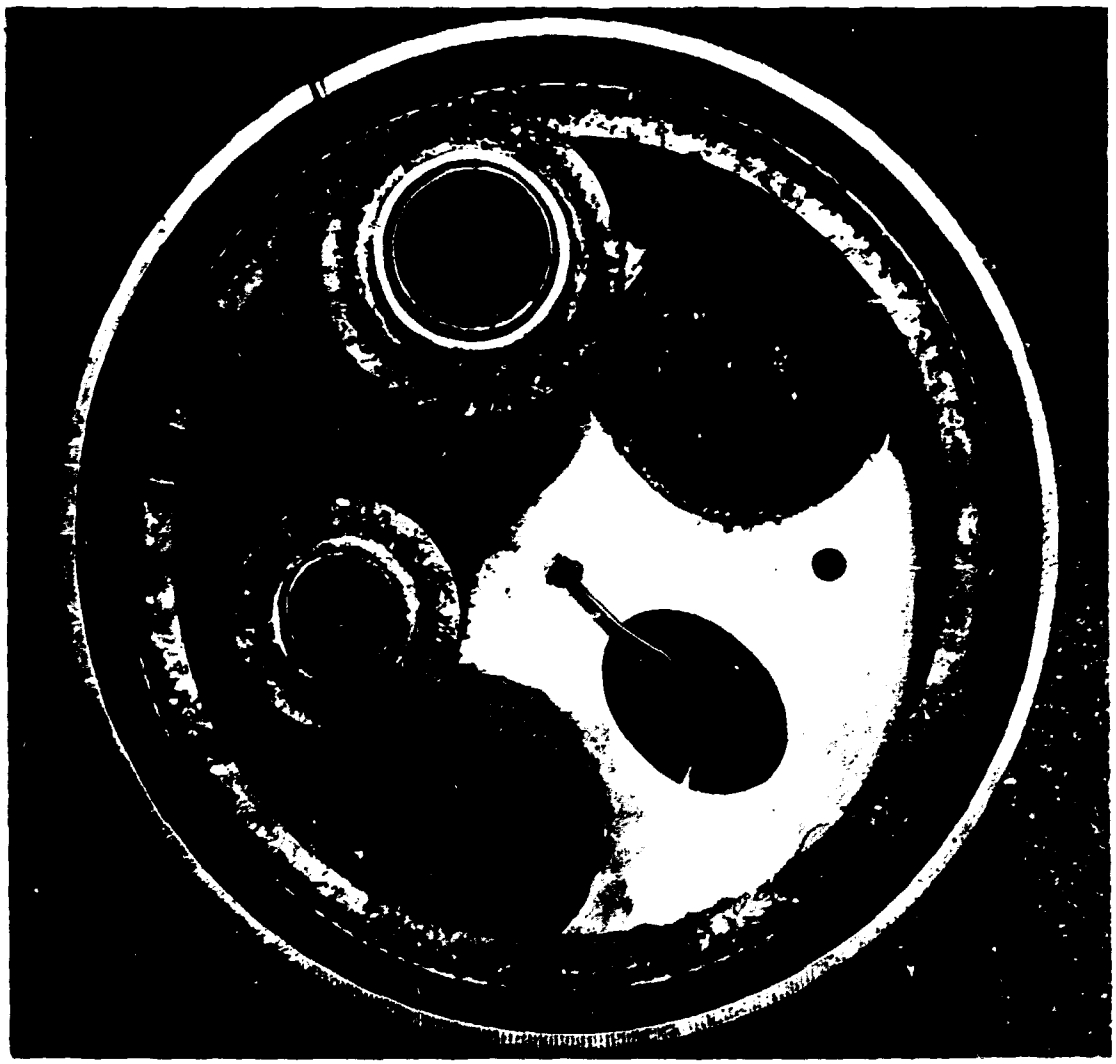

Fig. 12.5. Knockout defueling canister top head showing O_2-H_2 recombiner packets. Screen has been removed from a packet.

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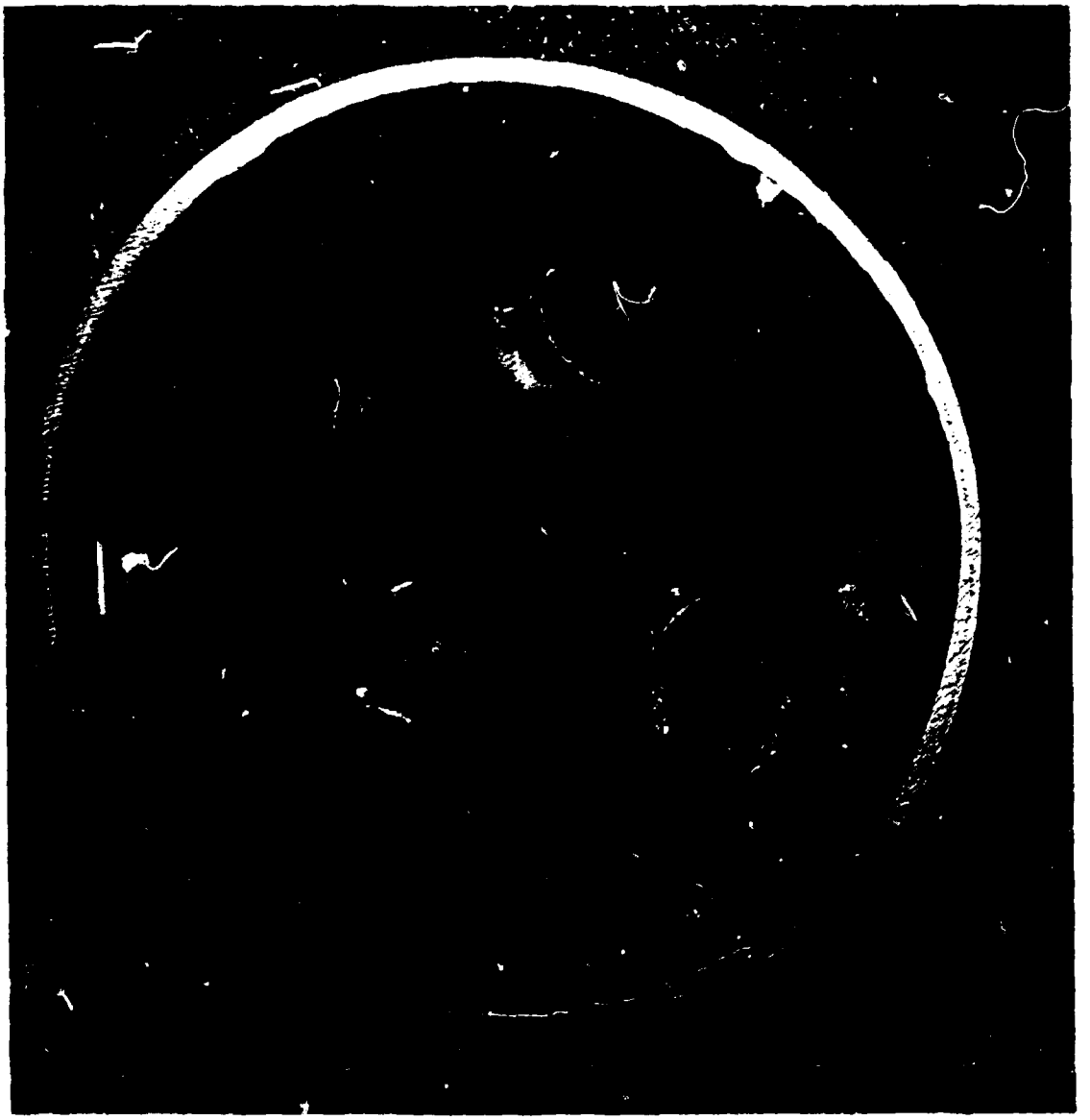

Fig. 12.6. Knockout defueling canister bottom head showing packets of O_2-H_2 recombiner pellets. Screen has been removed from one of the packets.

ORNL PHOTO 7871-85

Fig. 12.7. Longitudinal view of the internal assembly showing that the rods had not been displaced as a result of the drop test.

ORNL PHOTO 7873-85

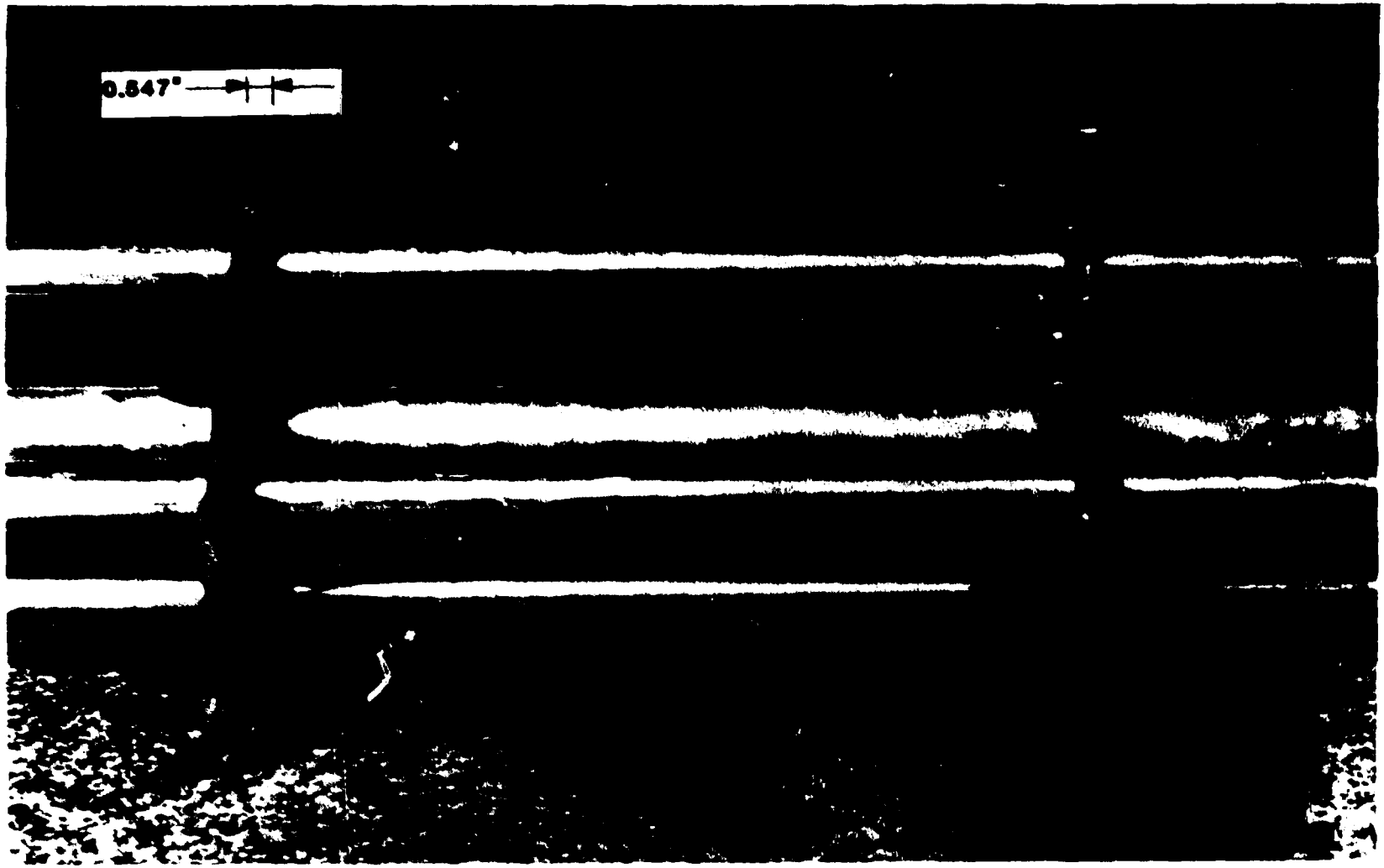

Fig. 12.8. Internal support spider showing displacement resulting from the drop tests.

were welded in place to position the inner assembly inside the top of the canister shell (Fig. 12.9).

12.2 METROLOGY OF INTERNAL ASSEMBLY

Measurements of the internal assembly were made in a manner identical to that used for measurements taken before the canister was assembled. A comparison of these two sets of measurements indicated that the maximum permanent deflection in any part of the internal assembly amounted to <14 mm (<0.5 in.); this was in the support spiders. The poison rods were deflected an average of ~0.5 mm (~0.02 in.) along their length, and the maximum deflection at any one spot was 3.0 mm (0.13 in.) (Fig. 12.10). The strong-back tube in the center of the assembly was deformed <0.5 mm (<0.02 in.) at one point but averaged <0.005 mm (<0.002 in.) deformation along the length of the rod.

The poison rods were removed from the spiders, and measurements of their straightness were made. The average deviation from a theoretical centerline was <1.0 mm (<0.04 in.), and the maximum at one spot was 3.7 mm (0.15 in.). The dimensions measured when the rods were out of the assembly are slightly larger than those measured while the rods were still encased in the spiders; this indicates that the spiders were exerting very little pressure on the rods to keep them straight.

12.3 X-RAY INSPECTION OF THE POISON RODS

The poison rods were radiographed along their length to determine whether the pellets had sustained any damage as a result of the drop tests. An examination of the exposed film revealed that several of the

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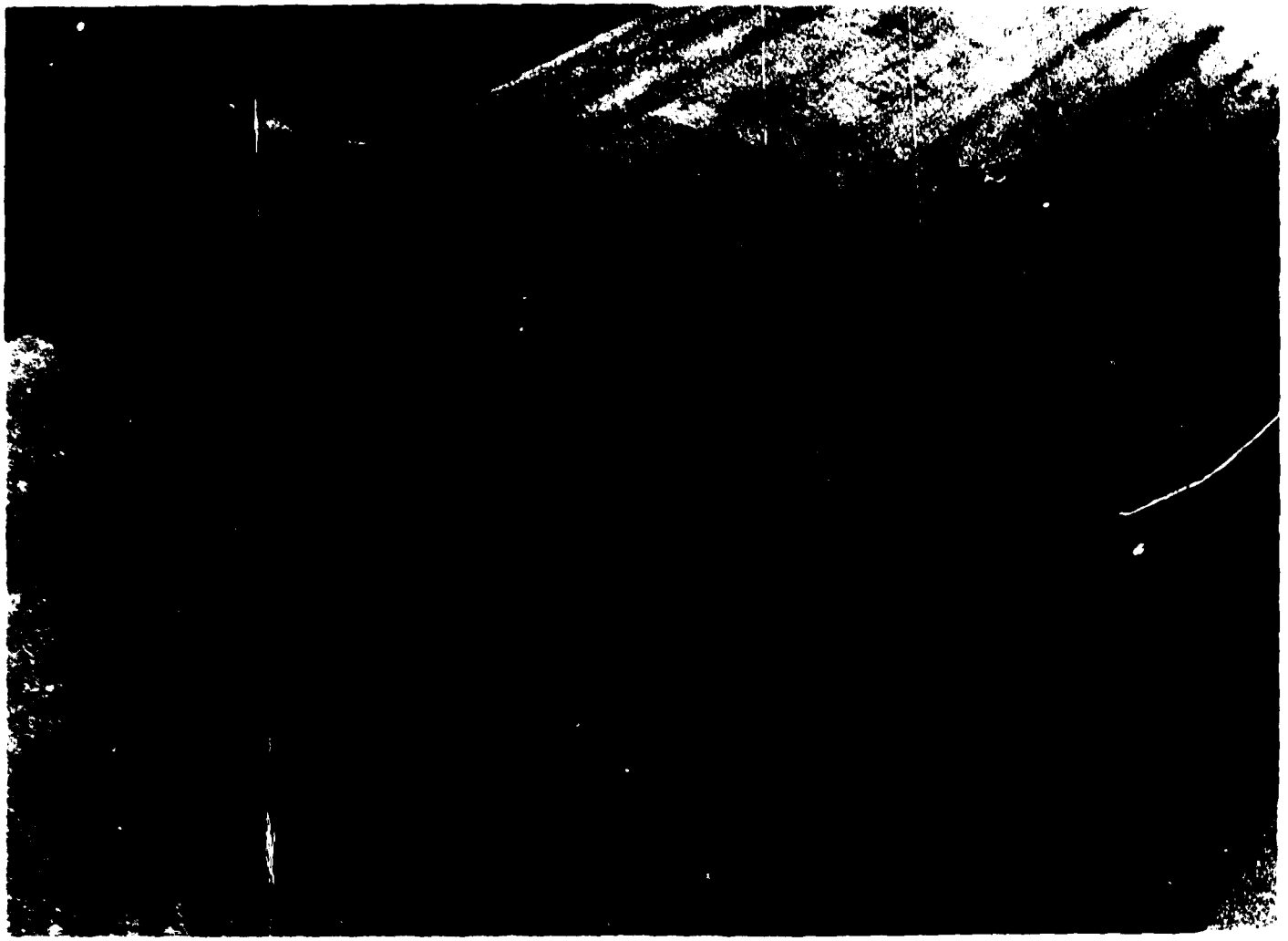

Fig. 12.9. Deformation in the wedges that hold the inner assembly in position resulting from the drop tests.

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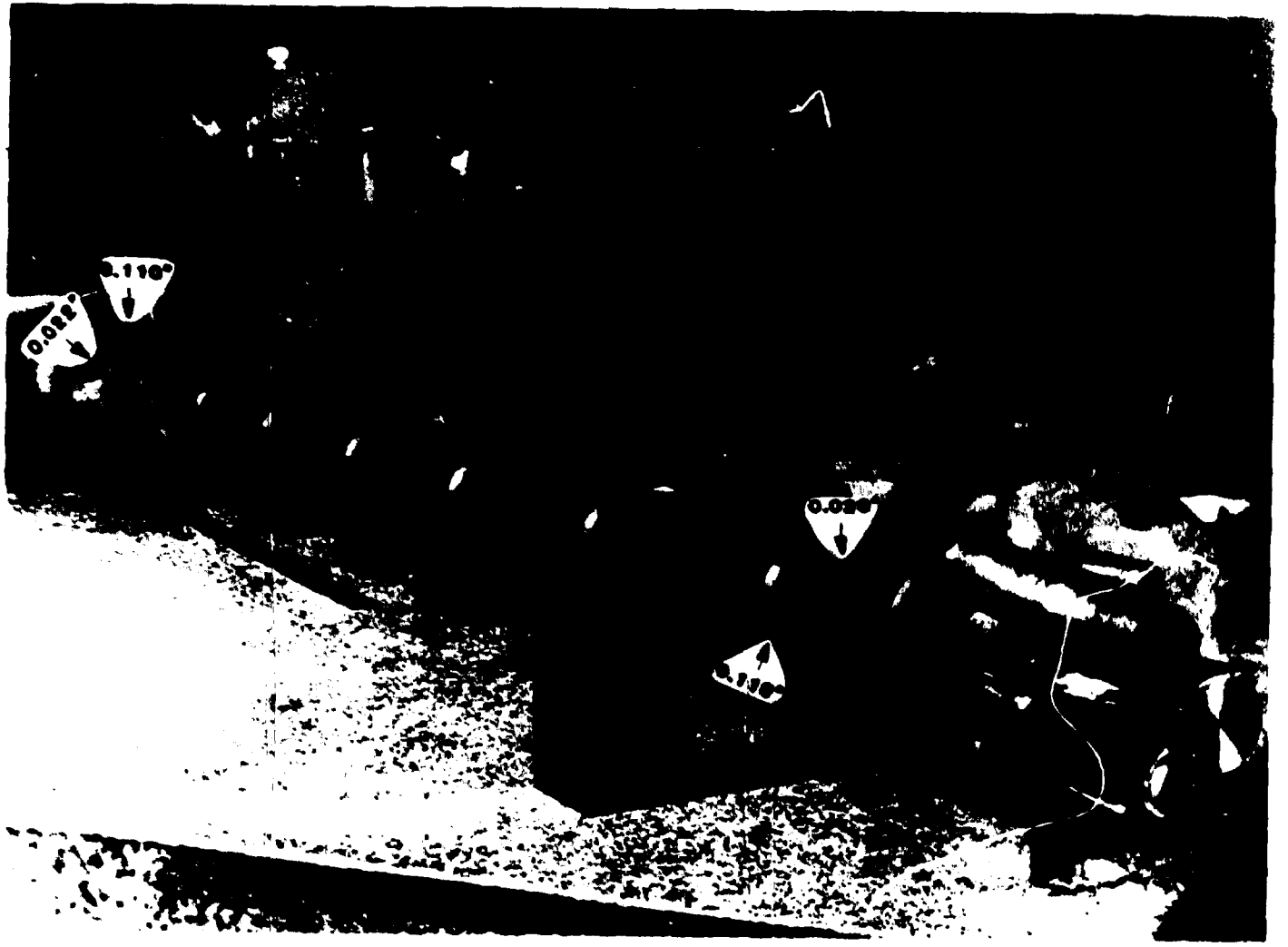

Fig. 12.10. Inner assembly with typical displacement of the poison rods marked on the photograph.

pellets in tube B had cracked, causing the stack within the tube to be ~10 mm (~0.45 in.) shorter than its original length (Fig. 12.11). The broken pellets generally remained in pieces, thus contributing to the overall criticality control. The pellets in the remaining tubes were still in pristine condition, with no void space in the end when the tube was placed upright.

13. SUMMARY OF DROP TEST RESULTS

13.1 VERTICAL BOTTOM DROP TEST (TEST 1)

An accelerometer mounted on the canister measured a maximum vertical acceleration of 981 m/s^2 (100 g). This is well above the 392-m/s^2 (40-g) magnitude observed in the reference cask quarter-scale tests. Test parameters and impact loads recorded in the tests are shown in Tables 13.1 and 13.2.

After the drop, no leakage was detected around the Thaxton plugs, inlet/outlet couplers, or the other quick-disconnect fittings. A pressure check indicated an internal pressure of 110 kPa, gauge (16 psig). This slight increase over the pretest value resulted because of an increased temperature inside the canister. Although one of the caps on the quick-disconnect fittings came off, the pressure boundary was maintained. These caps function only as backup seals.

X-ray techniques were used to nondestructively examine the canister internals. The only measurable deformation from the drop was a dome-like area on the reduced thickness region of the retention plate under the center poison rod. That condition would permit a maximum axial movement of the center poison tube of 0.48 cm (0.187 in.) and was judged

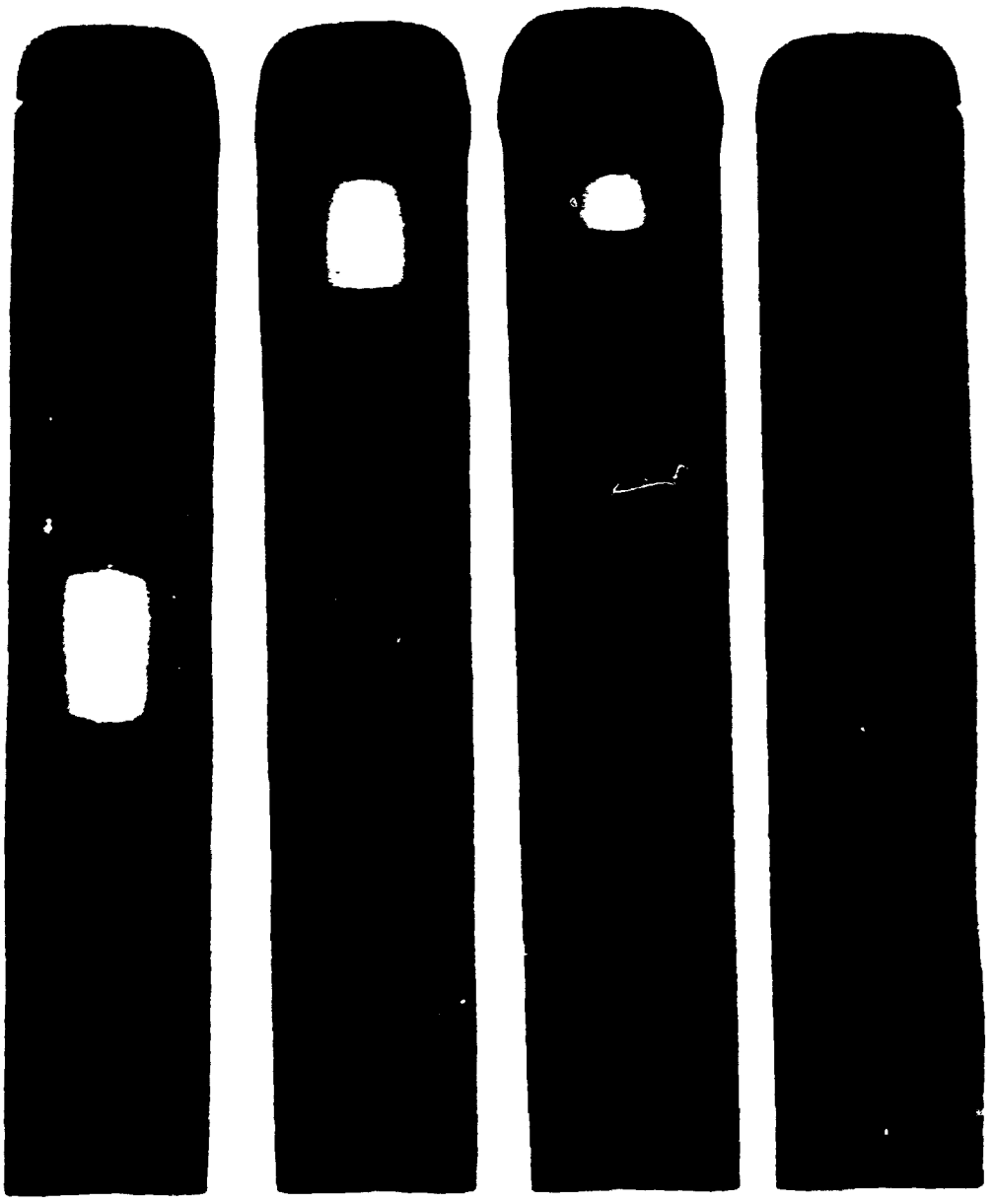

Fig. 12.11. X-ray photograph of the absorber rods after the drop tests. The dark spaces are vacancies resulting from cracked pellets.

Table 13.1. Parameters for drop tests on knockout defueling canister

Test No.	Configuration		Test parameter		Reference cask measurement[a] (m/s^2)
	Canister orientation	Frozen debris	Drop height	Target load (m/s^2)	
1	Impact on bottom	Yes	9 m	588–785	392
2	Side impact	Yes	9 m	785–1177	588
3	Impact on top	No	9 m	588–785	392
4	Side impact/torque	Yes	9 m	785–1170	60

[a]Reference cask impact (m/s^2) loads from measurements made during quarter-scale drop test of shipping cask.

Table 13.2. Impact loads recorded in drop tests on knockout defueling canister

Test No.	Canister orientation	Cask reference[a] (m/s^2)	Minimum test target load (m/s^2)	Test results (m/s^2)
1	Impact on bottom	392	588	980
2	Side impact	588	785	1177–1569
3	Impact on top	588	588	883
4	Side impact/torque	588	785	775[b]

[a]Reference cask impact (m/s^2) loads from measurements made during quarter-scale drop test of shipping cask.

[b]An average value of 618 m/s^2 at one end of the CSV and 922 m/s^2 at the other end. A secondary impact in Test 4 put a side load of at least 4904 m/s^2 on the canister, although the position of the debris put little of the load on the internals.

insignificant with respect to the criticality analysis. No structural defects were observed during the final post-test examination. No debris had migrated into the sump region below the lower support plate.

13.2 SIDE IMPACT (TEST 2)

In the second test, the canister (in its CSV) was oriented in a horizontal position for the drop. The fuel-simulant debris was located on the row of support plate legs opposite those used in the first test (Fig. 6.1, Configuration B).

As in the preparation for the first test, the canister was placed horizontally and chilled to approximately -14°C (6°F). Note that, during freezing, the canister had been rotated 180° so that the debris was attached to Tube C. After removal from the refrigerated truck, the internal pressure of the canister was checked at 110 kPa, gauge (16 psig). The canister was placed in the CSV with the mass in the upper half, and wooden wedges were used to maintain this orientation with respect to the CSV. Accelerometers were attached to both ends of the canister. The test package was then raised to a height of 9 m (30 ft), released, and allowed to free fall onto the impact pad.

A maximum acceleration of 1569 m/s^2 (160 g) (on the canister top head) and 1177 m/s^2 (120 g) (on the canister bottom end) were measured during the impact. These values are well above the 588 m/s^2 (60 g) measured in the shipping cask tests. Visual examination found that the bottom end of the test package impacted ~0.03 s before the top end, which accounts for the differing accelerometer readings.

No leakage was detected. After the drop, the pressure check showed no change from the pretest value of 110 kPa, gauge (16 psig).

X-ray examination of the canister internals indicated that only a minor deformation of one of the small poison rods had occurred during this drop test. In the top span (and above the upper support plate), rod C had been displaced laterally by ~3 mm (~0.13 in.). In all other spans, the rod remained in its initial condition. All other rods or support plates were undamaged. The simulated fuel debris remained in the prescribed area and had not migrated into the region above the upper support plate or below the lower support plate.

Some minor shifting of the as-built gap between the poison pellets was noted. A 6.0-mm (0.25-in.) maximum cumulative void was permitted by design in the pellet stack for considerations during loading of the pellets. This small shifting of the gap (or pellets) is not significant with respect to the criticality analysis.

13.3 VERTICAL TOP HEAD DROP TEST (TEST 3)

The third test in the series was a vertical drop with the impact on the top head of the canister. Since the debris was not frozen as in the previous test, it quickly filled the lower region of the inverted canister. Minor modification to the upper support plate (Sect. 8) prevented all but a small amount of debris from entering the plenum region between the upper support plate and the upper head. This was later verified by the post-drop X rays.

Ambient temperature during the test was approximately 16°C (60°F) at the test site. After the canister was pressurized to 103 kPa, gauge

(15 psig), it was loaded into the CSV for the vertical drop. Raised to a height of 9 m (30 ft), the canister/CSV assembly was released and allowed to free fall onto the impact pad. A tether system of cables prevented a canister slap-down after the vertical impact.

Accelerometers mounted to the top of the canister measured a maximum impact loading of 883 m/s^2 (90 g) during the test. This is well above the 392 m/s^2 (40 g) experienced in the shipping cask testing.

As in the previous drop tests, no leakage of the simulated fuel mixture from the canister had occurred. The post-drop pressure check indicated a minor reduction in the internal pressure to 102 kPa, gauge (14.75 psig), compared to the initial value of 103 kPa, gauge (15 psig); however, the pressure difference was within the accuracy of temperature and/or instrument measurements. To illustrate the tightness of the canister, a second pressure check made later also read 102 kPa, gauge (14.75 psig), thus verifying its stability over time. One of the Hansen caps had come off of a quick-disconnect fitting; but, as discussed in relation to the results of the first drop, this had no effect on the primary seals of the canister.

X-ray examination of the canister indicated that some bending of the two upper support plates had occurred. (Post-test measurements showed a maximum axial movement of 15 mm (<0.6 in.) at the outer extremity of the spider). No deformation of the poison tubes due to this test was observed. The X rays also revealed that several poison pellets had suffered minor cracking. No deformations were noted that would approach those assumed for the criticality analyses.

13.4 SIDE IMPACT/TORQUE (TEST 4)

To evaluate the effect of a possible torsional moment developing from an offset center of gravity of the fuel debris, a fourth drop test was performed. This test was almost identical to the second test, except that the frozen fuel debris was rotated 90°, rather than 180°, from vertical. With this configuration, the inertia of the debris would cause rotation of the debris around the center strong-back tube.

Placed in a horizontal position, the canister was chilled to well below freezing. The debris/water mixture completely encased the "A" tube while only partially enveloping the "B" tube, as shown in Fig. 6.1, Configuration D. At the time of the drop, the internal canister pressure was 107 kPa, gauge (15.5 psig).

The canister was positioned within the CSV with the debris mass offset to the side. Wooden wedges were used to maintain this orientation during the drop. Considerable difficulty was encountered in trying to keep the canister from rotating within the CSV before the wedges could be installed. (This indicates that, under actual shipping conditions, a torsional load would cause the canister to rotate within the cask, rather than stressing the internals as was done in the test). Accelerometers were attached to the top and bottom heads. At the time of the drop, the canister temperature was -2°C (29°F). The canister/CSV was raised to a height of 9 m (30 ft), released, and allowed to free fall onto the impact pad.

Because the simulated fuel mass in the canister was rotated in the CSV, the center of gravity did not coincide with the geometric center of the test piece. Hence, the test piece did not hang in a strictly

vertical attitude. As it fell, it rotated slightly and impacted at an angle of ~22° from vertical. The energy absorbers were only partially effective, crushing slightly before shearing the foam blocks at a 45° angle. With only part of the impact energy dissipated, the top-heavy CSV rotated ~90° and struck the armor plate surface of the impact pad.

The accelerometer on the canister bottom indicated an initial vertical impact loading of 618 m/s^2 (63 g), while the canister top accelerometer indicated a vertical impact loading of 922 m/s^2 (94 g). During the second impact, as the CSV hit the armor plate, the accelerometers measured estimated loads of over 4903 m/s^2 (500 g). This second load was sustained over a 0.1-s time period. The canister pressure had increased to 114 kPa, gauge (16.5 psig), when measured after the drop, and no leakage was observed.

13.5 POST-TEST EXAMINATION

After Test 4, the canister was transported to the machine shop, where the top and bottom heads were removed. A third cut, just above the bottom support plate, was made which allowed the internals to be taken out of the canister shell (Figs. 12.4 and 12.8). The separation of the internals and the outer shell was easily accomplished. No binding occurred as the internals were withdrawn, even though two of the support webs had minor deformations that resulted from the third drop.

A visual inspection of the major subassemblies was conducted. The four recombiners that were welded to the inside of the bottom head were intact. No visible damage to the screen and recombiners located in the top head (Fig. 12.4) and bottom head (Fig. 12.2) was evident. All poison tubes appeared to be straight. All welds were undamaged, as

shown in Figs. 12.4 and 12.8, although minor bending of two support plates was observed. No fuel debris had migrated to the region below the lower support plate. Figure 13.1 shows the top of the lower support plate, including the filter screen and its welds. The lower support welds were found to be sound (see Fig. 12.3). Post-drop measurements were made by the Metrology Department at ORNL. A summary of the dimensional results is presented in Tables 13.3 and 13.4. Table 13.3 lists the measured positions of the poison rods and the allowable limits, and Table 13.4 lists the dimensions of the support plates before and after the drop tests and gives the changes in these measurements.

In general, very little deformation of the internals occurred. Only a minor displacement near the end of two of the four outer poison tubes (maximum displacement of 4.6 mm (0.182 in.) was noted. This was a local condition affecting only one span between support plates. Two support plates exhibited some out-of-plane bending. This occurred during Test 3, vertical impact on top head, due to the shifting of the simulated fuel debris. The two worst-case plate legs had been bent 14 and 7.5 mm (0.547 and 0.297 in.) from their initial condition, but this did not affect the positioning of the four outer tubes. The localized dome-like deformation of the retention plate was determined to protrude 10 mm (0.4 in.) above the plane of the plate. Deformation of the tip of the chock block that had been encased in the frozen debris for Test 4 indicated that a significant torsional load was present.

Pressure measurements taken before and after each drop test revealed that the canister remained leak-tight throughout the entire test series. The slight pressure rise was the result of an increase in

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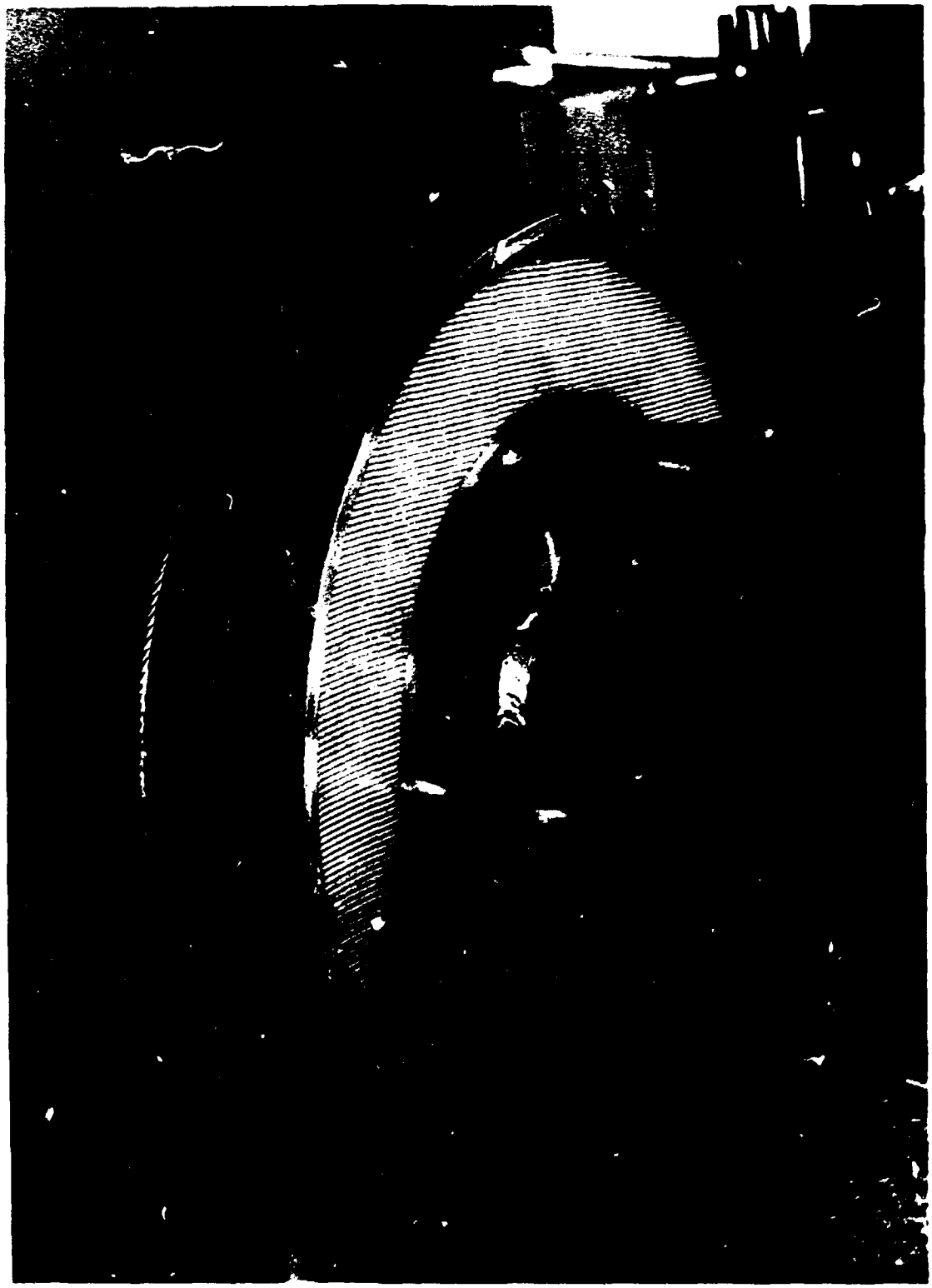

Fig. 13.1. Top surface of the lower support plate of the knockout defueling canister after drop testing.

Table 13.3. Poison rod deviations from vertical after drop tests

Poison rod	Measured deviation[a] (mm) x axis	y axis	Projected[b] maximum displacement (mm)	Calculated maximum allowable displacement[c] (mm)
Outer tube A	0.177	0.38	5.82	19–25.4
Outer tube B	3.66	1.35	9.27	19–25.4
Outer tube C	0.86	0.41	6.35	19–25.4
Outer tube D	0.56	4.60	10.01	19–25.4
Center tube	0.33	0.13	6.22	19–25.4

[a]Centerline displacement values from original measurements at mid-span between support plates and at tip.

[b]This projection is based on the sum of the maximum possible movement of the rods within the support spiders and the maximum deformation resulting from the drop tests.

[c]Calculated maximum allowable tube displacements used in the criticality analysis varied from 19 to 25.4 mm along the canister length.

Table 13.4. Measurements of support plate deformation after drop tests

Support plate	Distance from the bottom plate[a] Before test (cm)	After test (cm)	Change[b] (mm)
U	39.77	39.73	0.36
T	79.93	79.89	0.41
S	119.62	119.58	0.41
R	159.58	159.58	0
Q	199.51	199.63	1.19
P	239.44	240.83	13.83
O	279.52	280.27	7.54
N	320.72	320.99	2.77

[a]Measurements were made from the top of the bottom support plate to the top of the next plate only at position A. Plate deformation was approximately the same in positions B, C, and D (see Fig. 5.1).

[b]Change in location relative to the bottom support plate.

internal temperature while the drop tests were being conducted (Table 13.5).

Table 13.5. Internal pressure changes measured in drop tests on knockout defueling canister

Test No.	Orientation	Pressure measurements[a] Before test (kPa)	Before test (psig)	After test (kPa)	After test (psig)
1	Impact on bottom	103	15	103	15
2	Side impact	103	15	110	16
3	Impact on top	103	15	102	14.75[b]
4	Side impact/torque	107	15.5	114	16.5

[a]Minor pressure variations were caused by changes in canister temperature.

[b]Checked immediately after the test and several hours after the test, with identical results.

14. SUMMARY OF RESULTS

A review of the results from the post-test examination and the observations made after each test in the sequence indicates that no significant deformations occurred in the knockout canisters as a consequence of the drop testing. Including manufacturing tolerances and clearances, the range of possible tube dislocations is well within the range of assumptions used in the criticality analysis.

No fuel debris migrated into the region below the lower support plate as a result of these drop tests, nor were any migration paths opened. This validates the assumptions used in the criticality analysis.

Measurements made on the shell after the drop tests indicated no significant change from the initial condition.

The canister remained pressure-tight after the drop tests, as demonstrated by the pressure checks made before and after the impacts. No fuel debris leakage from the canister was observed. A protective cap was lost from one of the quick-disconnect fittings during the vertical impacts, but this was a secondary seal and its removal did not affect the performance of the canister.

APPENDIX A. TEST CRITERIA AND DATA FOR DROP TESTS ON THE KNOCKOUT DEFUELING CANISTER

Table A-1. Test criteria for TMI-2 knockout canisters

- Maintain a poison tube array within the limits established by the criticality analysis.
  - Maximum lateral displacement of any of the five poison tubes is less than 1.9/2.5 cm (0.75/1.00[a] in.) from its theoretical location.
  - No significant axial movement.
  - No breach of the boundary of the poison tubes.
- Maintain structural integrity of outer shell and internals after shipping accidents.
  - Remains pressure tight.
  - No gross structural deformations that compromise canister integrity.
  - No debris in lower head region.

[a]Displacement limit varies with axial position.

Table A-2. Accelerometer sensitivities and ranges

Test No.	Block	Accelerometer plane	Serial No.	Sensitivity (mV/g)	Accelerometer range (g)
1	A	x	NF83	0.519	±100
Vertical	A	y	NE87V	0.537	±100
(Top up)	Shell	z	NF92	0.503	±100
	B	x	NF98	0.518	±100
	B	y	NE99V	0.517	±100
	B	z	ND72	0.2874	±200
2	A	x	NE99V	0.517	±100
Horizontal	A	y	JF44H	0.2822	±200
(Side D up)	A	z	NF98	0.518	±100
	B	x	NE87V	0.537	±100
	B	y	LP22	0.2322	±200
	B	z	NF83	0.519	±100
3	A	x	NE87V	0.537	±100
Vertical	A	y	NF83	0.519	±100
(Top down)	A	z	LP22	0.2322	±200
	Shell	z	JE144	0.2654	±200
	B	y	NE99V	0.517	±100
	B	z	JF44H	0.2822	±200
4	A	x	NE87V	0.537	±100
Horizontal	A	y	KF88	0.2555	±200
(Side D up,	A	z	NF83	0.519	±100
with torque)	B	x	NE99V	0.517	±100
	B	y	JF44H	0.2822	±200
	B	z	NE92V	0.450	±100

APPENDIX B. ACCELEROMETER TRACINGS OF DROP TESTS

APPENDIX B

DROP	BLOCK	ACCEL.	SER. NO.	SENSITIVITY IN MV/G	RANGE IN G's
NO. 1 VERTICAL TOP UP	"A"	"X"	NF83	0.519	+/- 100
	"A"	"Y"	NE87V	0.537	+/- 100
	SHELL	"Z"	NF92	0.503	+/- 100
	"B"	"X"	NF98	0.518	+/- 100
	"B"	"Y"	NE99V	0.517	+/- 100
	"B"	"Z"	ND72	0.2874	+/- 200
NO. 2 HORIZONTAL SIDE D UP	"A"	"X"	NE99V	0.517	+/- 100
	"A"	"Y"	JF44H	0.2822	+/- 200
	"A"	"Z"	NF98	0.518	+/- 100
	"B"	"X"	NE87V	0.537	+/- 100
	"B"	"Y"	LP22	0.2322	+/- 200
	"B"	"Z"	NF83	0.519	+/- 100
NO. 3 VERTICAL TOP DOWN	"A"	"X"	NE87V	0.537	+/- 100
	"A"	"Y"	NF83	0.519	+/- 100
	"A"	"Z"	LP22	0.2322	+/- 200
	SHELL	"Z"	JE144	0.2654	+/- 200
	"B"	"Y"	NE99V	0.517	+/- 100
	"B"	"Z"	JF44H	0.2822	+/- 200
NO. 4 HORIZONTAL SIDE "D" UP	"A"	"X"	NE87V	0.537	+/- 100
	"A"	"Y"	KF88	0.2555	+/- 200
	"A"	"Z"	NF83	0.519	+/- 100
	"B"	"X"	NE99V	0.517	+/- 100
	"B"	"Y"	JF44H	0.2822	+/- 200
	"B"	"Z"	NE92V	0.450	+/- 100

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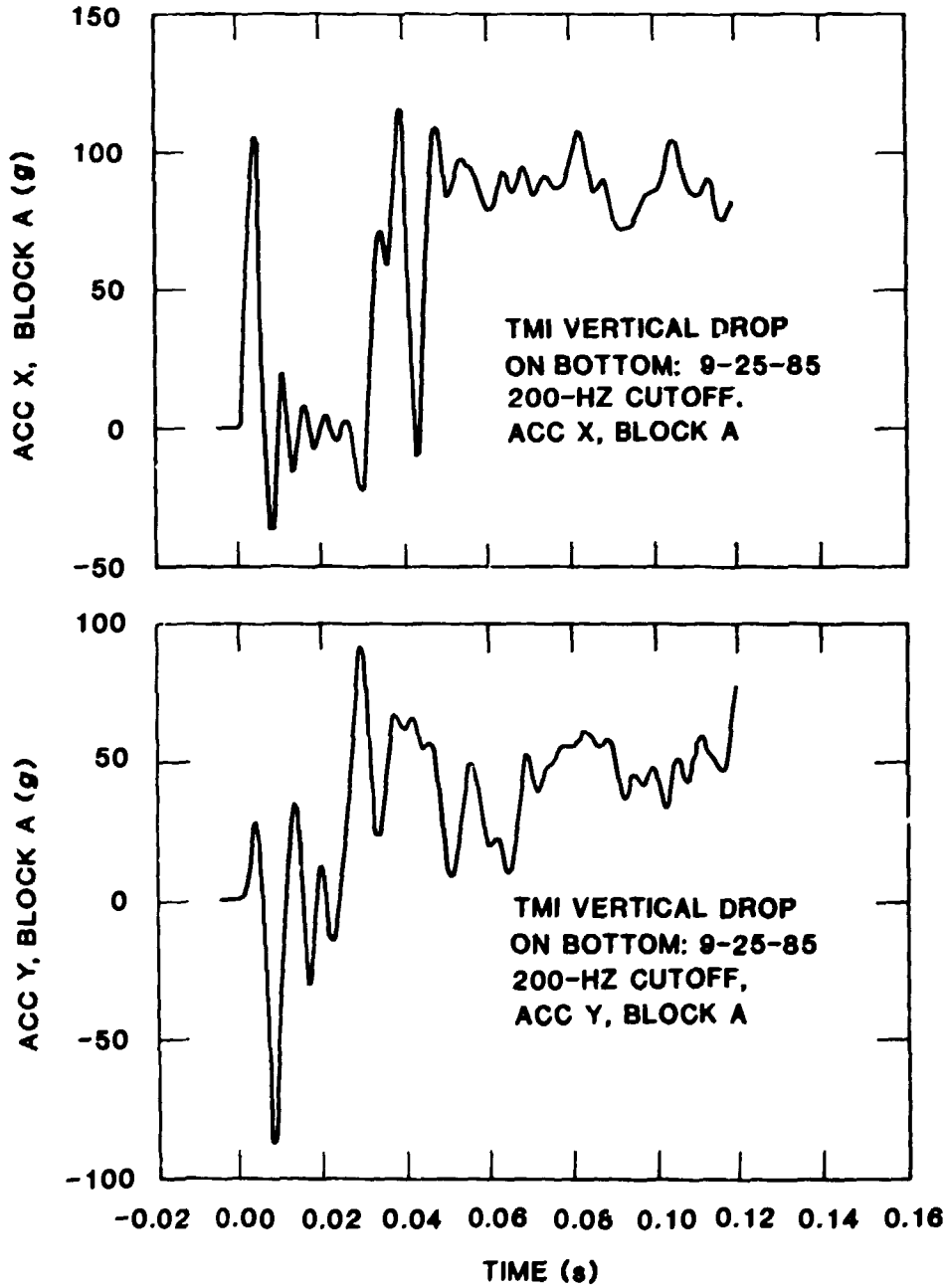

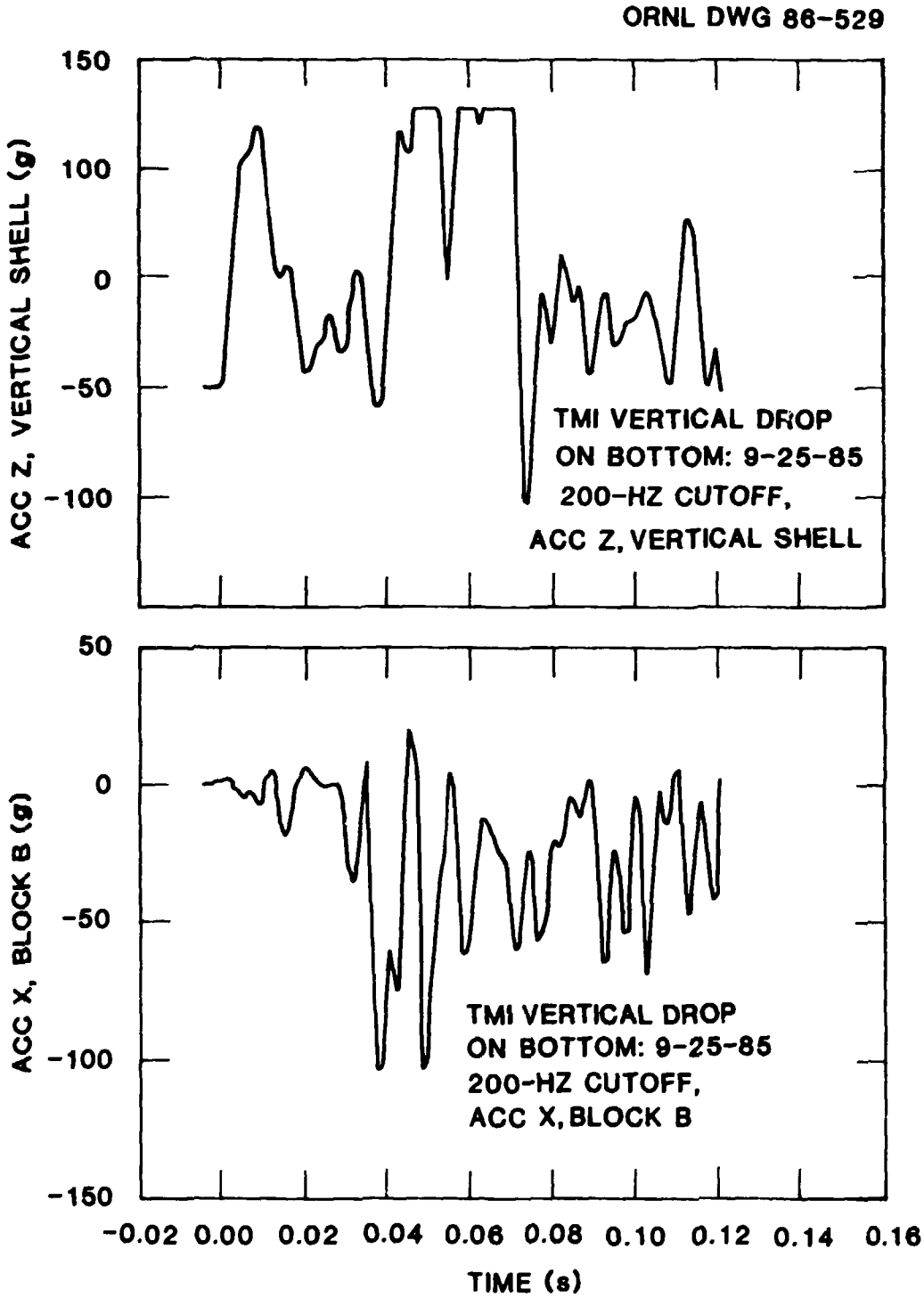
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ACC Z, VERTICAL SHELL
50
0
-50
-100
-150
ACC X, BLOCK B (g)
TMI VERTICAL DROP
ON BOTTOM: 9-25-85
200-HZ CUTOFF,
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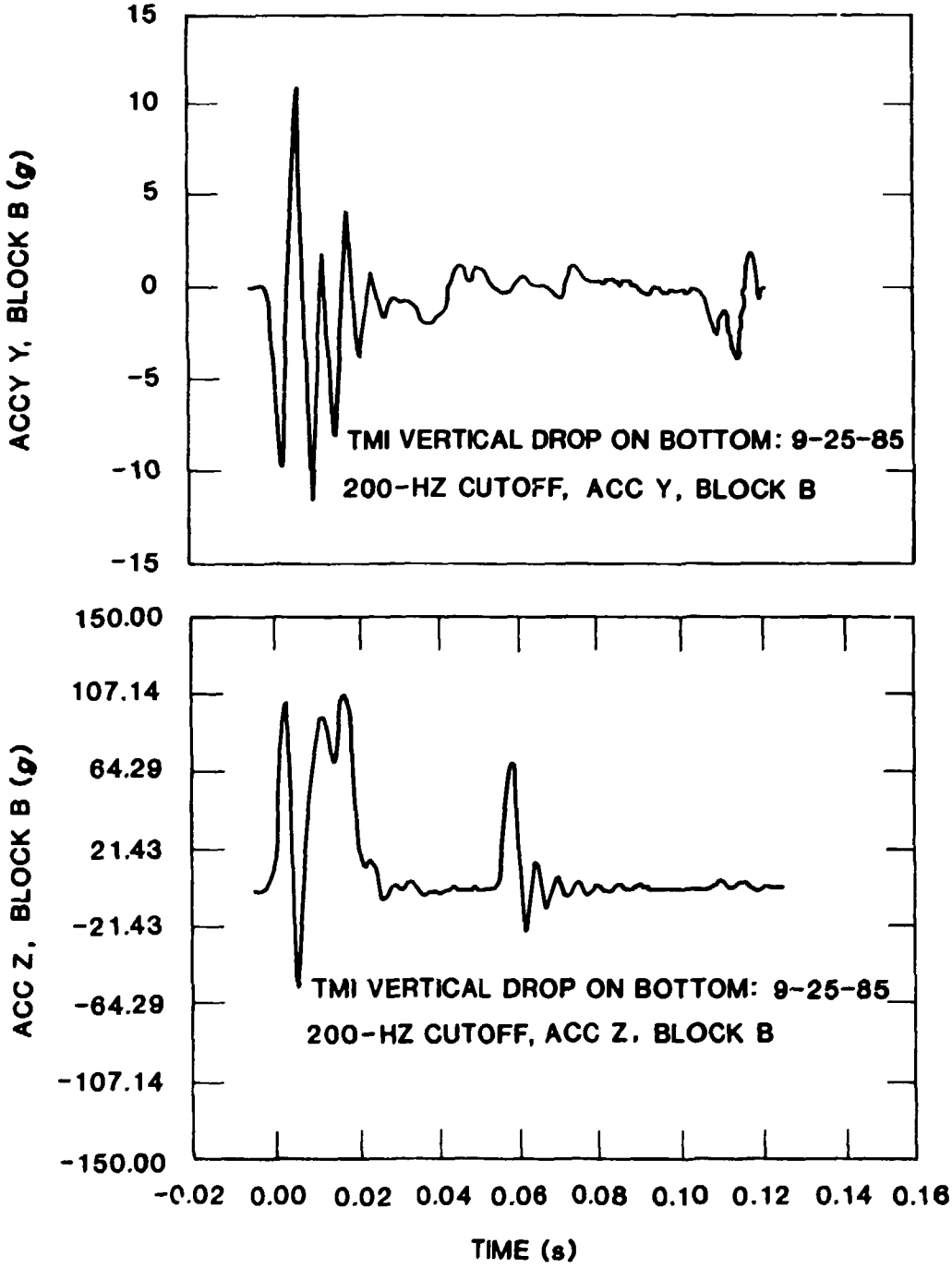

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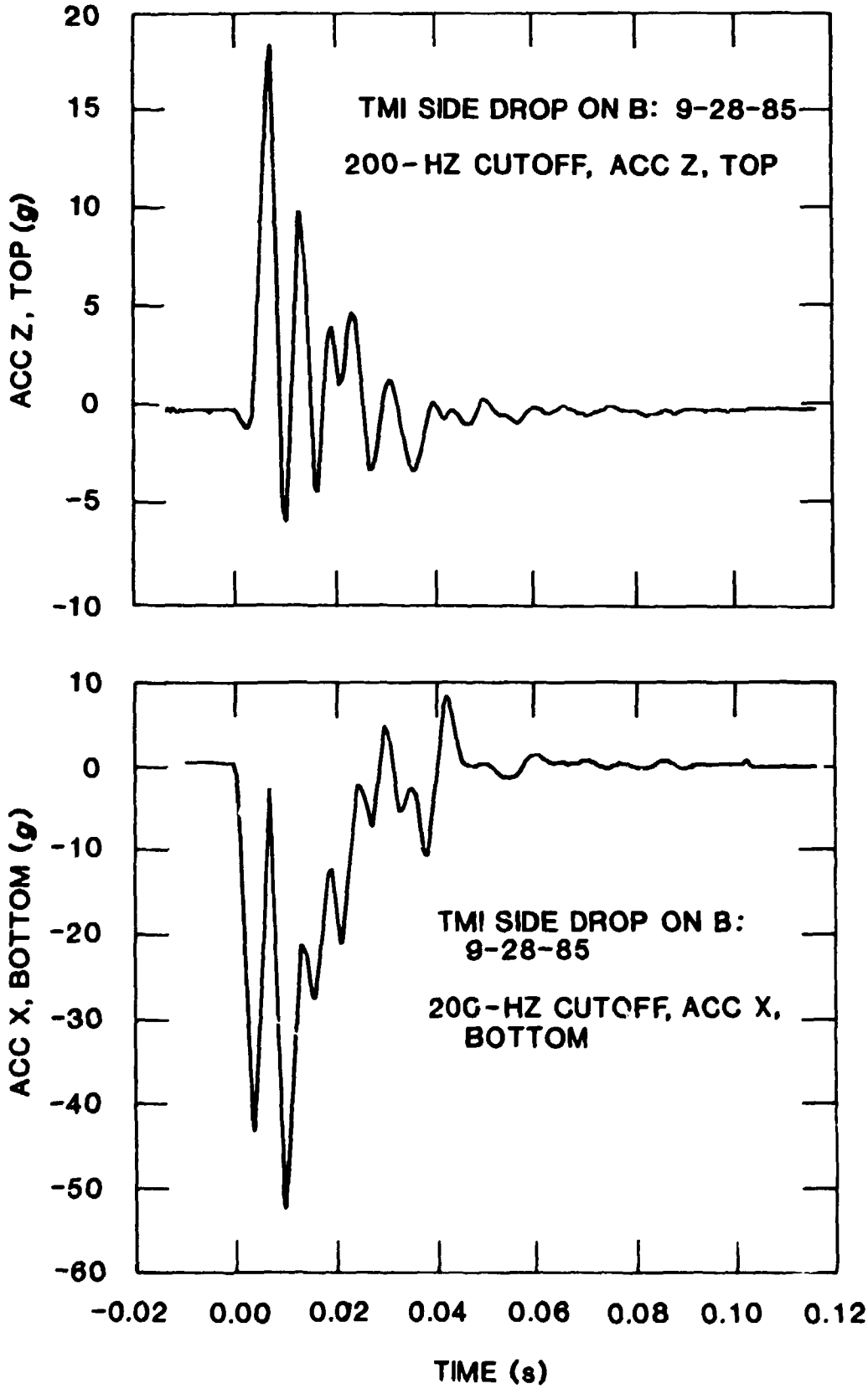

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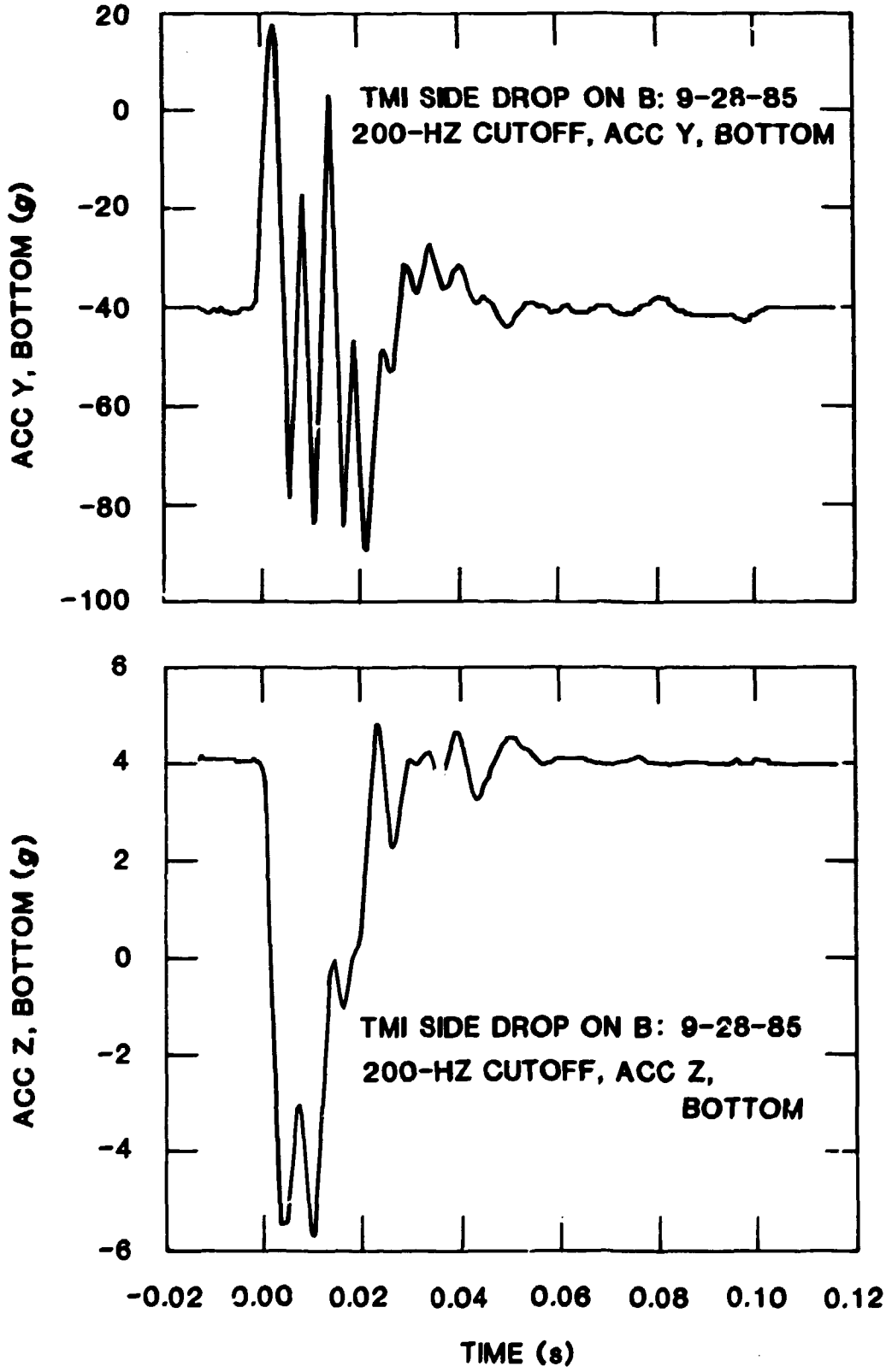

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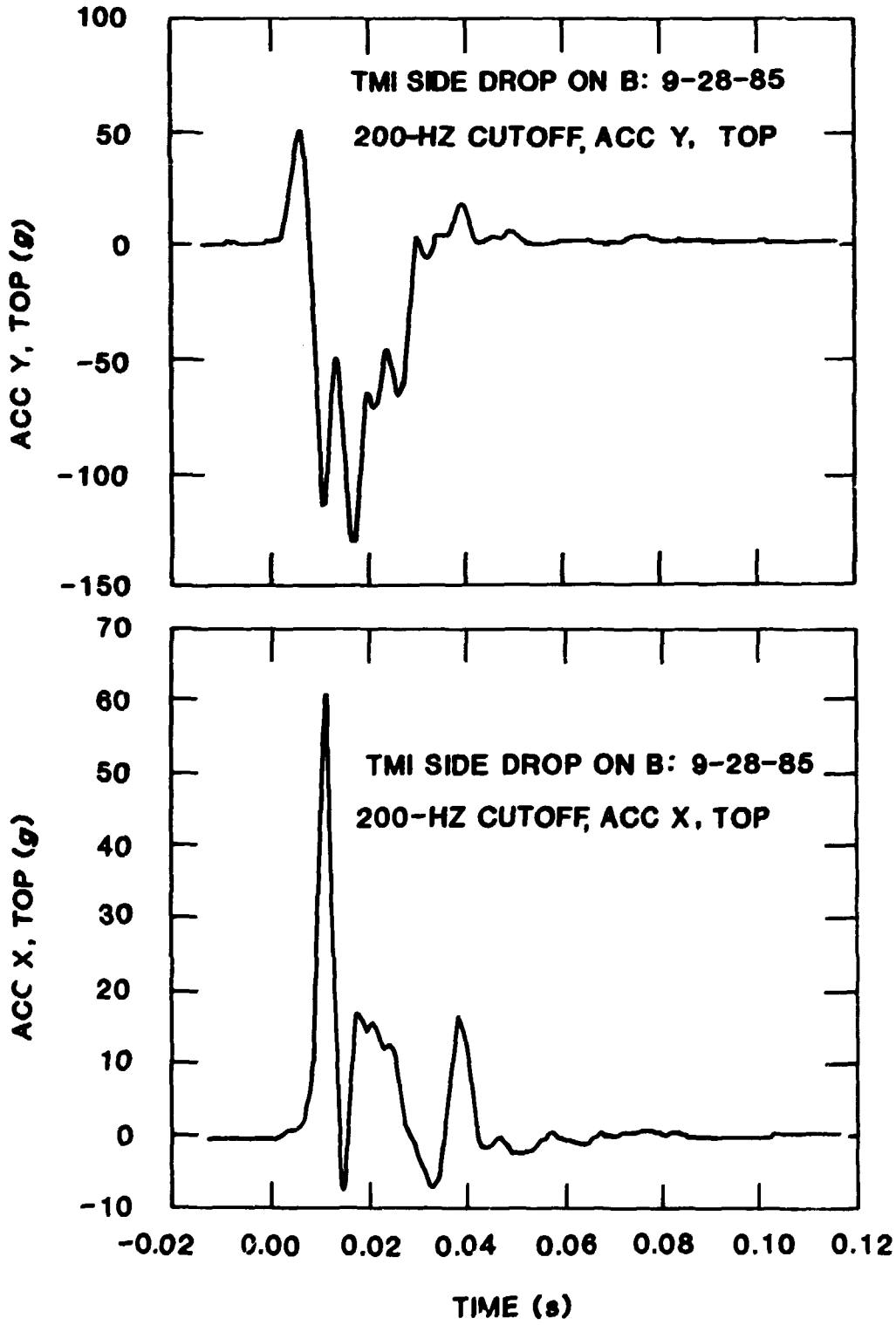

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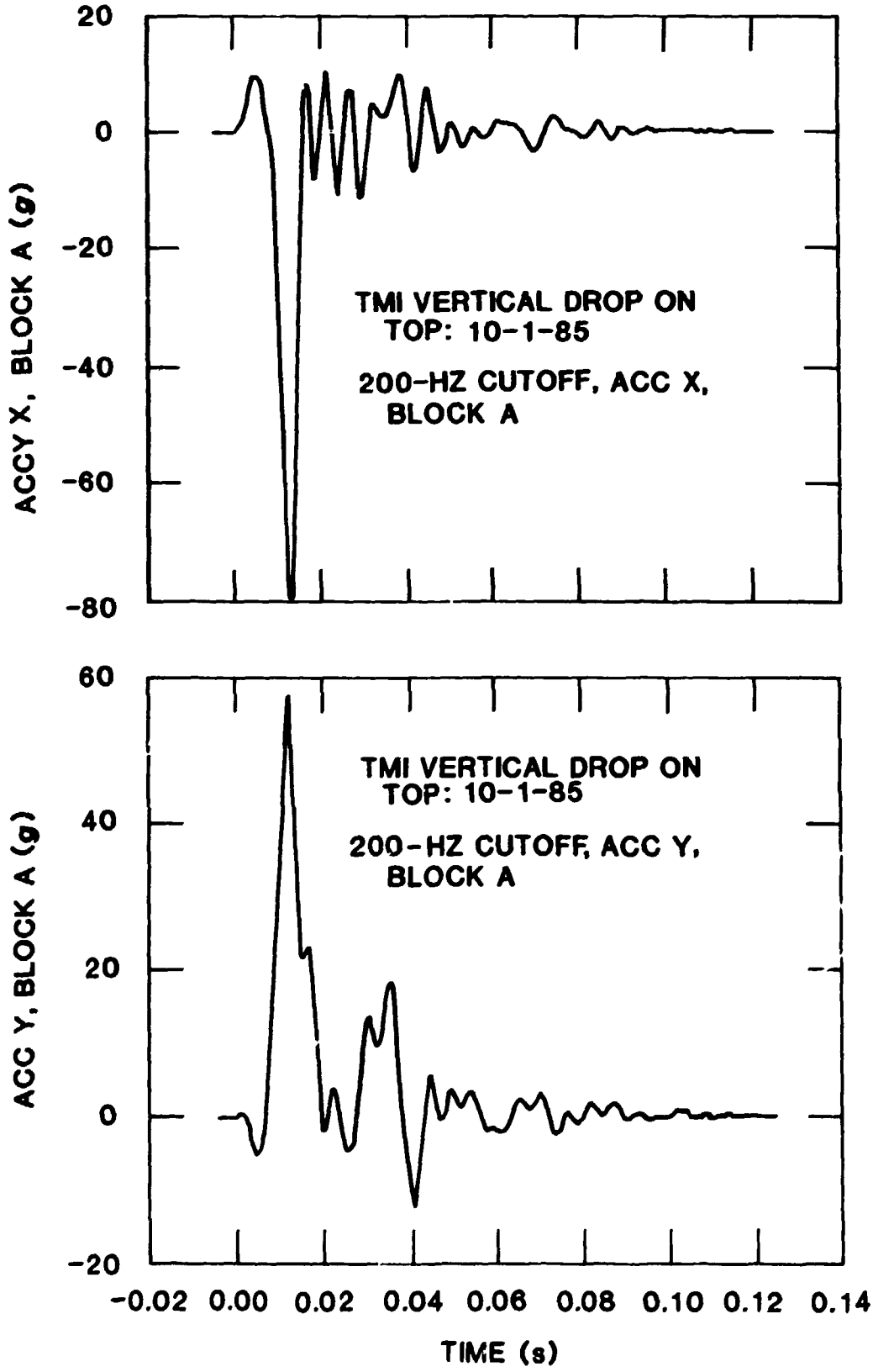

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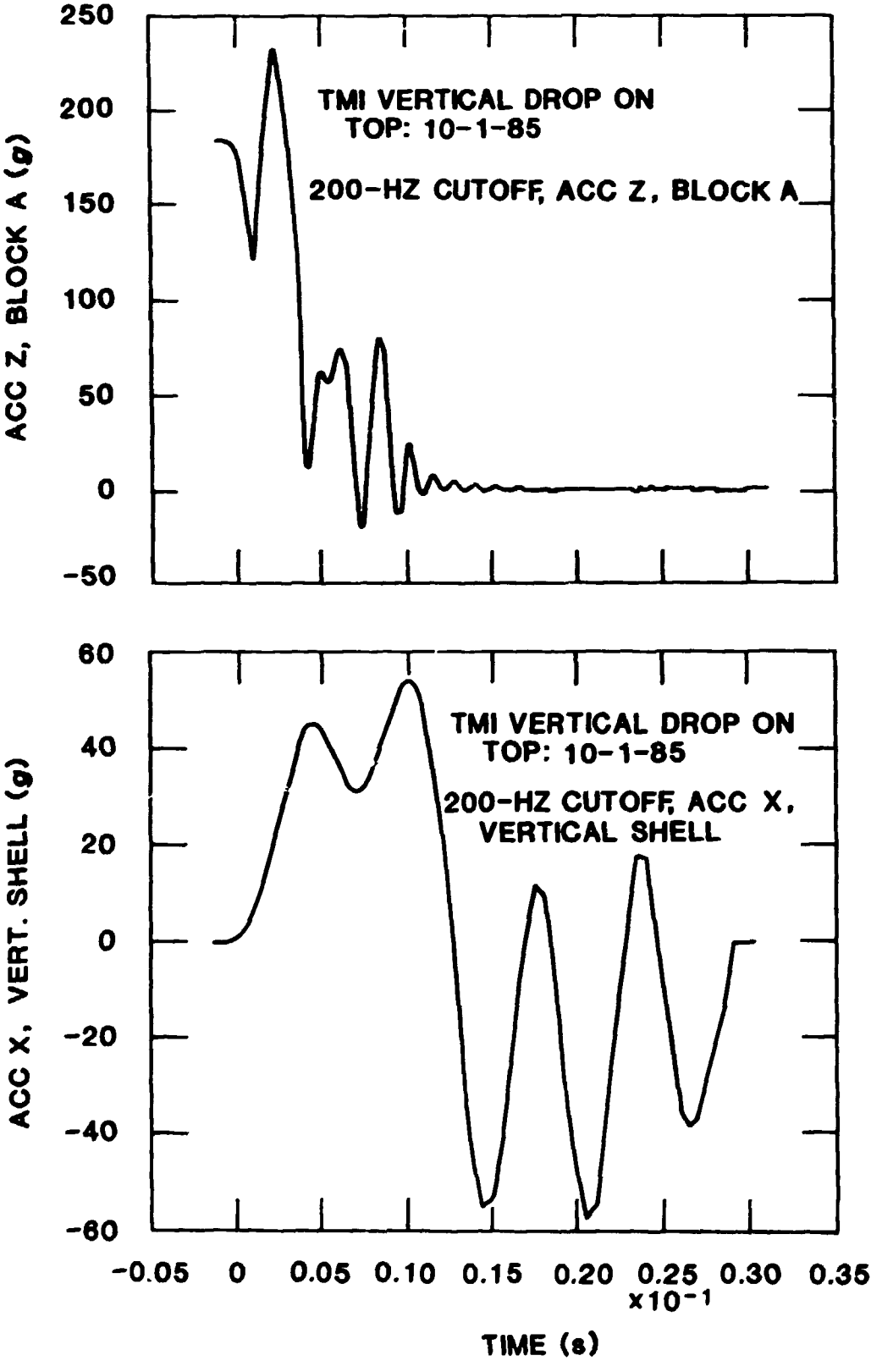

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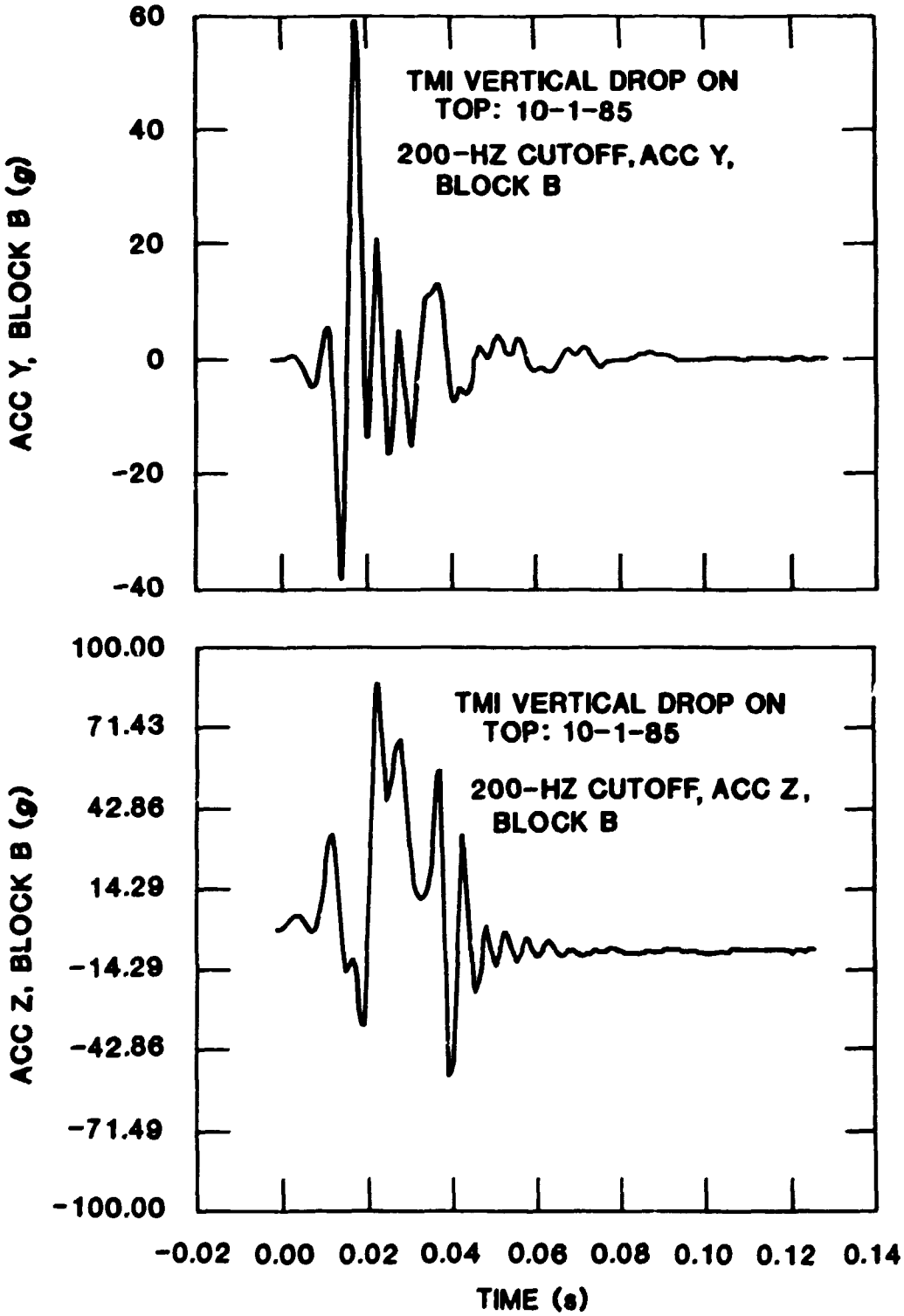

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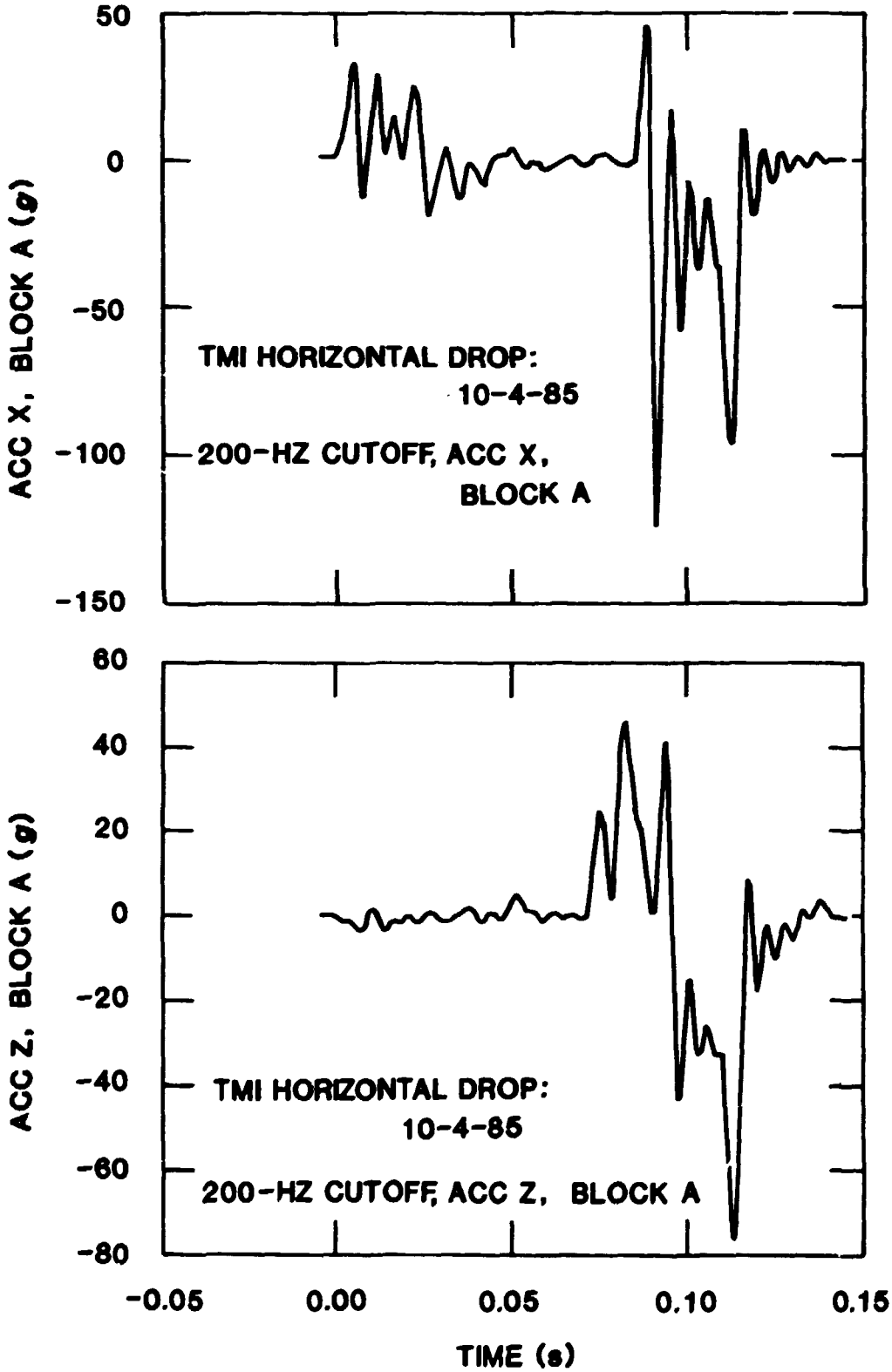

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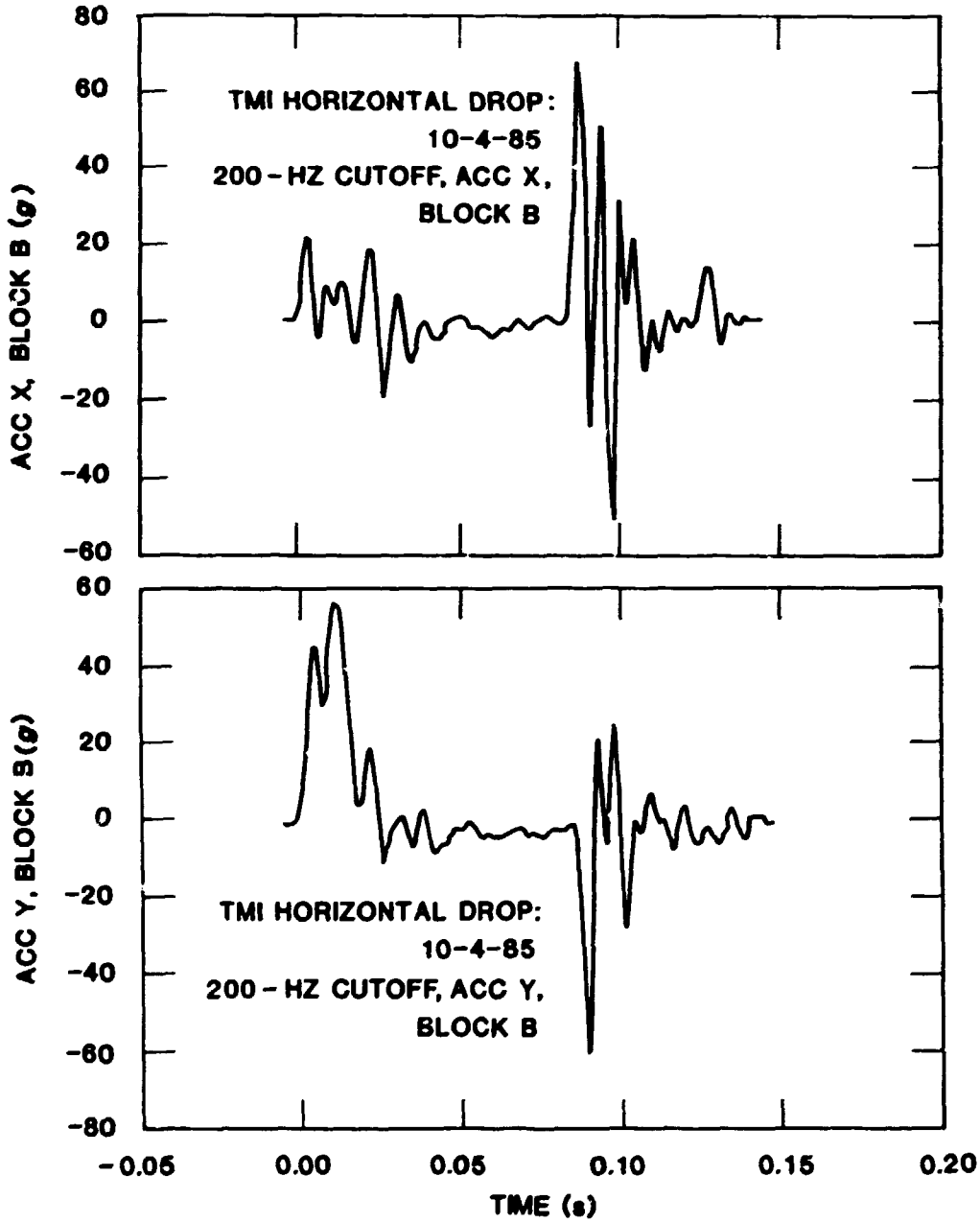

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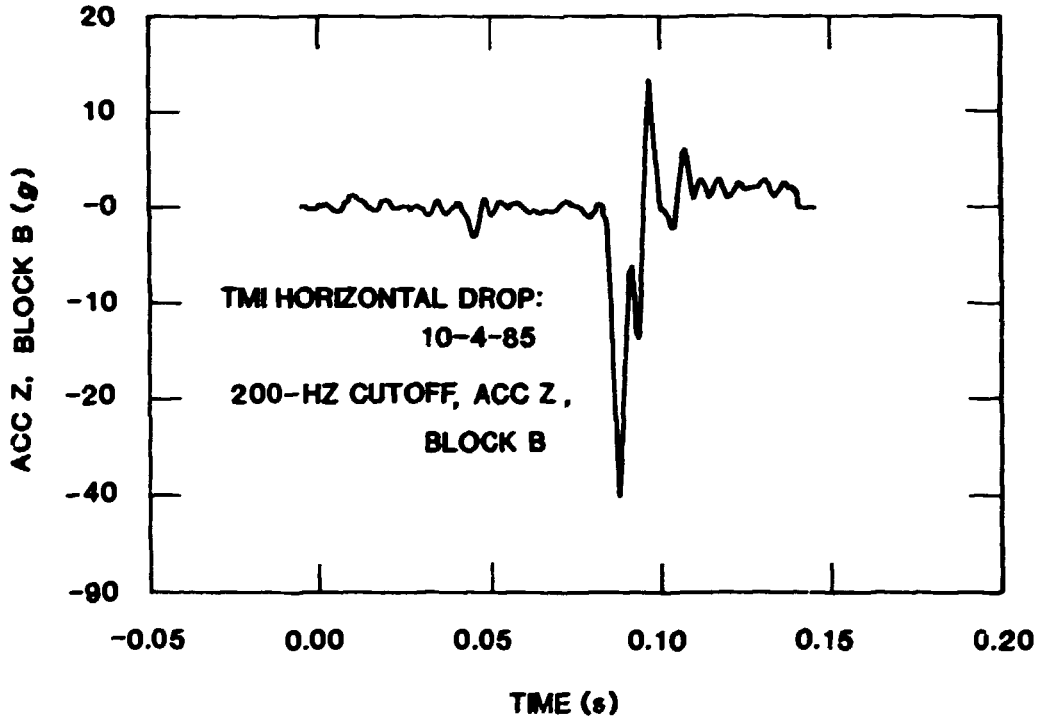

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