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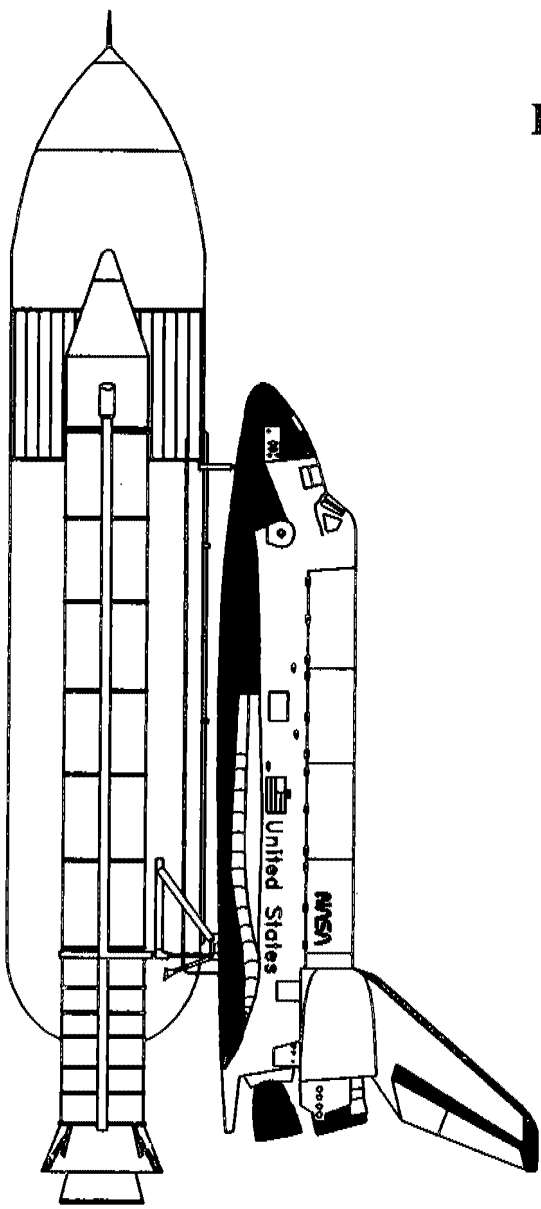
Test Report

Demonstration of Hazardous Hypervelocity Test Capability



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Test Report

Demonstration of Hazardous Hypervelocity Test Capability

Issued By
National Aeronautics and Space Administration
Johnson Space Center
White Sands Test Facility
Laboratories Office

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Abstract

NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) participated in a joint test program with NASA JSC Hypervelocity Impact Research Laboratory (HIRL) to determine if JSC was capable of performing hypervelocity impact tests on hazardous targets. Seven pressurized vessels were evaluated under hypervelocity impact conditions. The vessels were tested with various combinations of liquids and gasses at various pressures. Results from the evaluation showed that vessels containing 100-percent pressurized gas sustained more severe damage and had a higher potential for damaging nearby equipment, than vessels containing 75-percent liquid, 25-percent inert pressurized gas. Two water-filled test vessels, one of which was placed behind an aluminum shield, failed by bulging and splitting open at the impact point; pressure was relieved without the vessel fragmenting or sustaining internal damage. An additional water-filled test vessel, placed a greater distance behind an aluminum shield, sustained damage that resembled a shotgun blast, but did not bulge or split open; again, pressure was relieved without the vessel fragmenting. Two test vessels containing volatile liquids (nitromethane and hydrazine) also failed by bulging and splitting open; neither liquid detonated under hypervelocity test conditions. A test vessel containing nitrogen gas failed by relieving pressure through a circular entry hole; multiple small penetrations opposite the point of entry provided high velocity target debris to surrounding objects. A high-pressure oxygen test vessel fragmented upon impact; the ensuing fire and high velocity fragments caused secondary damage to surrounding objects. The results from the evaluation of the pressurized vessels indicated that JSC is capable of performing hypervelocity impact tests on hazardous targets.

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1.0 Introduction

During the summer of 1988, the NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) participated in a joint test program with the NASA JSC Hypervelocity Impact Research Laboratory (HIRL). The test program was designed to demonstrate JSC's ability to perform hypervelocity impact tests on hazardous targets.

To design spacecraft for the increasingly dangerous micrometeoroid/orbital debris environment, NASA relies on hypervelocity impact testing of components and materials. Testing is generally performed using a two-stage light gas gun. Although three NASA centers operated such devices in the spring of 1988, none had the capability to test toxic materials or potentially hazardous target configurations. Anticipating a need within NASA for a hypervelocity test site for hazardous targets, the manager of the HIRL and the Chief of the WSTF Laboratories Office coordinated a trial test program for hypervelocity impact testing at WSTF.

2.0 Objectives

The primary objective of the test program was to demonstrate JSC's ability to perform hypervelocity impact testing on hazardous targets. Two technical objectives were established for this test program: (1) evaluate damage to pressurized vessels containing combinations of reactive and inert fluids during hypervelocity projectile impact and (2) evaluate damage to beryllium foils as part of a JSC Space and Life Sciences Division cosmic dust evaluation.

3.0 Scope

This report identifies the approach, test articles, test system, and results of the pressure vessel evaluation. Information pertaining to the beryllium-foil tests is not discussed in this document.*

4.0 Approach

4.1 Test Team

The test director was Jeanne Lee Crews, NASA Manager of the HIRL. Project engineers were Joel Stoltzfus (NASA/WSTF) and Harold Beeson (Lockheed Engineering and Sciences Company (LESC/WSTF). All testing was performed by Ken Oser (LESC/JSC), HIRL's lead gun operator, and Danny Fernandez (LESC/WSTF), WSTF test support engineer. HIRL provided the 4.3 mm (0.17 caliber) light gas gun, a gun operator, and hypervelocity test design expertise. WSTF provided a remote test area, gun downrange assembly,

*The beryllium-foil test information can be obtained from Dr. Michael E. Zolensky of the Planetary Science Branch of the Solar System Exploration Division, NASA Johnson Space Center.

evacuation/gas supply system, instrumentation, operational and safety documentation, and hazardous materials handling expertise.

4.2 Test Matrix

Table 1 shows the test matrix used for the hypervelocity impact testing. Identical vessels were chosen for six of seven tests. Various combinations of liquids and gasses were used to test five vessels at pressures of 2.07 MPa (300 psig), one vessel at ambient pressure, and one vessel at 20.7 MPa (3000 psig). Both inert and reactive fluids were evaluated, and two of the test vessels were protected by single-sheet Aluminum shields. A 2017-aluminum projectile, with a 0.318-cm (0.125-in) diameter, was used for all tests. The projectile material and size were held as constant as possible throughout the test program; however, the projectile velocity varied from 6.0 - 6.4 km/s (19,685 - 20,997 ft/s).

4.3 Procedures

Test articles were suspended from two lengths of all-thread rod by stainless steel wire (Figure 1). Each test article was placed 20.96 cm (8.25 in) away from the face plate. The two-stage light gas gun was aimed approximately mid-point of each test article. The light gas gun then launched a saboted aluminum projectile using two propulsion stages. In the first stage, a solenoid-actuated priming mechanism ignited a gunpowder charge. This charge forced a small plastic piston to move along the pump tube. Pressurized "light" gas (hydrogen) was sealed in the pump tube, between the piston at one end and a thin shear plate at the other (Figure 2). As the piston moved, it compressed and funneled the hydrogen (second stage) into the high-pressure coupling, eventually rupturing the shear plate. A projectile, encased in a protective nylon sabot, was located in the mouth of the launch tube, just downstream of the shear plate. When the shear plate ruptured, the high-pressure hydrogen gas drove the projectile through the rifled launch tube and into an evacuated flight range. The hydrogen expansion chamber also housed a sabot catching device, which allowed only the aluminum projectile to continue onto the target chamber.

5.0 Test Articles

5.1 Stainless Steel Vessels

WSTF fabricated six, small, thick-walled pressure vessels for use in this test program. The 304 stainless steel cylinders (Figure 3) were 8.9 cm (3.5 in) × 7.6 cm (3 in. OD), with a 0.89-mm (0.035-in) thick wall. Cylinder bodies were of seamless construction, with 0.64-cm (0.25-in) thick flat plates welded to either end of the shell. A 1/4-in. NPT fitting, welded to the top plate of each cylinder, accommodated an isolation valve. Each 300-ml vessel weighed approximately 627 g. For handling purposes, a 4 to 1 factor of safety was designed into the 2.07 MPa (300 psig) Maximum Allowable Working Pressure (MAWP) vessels.

5.2 Kevlar-Overwrapped Aluminum Vessel

A surplus Portable Oxygen System (POS) bottle was also provided by WSTF for use as a test article. The 1065-ml cylinder (Figure 1) measured approximately 30.5 cm (12 in) × 8.4 cm (3.3 in. OD) and consisted of a 0.15-cm (0.06-in) thick aluminum shell overwrapped with

Table 1
Test Matrix

Test No.[a]	Target Type	WSTF ID No.	Media[b]	Pressure MPa	Pressure (psig)	Shield
HYP-1	300-ml Stainless Steel Cylinder	05	Water/ GN_2	2.07	300	None
HYP-2	300-ml Stainless Steel Cylinder	02	Hydrazine/ GN_2	2.07	300	None
HYP-5	300-ml Stainless Steel Cylinder	06	Gaseous Nitrogen	2.07	300	None
HYP-6	300-ml Stainless Steel Cylinder	04	Water/ GN_2	2.07	300	0.25 cm (0.1 in) 1100 Aluminum at 10.1 cm (4 in) in front of target
HYP-8	300-ml Stainless Steel Cylinder	08	Water/ GN_2	2.07	300	0.25 cm (0.1 in) 1100 Aluminum at 7.6 cm (3 in) in front of target
HYP-9	1065-ml Kevlar-overwrapped Aluminum bottle	N/A[c]	Gaseous Oxygen	20.7	3000	None
HYP-10	300-ml Stainless Steel Cylinder	09	Nitro-methane/ GN_2	0.85	12.3	None

[a]Tests HYP-3, HYP-4, HYP-7, HYP-11, and HYP-12 were performed on beryllium foil
[b]Liquid tests were conducted with 5/6 liquid and 1/6 gas
[c]N/A = Not available

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(As Indicated By Revision Bars)

Kevlar for added strength. A 1/4" NPT fitting at one end of the shell accommodated a 206.9 MPa (30,000 psig) isolation valve. The "zero stress" bottle was designed for a 25.3 MPa (3670 psig) Maximum Operating Pressure (MOP), with a 50.4 MPa (7310 psig) burst pressure.

5.3 Test Fluids

Three liquids (water, nitromethane, and hydrazine) and two gasses (nitrogen and oxygen) were used in this test program. Water, hydrazine, and nitrogen were tested at 2.07 MPa (300 psig), the maximum man-rated handling pressure of the test vessels per WSTF regulations.* Oxygen was tested at 20.7 MPa (3000 psig), also the man-rated handling pressure per WSTF regulations. Nitromethane was tested at 1 atm [0.85 MPa (12.3 psig)] for reasons outlined below. Table 2 compares the properties of the five test fluids.

In the spectrum of reactive liquids, water represented the inert end; nitromethane represented the explosive extreme. In addition to its inherent safety, water was a useful baseline test fluid, because some of its properties closely simulate hydrazine. Logic dictated that nitromethane would be the liquid most likely to detonate if a hypervelocity impact could cause such a reaction (US Army 1978).** Therefore, to minimize hazards associated with a potential nitromethane detonation, the nitromethane was only pressurized to 1 atm (0.85 MPa [12.3 psig]). The detonability of nitromethane or hydrazine under hypervelocity impact conditions was not known prior to this test program. Nitrogen was chosen as the inert gas, because nitrogen has properties similar to the more reactive oxygen.

6.0 Test System

6.1 Test Area

Tests were conducted at the WSTF 270 area, a remote location designed for detonation research and tests involving explosives. The controlled-access test area was equipped with a blast cell and blast mats to isolate the instrumentation shack and control room from the gun and test article (Figure 4).

6.2 HIRL-Provided Hardware

The HIRL 4.3 mm (0.17 caliber) two-stage light gas gun consisted of a rifled launch tube, high-pressure coupling, pump tube, powder breech, and solenoid assembly (Figure 2). The gun was previously in operation at the HIRL where it repeatably launched saboted 1.59-mm (0.06-in) diameter aluminum spheres to velocities of 6.4 $\pm$ 0.2 km/sec (20,997 $\pm$ 656 ft/sec); accuracy was within $\pm$ 3.18 mm ($\pm$ 0.12 in) of the desired impact point.

6.3 WSTF-Provided Hardware

The gun downrange assembly (Figure 5) consisted of a 15.2-cm (6.0-in) diameter length of polyvinyl chloride (PVC) pipe (flight range), flanged to an aluminum expansion tank and a glass bell

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*White Sands Test Facility Instruction (WSTFI) 5.8, May 1990

**"Ignition and Thermal Hazards of Selected Aerospace Fluids," RD-WSTF-0001, NASA White Sands Test Facility, 1988.

Table 2
Comparison of Test Fluids[a]

Fluid	Phase	Molecular Weight	Density kg/m^3	Density slug/ft^3	Melting Point (°C)	Boiling Point (°C)
Water[b] (H_2O)	Liquid	18.016	998	1.937	0.0	100.0
Nitro-methane[c]	Liquid	61.041	1138	2.208	-29.0	101.2
Hydrazine[c] (N_2H_4)	Liquid	32.050	1004	1.948	2.0	113.5
Nitrogen[b] (N_2)	Gas	28.013	1.18	0.0023	-210.01	-195.79
Oxygen[b] (O_2)	Gas	31.999	1.34	0.0026	-218.4	-182.96

[a]Density and melting and boiling points are given at standard atmospheric pressures
[b]Density data from White (1979)
[c]Density data from Windholz (1976)

jar (target chamber). The evacuation/gas supply system consisted of gaseous hydrogen, helium, and nitrogen sources, isolation valves, pressure gages, and a vacuum pump. In addition, WSTF provided all gun mounting hardware.

6.4 Instrumentation

Projectile velocity was measured by using industry standard flash detection units mounted at the gun muzzle and sabot impact plate. Standard (30 fps) and high-speed video (100 fps) and cinema cameras (up to 10,000 fps) were used to monitor target reaction. Figure 4b shows the locations, orientations, and film speeds of the five cameras. All instrumentation and control was provided by WSTF.

7.0 Results and Discussion

Table 3 provides a summary of all test results.

7.1 Hypervelocity Impact Testing Capability

Because the test site was temporary, and therefore not sheltered from the elements, heat and dust caused some technical difficulties. The high ambient temperature caused off-gassing of the PVC flight range, making it difficult to maintain test system vacuum. The dust interfered with the sealing of the test equipment. Despite the difficulties posed by the temporary test site, JSC was able to conduct hypervelocity impact testing on hazardous targets.

7.2 Reaction of Liquid-Filled Vessels

7.2.1 Water Tests

Two of the three water-filled test vessels had the same failure mode: a circular entry hole, a split along the cylinder axis, and an outward bulge from the vessel face. Figure 6 shows front and side views of typical entry damage. Posttest measurements of test article HYP-1 show that the entry area was bulged outward a maximum of 0.86 cm (0.34 in) with a 4.3-cm (1.7-in) long axial split. The circular entry hole appeared to be approximately 0.71-cm (0.28-in) diameter, but was bisected by a maximum of 0.71 cm (0.28 in) by the split. Test article HYP-8, which was placed 7.6 cm (3.0 in) behind a 0.25-cm (0.01-in) thick aluminum shield, bulged only 0.46 cm (0.18 in). A 3.2-cm (1.26-in) long split terminated at the weld heat-affected zone boundary. The circular entry hole was smaller than the circular entry hole for test article HYP-1, measuring only 0.63-cm (0.25-in) diameter and separated by a maximum of 0.38 cm (0.15 in).

Test article HYP-6, placed 10.1 cm (4.0 in) behind a 0.25-cm (0.01-in) thick aluminum shield, displayed a different failure mode: damage to the vessel face resembled a shotgun blast, rather than the bulge and split evident in previous tests. Impacts, including several full penetrations, were concentrated in a circular, blackened area (Figure 7). The internal vessel wall, opposite the entry damage, was scarred with shallow impacts and scratches, but was not penetrated. Test article HYP-6 was not available for posttest measurement.

Table 3
Summary of Test Results (In Order of Testing)

Test No.	Target Media	Target Pressure MPa	Target Pressure psig	Projectile Velocity km/sec	Projectile Velocity ft/sec	Observations
HYP-1	Water/ GN_2	2.07	300	6.1	20,013	Circular penetration to front; bulge/ split face; no damage to back
HYP-6	Water/ GN_2	2.07	300	6.2	20,341	Full penetration of shield; circular penetration/bulge/split; no damage to back
HYP-8	Water/ GN_2	2.07	300	6.1	20,341	Full penetration of shield; circular penetration/bulge/split; no damage to back
HYP-10	Nitro- methane	0.85	12.3	6.0	19,685	Vessel rupture; shear @ weld; circumference expansion; no damage to back
HYP-2	Hydrazine GN_2	2.07	300	6.1	20,013	Circular penetration to front; bulge/ split face; no damage to back
HYP-5	Gaseous Nitrogen	2.07	300	6.1	20,013	Circular penetration to front; multiple penetrations to back; discoloration
HYP-9	Gaseous Oxygen	20.7	3000	6.4	20,997	Vessel rupture into 5 parts; oxygen fire; isolation valve thrown 18.3 m (60 ft)

Although failure modes varied between the three water-filled vessels, the net result was the same: the 2.07 MPa (300 psig) pressure was relieved, with no apparent vessel fragmentation. The single-sheet aluminum shields, placed 7.6 - 10.1 cm (3.0 - 4.0 in) in front of the test vessels, appear to have reduced the size of the penetrations sustained by the vessels.

7.2.2 Nitromethane Test

Test article HYP-10 sustained two impacts, one from the aluminum projectile and one from a piece of nylon sabot. The vessel face was split from end to end (Figure 8) with some shearing at the welds. Although there was no visible impact damage to internal vessel surfaces or end plates, wall expansion was evident throughout the vessel circumference. In addition, the glass bell jar was shattered (Figure 8). Following impact, the high-pressure nitromethane squirted out the entry hole causing the test article to swing upward toward the glass bell jar, shattering the glass bell jar. The nitromethane did not detonate, although high-speed film records* revealed an enhanced flash, possibly the result of ignition of some of the nitromethane. The test article was unavailable for posttest measurements.

7.2.3 Hydrazine Test

Test article HYP-2 contained hydrazine, pressurized to 2.07 MPa (300 psig) with gaseous nitrogen. Projectile impact of HYP-2 was just below the cylinder mid-point and in the liquid. The resulting circular entry hole, bulge, and split (Figure 9) were similar to that found on the water-filled vessels. Again, the 4.78-cm (1.88-in) split terminated on one end at a weld heat-affected zone boundary. The circular entry hole was approximately 0.69-cm (0.27-in) diameter, bulged 0.94 cm (0.37 in), and separated a maximum of 0.74 cm (0.29 in). Several scratches and very shallow pits were found opposite the entry damage, but both end plates were in pristine condition. As expected, based on the nitromethane test results, the hydrazine did not detonate.

7.3 Reaction of Gas-Filled Vessels

7.3.1 Nitrogen Test

Entry damage to the gaseous nitrogen-filled vessel (HYP-5) was different than that found on any of the liquid-filled vessels. Impact damage was limited to a single, circular entry hole, but no bulge or split was evident (Figure 10). The vessel wall opposite the 0.89-cm (0.35-in) diameter entry hole was peppered with impacts, including eight full penetrations of up to 0.26-cm (0.10-in) diameter. The "shotgun" damage pattern on HYP-5 was similar in appearance to that found on the face of the shielded, water-filled HYP-6 (Section 7.2.1), but the damage radius of HYP-5 was larger. Several dozen more circular impacts dimpled the external vessel surface. Black discoloration was found around some of the penetrations, and both end plates were scarred with shallow circular impacts and scratches.

7.3.2 Oxygen Test

The oxygen test proved to be the most violent of all the tests. High-speed cinema film (Figures 11 and 12) show the glass bell jar following impact. Figure 12 shows glass bell jar

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*WSTF Video Cassette #2098, recorded in 1988.

fragmentation as a fireball envelopes the target. Test article HYP-9 ruptured into five pieces: two end sections, two fragments of bare aluminum liner, and one isolation valve (Figure 12). The fracture terminated at the circumferential weld line (Figure 13). Pieces of unraveled Kevlar yarn were also found. The 737-gram (1.6-lb) isolation valve sheared off and was propelled up over the rear blast mats, 18.3 m (60 ft) into the desert; all other parts of the test article were contained within the blast cell, although shards of bell jar glass were found as much as 50 m (164 ft) away from the blast cell.

Discoloration, char, and localized melting of the aluminum liners, charred Kevlar fiber, film records, and aluminum oxide slag on the bell jar fragments gave conclusive evidence of an oxygen fire. Both aluminum liner fragments were flattened and charred, with melted and discolored edges. Although a metallic spray pattern was evident on both fragments, neither fragment exhibited the pinhole perforations found in the nitrogen vessel. The Kevlar overwrap on one end section was torn and charred, and the metal fitting had been flattened, presumably upon impact with the blast cell wall.

Although the oxygen test proved to be relatively spectacular, several factors, other than the test fluid, could have contributed to this result. Because test pressure was 10 times higher and test vessel volume was 3.5 times greater for this test than for previously discussed tests, the pressure-volume work potential was 35 times higher for this test configuration. As would be expected, the oxygen test caused more secondary damage to the surrounding area than the other tests.

Aside from having a larger volume than the other test vessels, the oxygen test vessel was also of unique construction. The "zero stress" overwrap design and brittle aluminum liner of the oxygen bottle would be expected to fail quite differently from the ductile, thick-walled stainless steel vessels, used for the other tests in this investigation. Hemispherical end caps, as opposed to the thick, flat-end plates used on the stainless steel vessels, also affected shell stress levels and could have influenced the vessel failure mode.

8.0 Conclusions

Despite the difficulties posed by the temporary test site, JSC has demonstrated the ability to perform hypervelocity impact tests on hazardous targets. Pressurized, potentially explosive, and toxic targets were all successfully handled, impacted, and secured without incident.

Thick-walled, flat-ended, cylindrical, stainless steel vessels containing non-detonable pressurized liquids and inert gas ullage failed during hypervelocity impact testing by bulging and splitting open at the impact point. Pressure was relieved without the vessel fragmenting, possibly due to the gas ullage minimizing "hydraulic ram" effects. Minimal internal vessel damage was found away from the entry point.

Thick-walled, flat-ended, cylindrical, stainless steel vessels containing detonable pressurized liquids and inert gas ullage also failed during hypervelocity impact by bulging and splitting open at the impact point. Again, pressure was relieved without the vessel fragmenting, and minimal internal vessel damage was found away from the entry point. Neither the nitromethane, at 0.85 MPa (12.3 psig), nor the hydrazine, at 2.07 MPa (300 psig), detonated under hypervelocity impact conditions.

A single 0.25-cm (0.01-in) aluminum sheet, placed 7.6 - 10.1 cm (3.0 - 4.0 in) in front of a test vessel acted to distribute debris over a larger area, thus reducing penetration damage to the vessel.

A flat-ended, cylindrical, stainless steel vessel containing inert 2.07 MPa (300 psig) gas failed under hypervelocity impact by relieving pressure. Although the vessel did not fragment, there was penetration of the internal vessel wall, opposite point of entry. The resulting spall demonstrated a potential for secondary damage to nearby equipment.

A zero-stress, Kevlar-overwrapped, aluminum bottle containing 20.7 MPa (3000 psig) gaseous oxygen reacted violently under hypervelocity impact conditions. The ensuing fire and large, high velocity fragments demonstrated a potential for secondary damage to surrounding structures.

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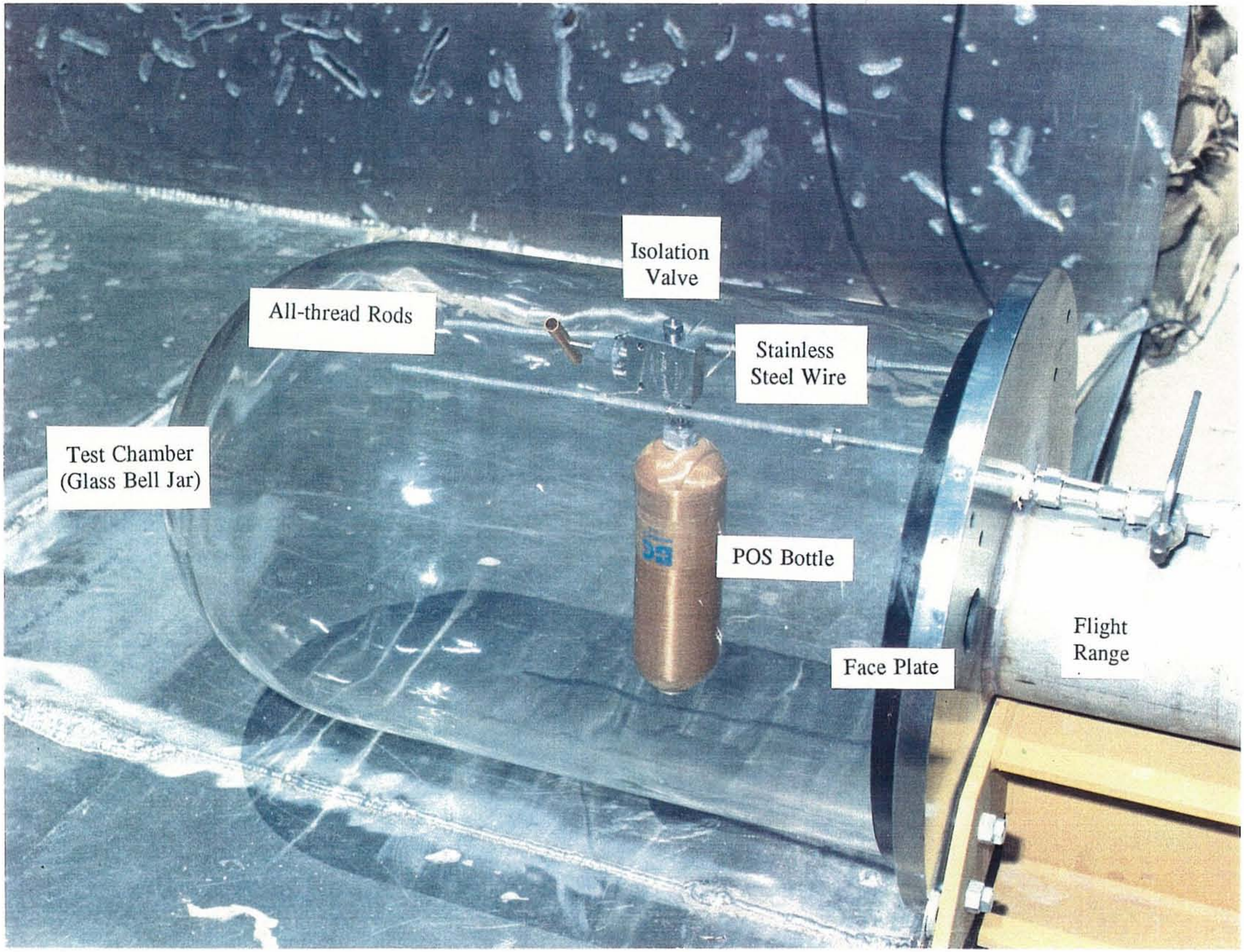


Figure 1
Kevlar-Overwrapped Aluminum Bottle
Pretest Configuration

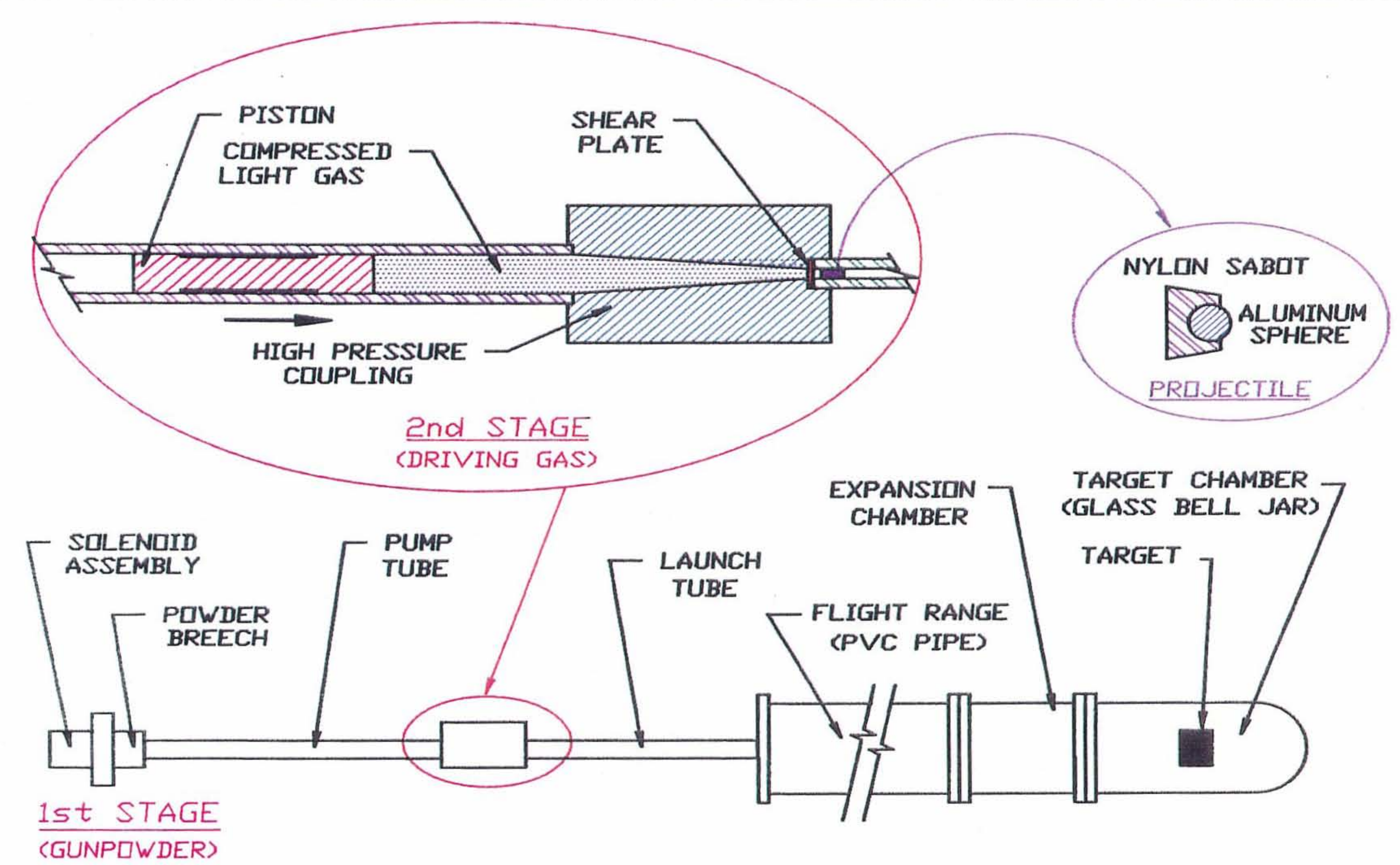
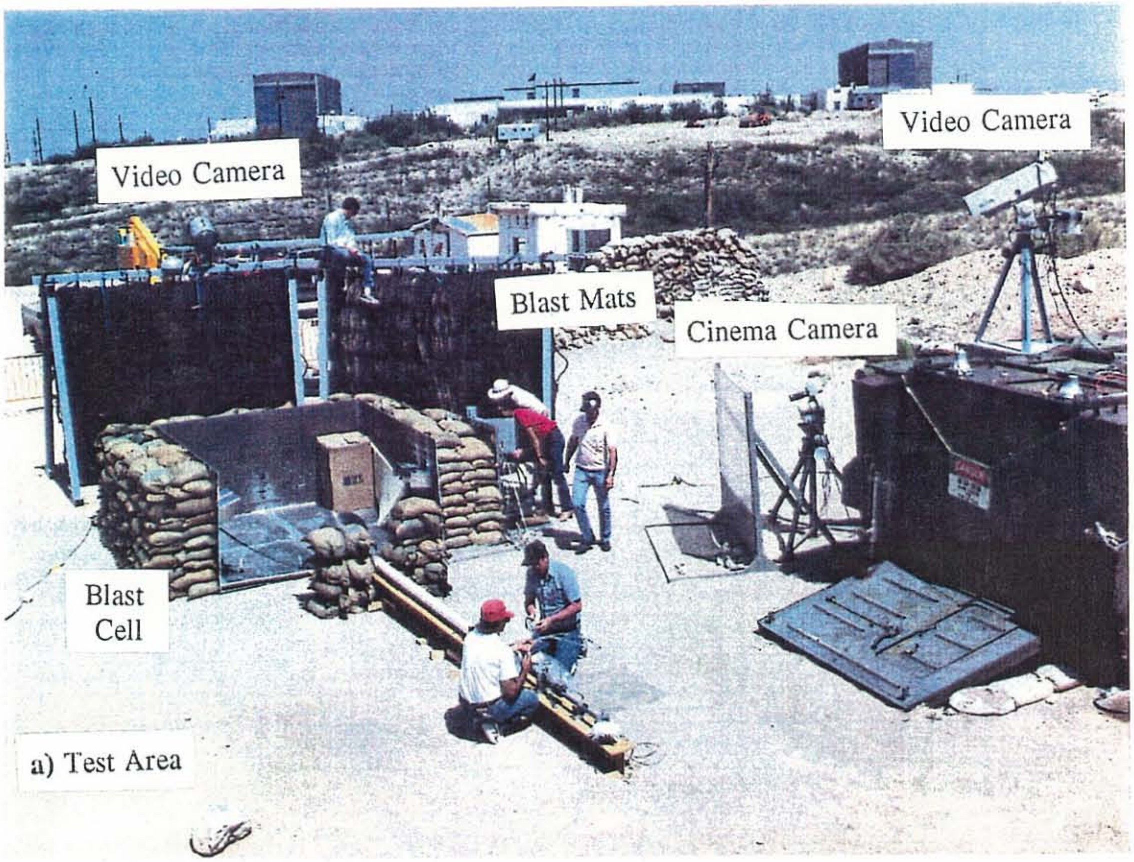


Figure 2
HIRL 4.3 mm (0.17 Caliber) Two-Stage
Light Gas Gun

Figure 3
Stainless Steel Test Article



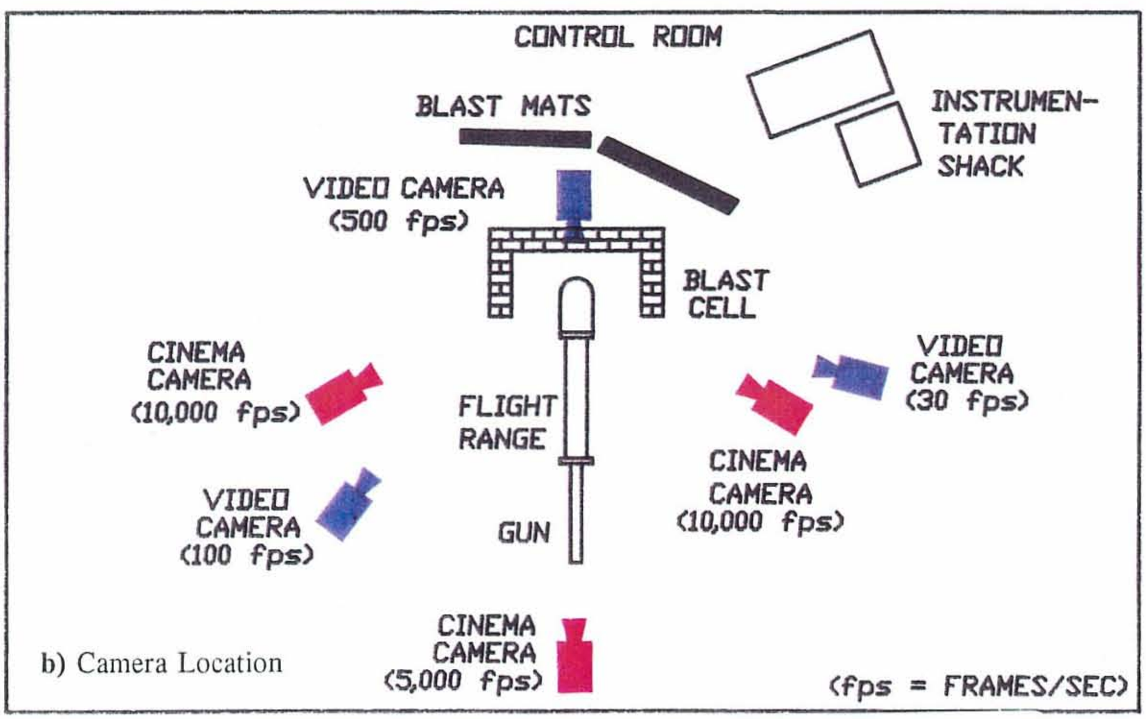


Figure 4
Test Setup a) Test Area b) Camera Location

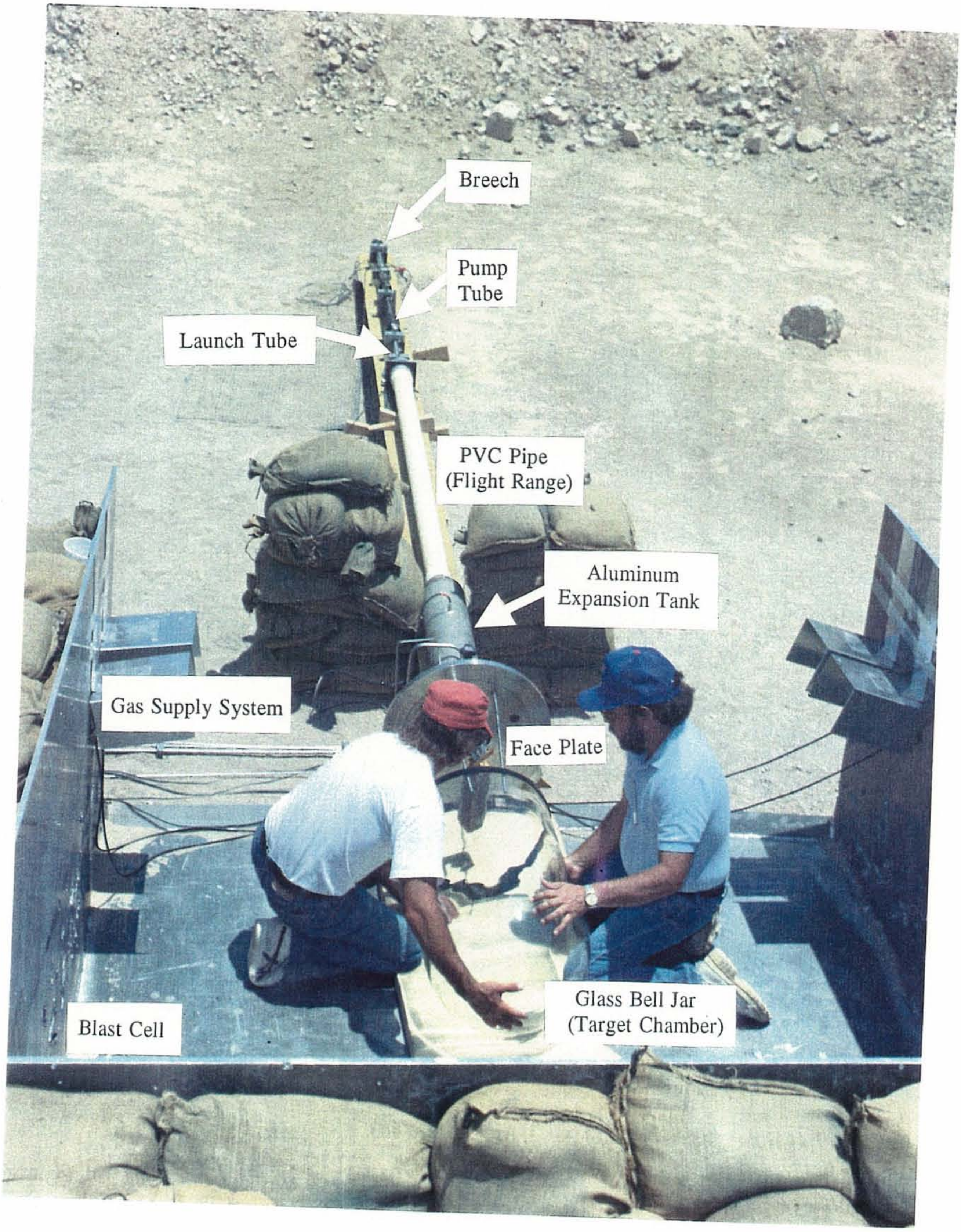


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Figure 5
Gun and Downrange Assembly

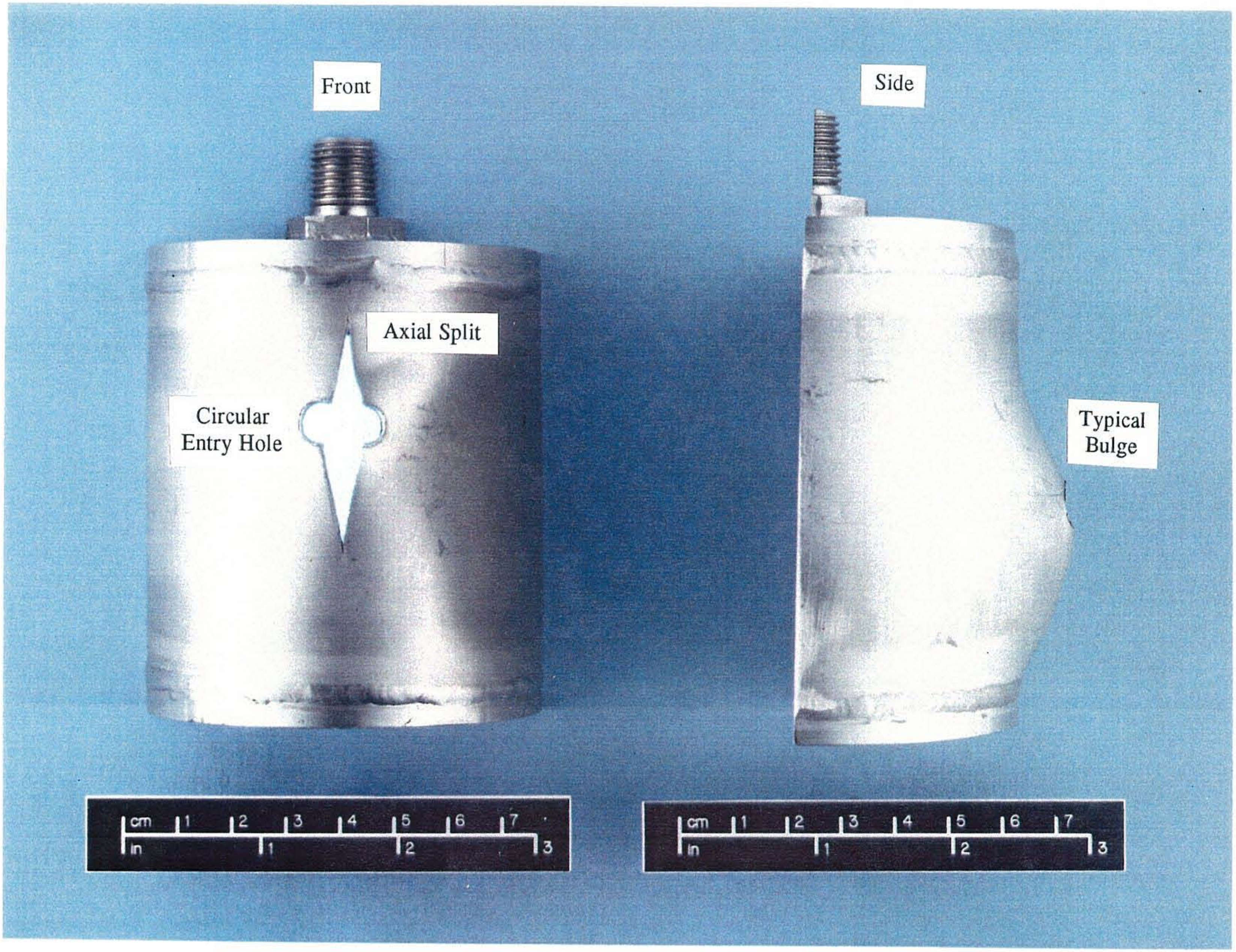


Figure 6
Bulged Entry Damage to Liquid-Filled Vessels

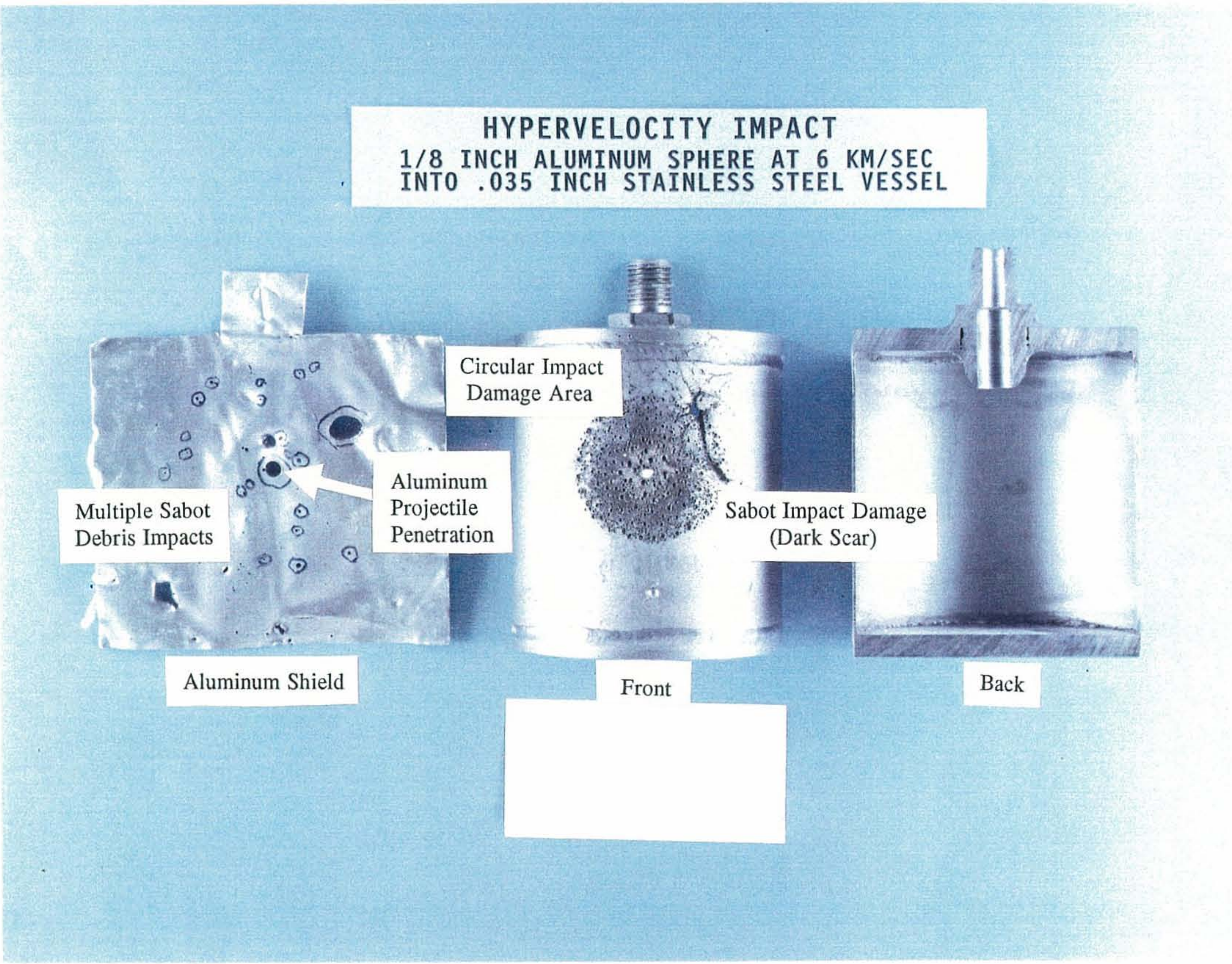


Figure 7
Posttest of Sectioned 2.07 MPa (300 psig)
Shielded Water Test Vessel

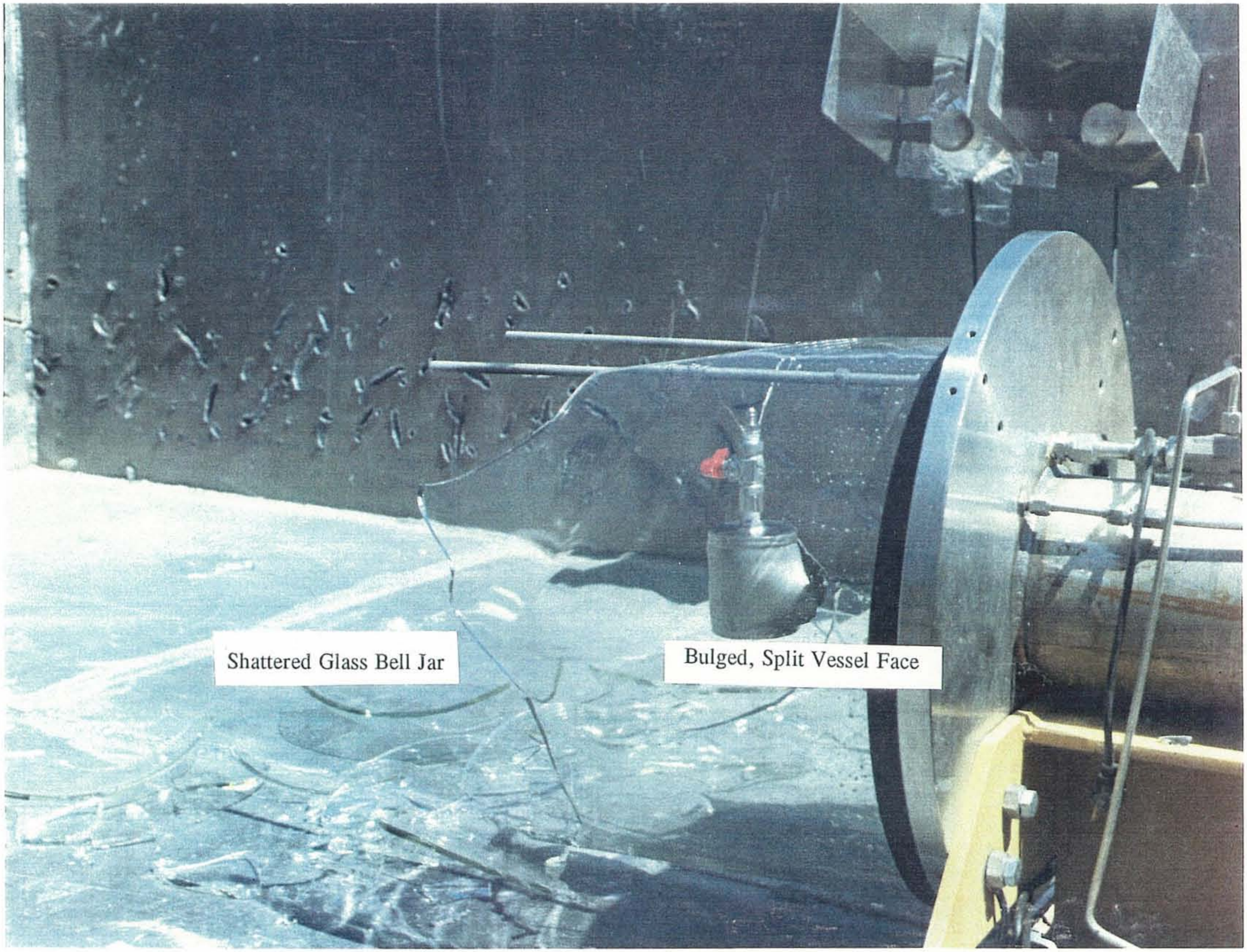


Figure 8
Posttest 0.85 MPa (12.3 psig)
Nitromethane Test Vessel

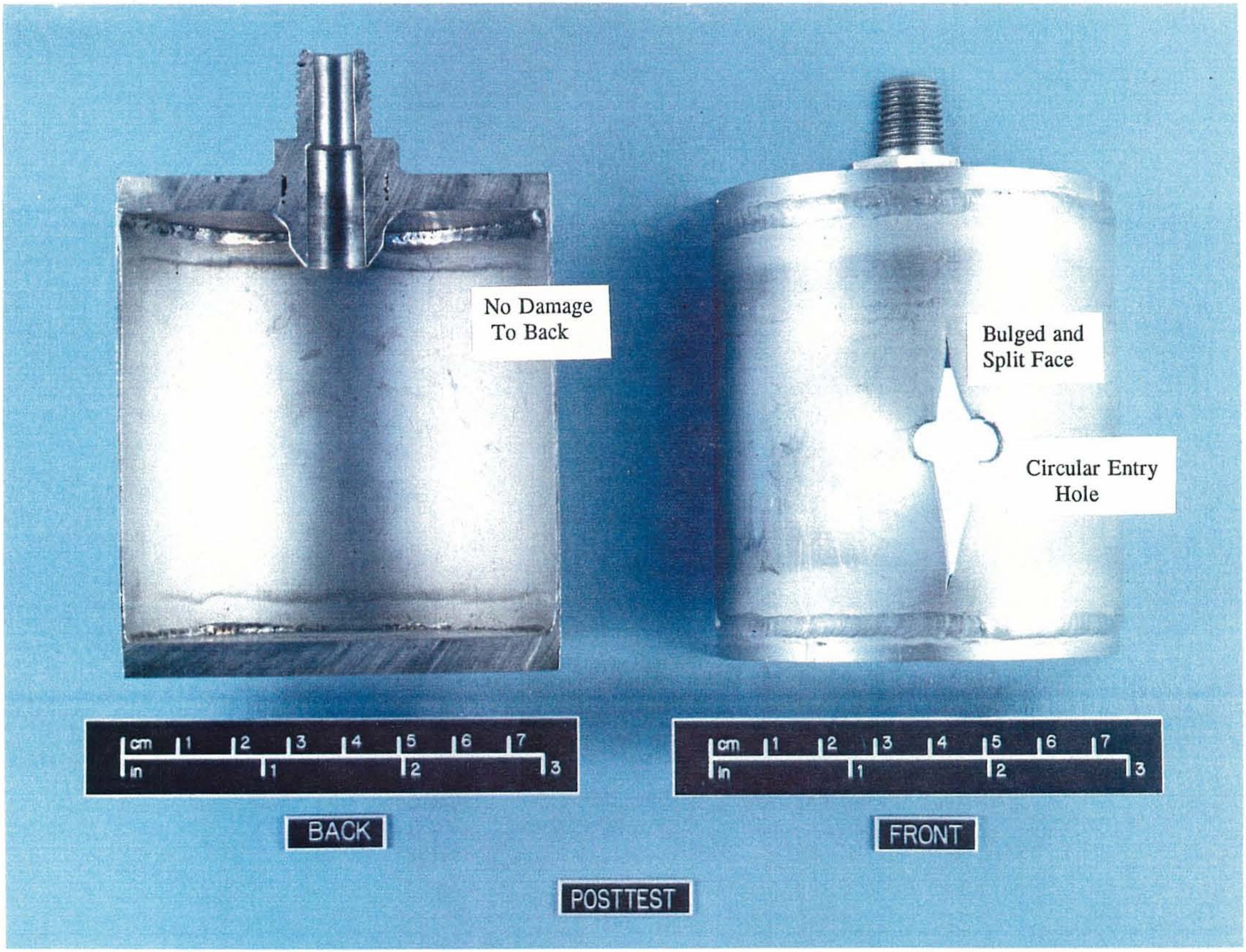


Figure 9
Sectioned 2.07 MPa (300 psig)
Hydrazine Test Vessel

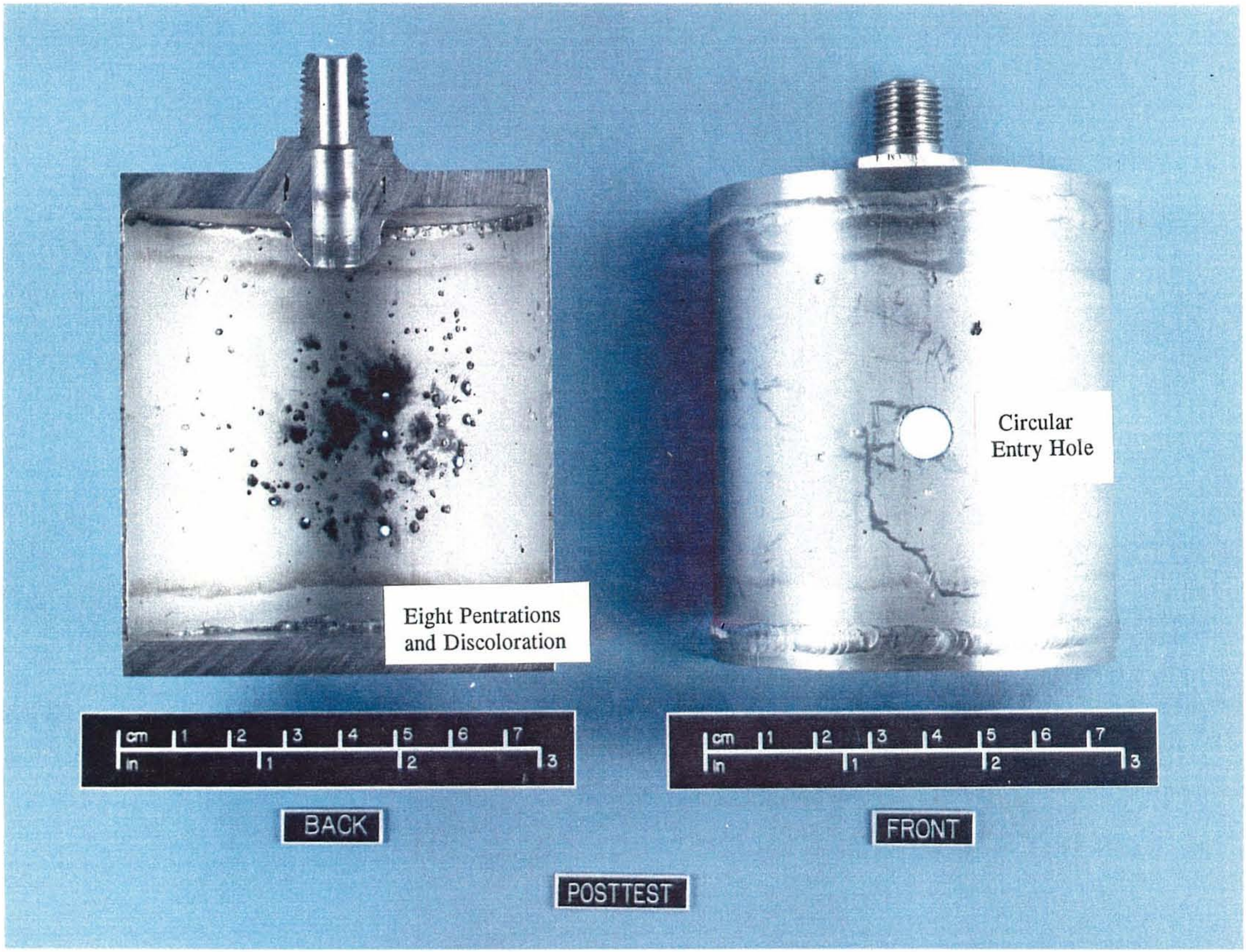
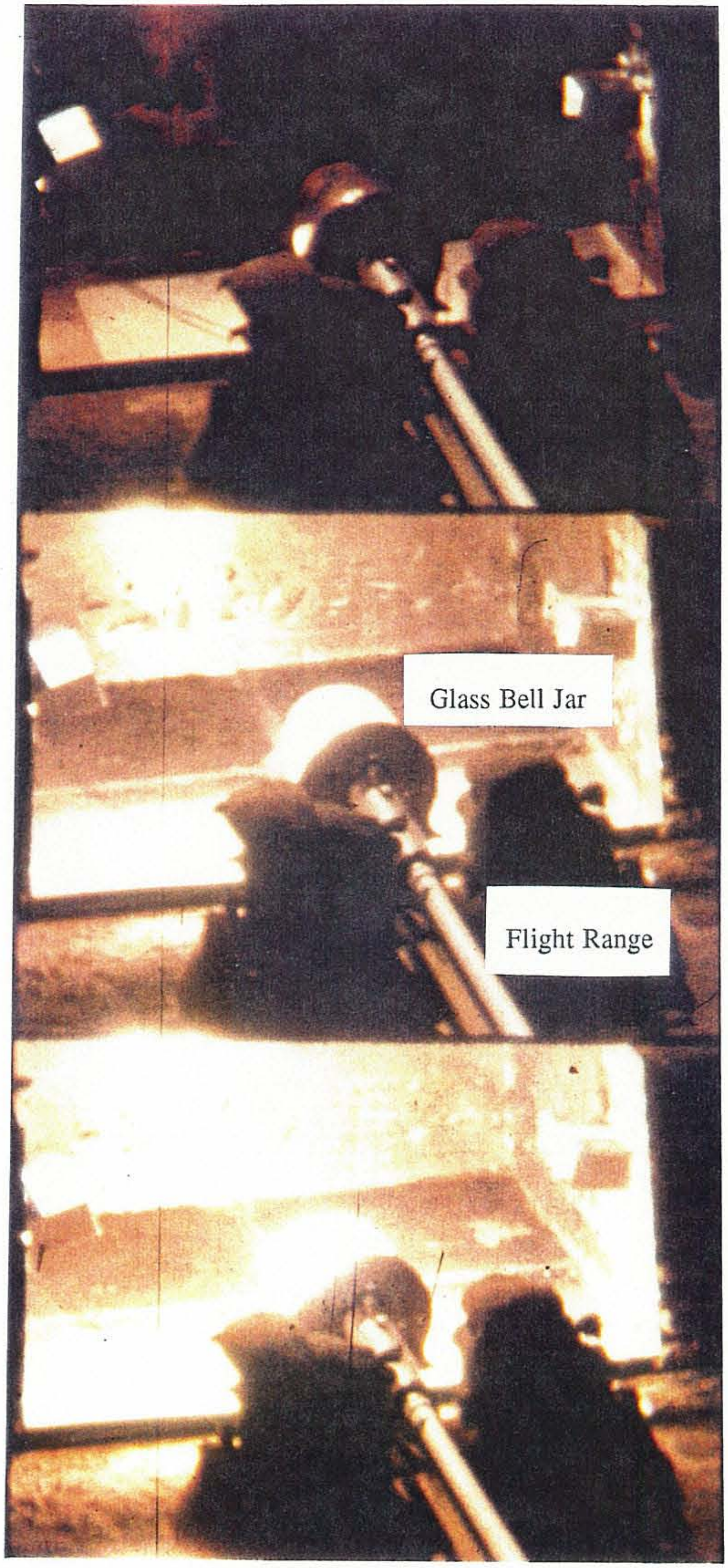


Figure 10
Sectioned 2.07 MPa (300 psig)
Nitrogen Test Vessel



0.0 msec

0.6 msec

1.2 msec

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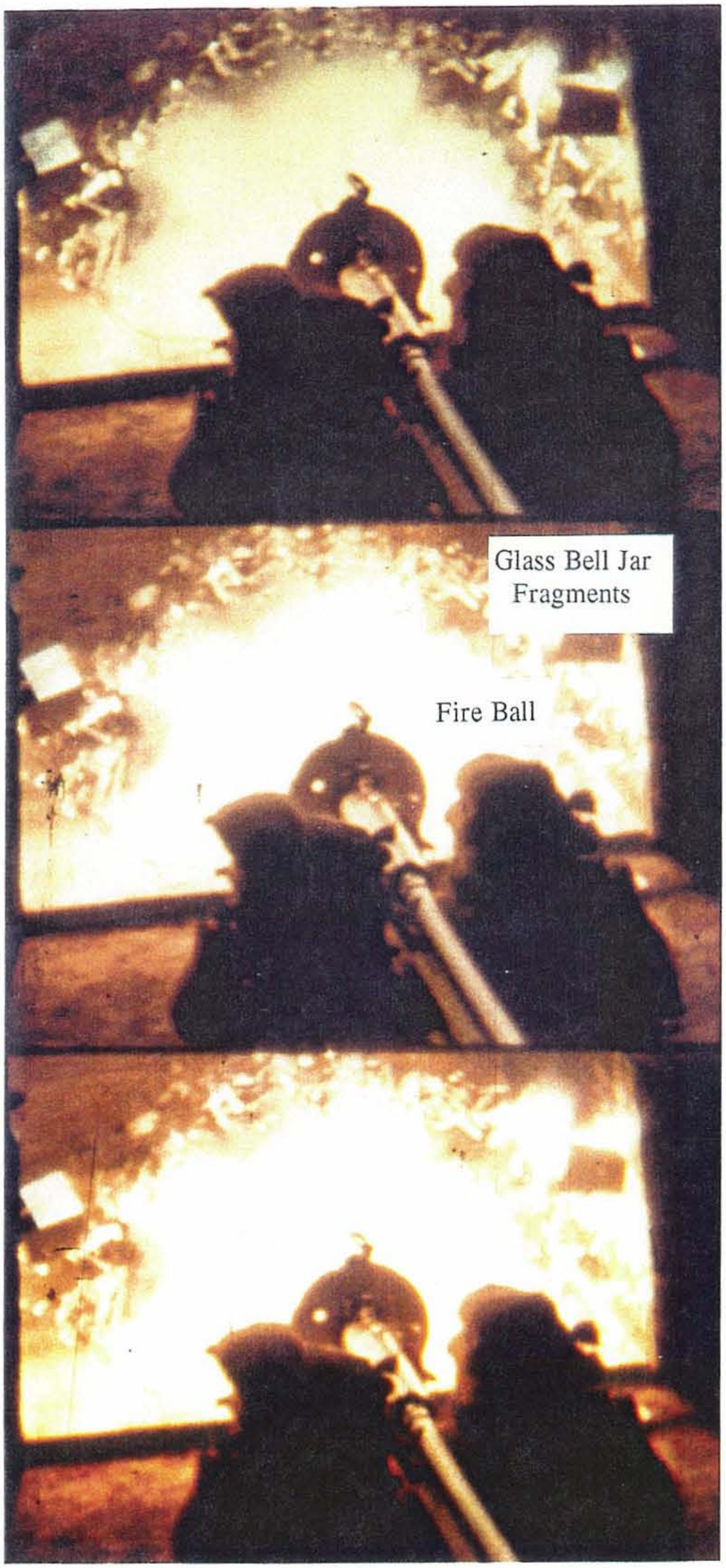
Figure 11
Impact of 20.7 MPa (3000 psig)
Oxygen Test Vessel



1.8 msec

2.4 msec

3.0 msec

Figure 11 (Continued)
Impact of 20.7 MPa (3000 psig)
Oxygen Test Vessel

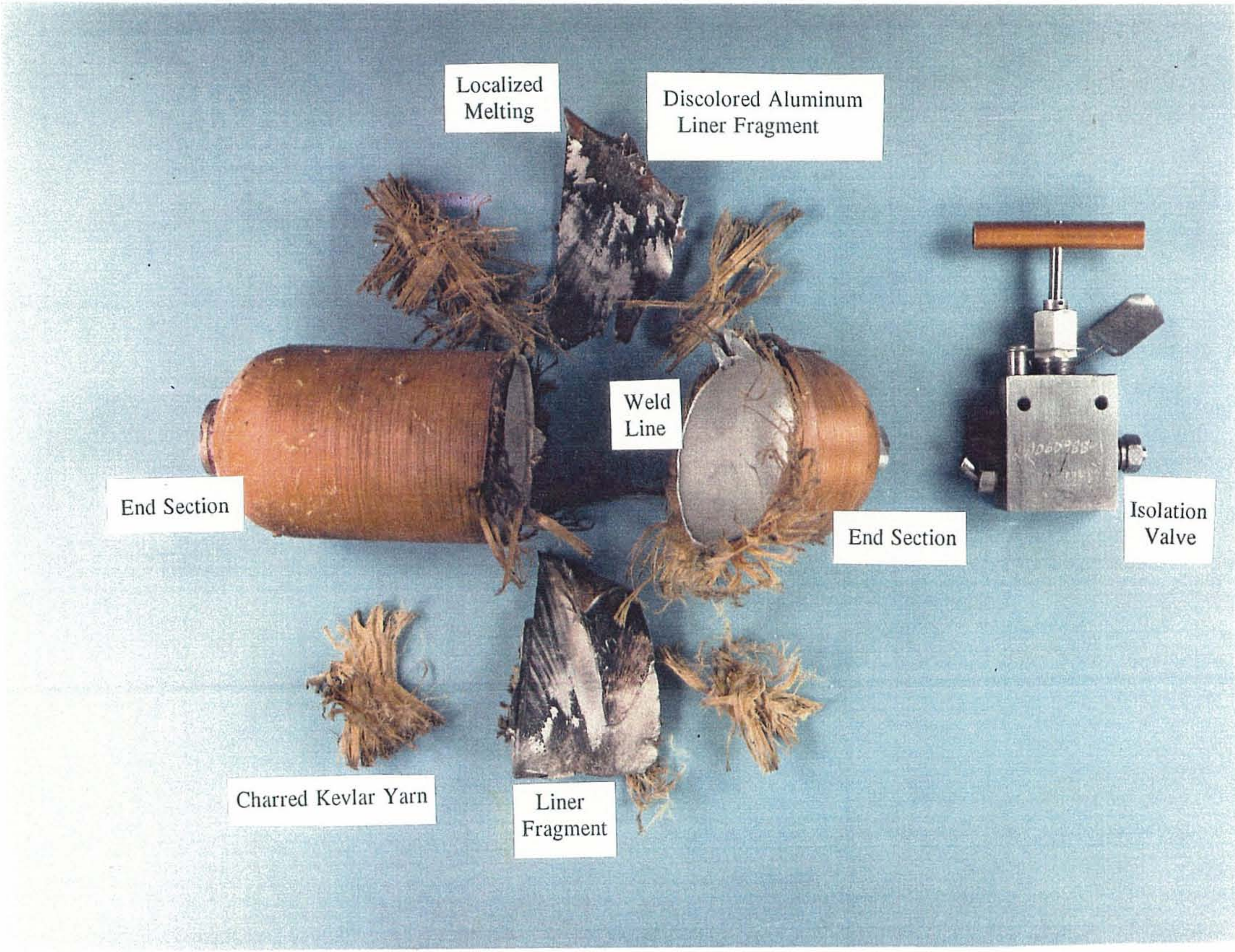


Figure 12
Ruptured 20.7 MPa (3000 psig) Oxygen Test Vessel

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