Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

EVALUATION OF PRESSURIZED VESSELS FOLLOWING HYPERVELOCITY PARTICLE IMPACT

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ABSTRACT

Preliminary results are presented from hypervelocity impact tests on aluminum pressure vessels filled with 50% water and 50% gaseous nitrogen, by volume. The testing and analysis were performed at the NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF). Two variables were observed to have an effect on the degree of vessel failure: vessel internal pressure and vessel mount. Differences in vessel response following impact are discussed.

1. INTRODUCTION

Increasing amounts of orbital debris have put spacecraft at a greater risk of sustaining hypervelocity impacts (Ref. 1). While material responses to hypervelocity impacts have been investigated (Ref. 2), limited testing has been performed on components, particularly pressure vessels. Research into the effects of hypervelocity impacts on pressure vessels containing various fluids is being conducted at WSTF.

Previous testing at WSTF (Ref. 3) was conducted on thick-walled steel and flight-weight, Kevlar-overwrapped aluminum pressurized containers. The JSC Hypervelocity Impact Test Facility (HIT-F) has performed testing on low pressure, thin-walled, aluminum pressure vessels (Ref. 4 and 5) and thin-walled titanium and Inconel pressure vessels (Ref. 6).

In 1991 WSTF was given funding to pursue a research effort to understand the effects of simulated orbital debris impacts on pressure vessels containing liquid and gas combinations. In tests presented here, vessel design and projectile parameters were held constant while the vessel pressure and mounting structure were varied. Results provided insight into the effect of internal pressure and mounting structure on the degree of pressure vessel failure.

2. TEST ARTICLES

The test articles were fabricated from 6061-T62 aluminum (Fig. 1). The cylindrical pressure vessels were approximately 23.4 cm in length and 8.9 cm inner diameter, with a wall thickness at the mid-point of 2.2 mm. Both ends were hemispherical; one end contained a fill port into which fluids were introduced. The rated maximum operating pressure of the vessels was 6.9 MPa, with a burst pressure rating of 15.3 MPa.

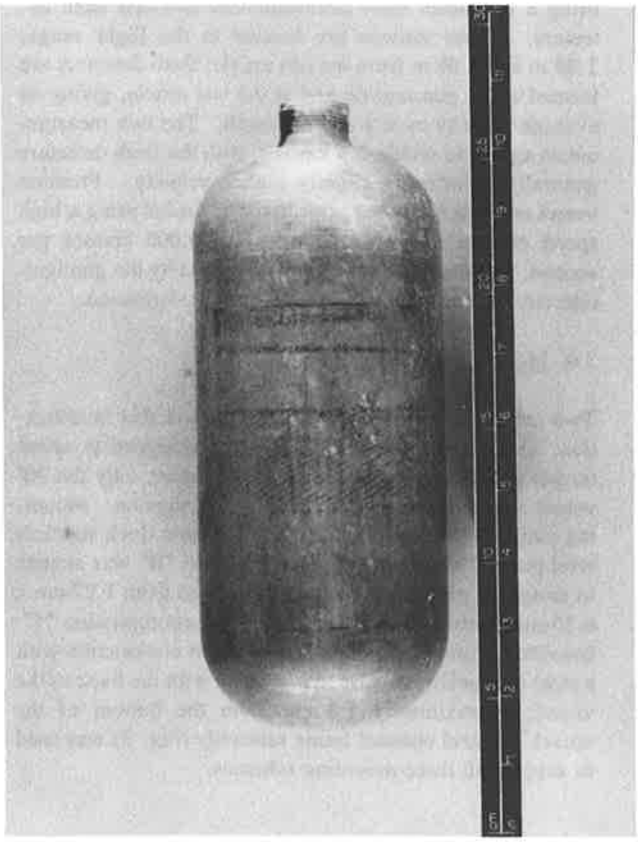


Figure 1. Test article.

The pressure vessels were manufactured by Structural Composites Industries (SCI) and provided to WSTF in exchange for impact data. The vessels were actually metal liners used in the production of composite overwrapped vessels.

3. TEST APPARATUS

The test apparatus consisted of a two-stage light gas gun, a 4.6 m long flight range, a target chamber, and data acquisition and control instrumentation.

3.1 Light gas gun

The 4.3 mm two-stage light gas gun, which is on loan to WSTF from HIT-F, is capable of launching 3.18 mm diameter projectiles at velocities to 6.8 km/sec.

3.2 Target chamber

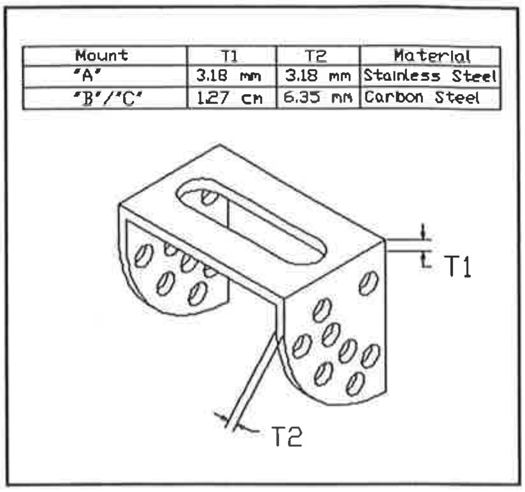
The cylindrical target chamber was constructed of 1.2 cm thick carbon steel, with an internal volume of approximately 0.38 m^3. The chamber is designed to safely withstand a 172 kPa overpressure.

3.3 Data acquisition and control

Redundant projectile velocity measurements were taken using a two-beam laser intervalometer and two flash detectors. Laser stations are located in the flight range, 2.08 m and 2.69 m from the test article; flash detectors are located at the gun muzzle and at the test article, giving an average velocity over a 4.6 m length. The two measurements agreed to within 0.3 km/sec, with the flash detectors generally reporting a slightly higher velocity. Pressure vessel reaction following impact was recorded using a high speed cinema camera, operating at 10,000 frames per second. All instrumentation was triggered by the gun ignition circuit, and timed for known gun performance.

3.4 Mounting hardware

Two mounting plates (Fig. 2) were used in this investigation. A semi-circular hole pattern was designed to orient targets at different impact angles. However, only the 90° vessel orientation was used for this investigation. Mounting plate "A" was fabricated from 3.18 mm thick stainless steel plate. The design for mounting plate "B" was similar to mounting plate "A", but was fabricated from 1.27-cm x 6.35-mm carbon steel plate. Mounting configuration "C" consisted of mounting plate "B," used in conjunction with a steel channel brace, placed in contact with the back of the vessel, approximately 3.8 cm from the bottom of the vessel. A steel channel frame assembly (Fig. 3) was used to support all three mounting schemes.



Mount	T1	T2	Material
"A"	3.18 mm	3.18 mm	Stainless Steel
"B"/"C"	1.27 cm	6.35 mm	Carbon Steel

Figure 2. Mounting plate.

4. TEST PROCEDURES

After marking the desired water level and impact point, pressure vessel dry weight was measured and recorded. The vessel was then filled to the mid-point with water and weighed again. The test article was mounted inside the target chamber, in a vertical position, with the fill port at the top. The test article and the target chamber were purged with nitrogen, then evacuated. The test article was then pressurized to the test pressure with gaseous nitrogen. After securing the target chamber, the gun was loaded and testing was initiated via a remote firing panel which controlled the gun and all instrumentation. Following impact, the test article was inspected, carefully removed, labelled and measured.

5. TEST CONDITIONS

Vessels were tested at pressures ranging from below 0.7 kPa to 6.9 MPa. The impact point was 2.5 cm below the water level; the water level for all tests was at the vertical mid-point of the vessel.

Spherical 3.18 mm diameter 2017-T4 aluminum projectiles with an average mass of 47 mg were used for all tests. Projectile velocities ranged from 6.2 km/sec to 6.8 km/sec, averaging about 6.4 km/sec. Impact accuracy was typically +/- 3.0 mm along the vessel vertical axis, and +/- 1.0 mm along the vessel circumference.

6. OBSERVATIONS

Failure modes of vessels filled with 50% water and 50% nitrogen ranged from slight bulging and cracking around an oblong entry hole (Fig. 4) to severe bulging and fracture

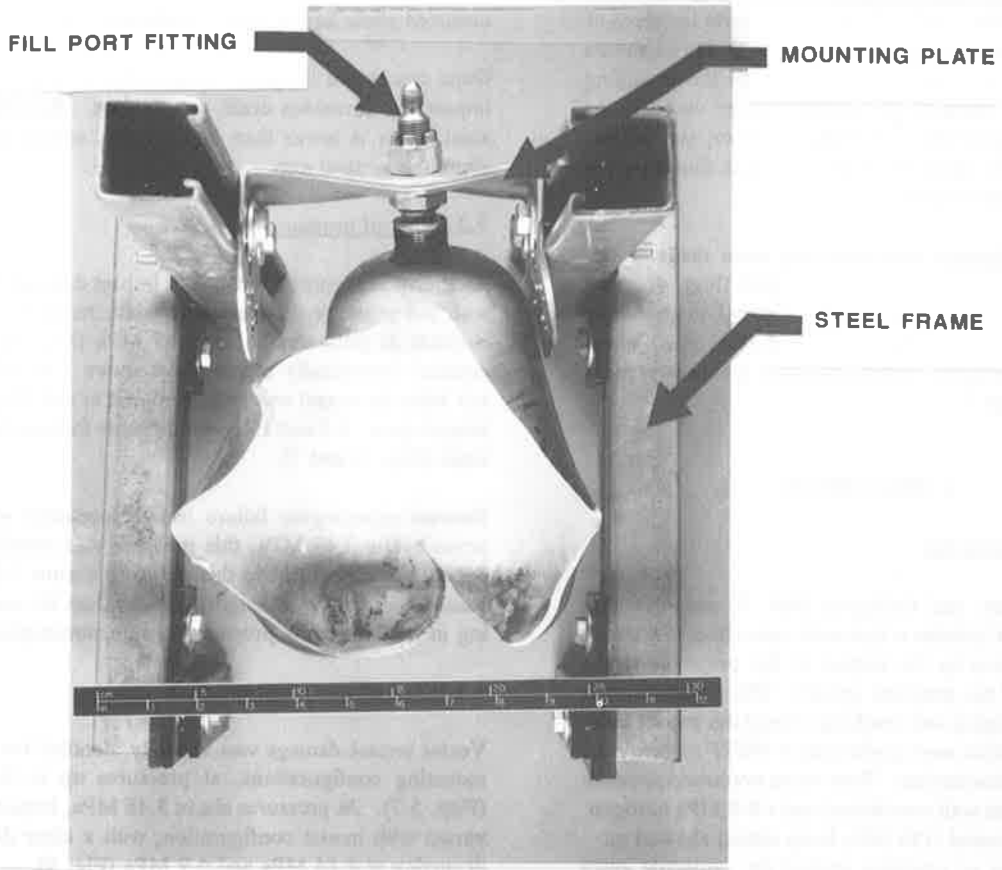


Figure 3. Catastrophic vessel failure.

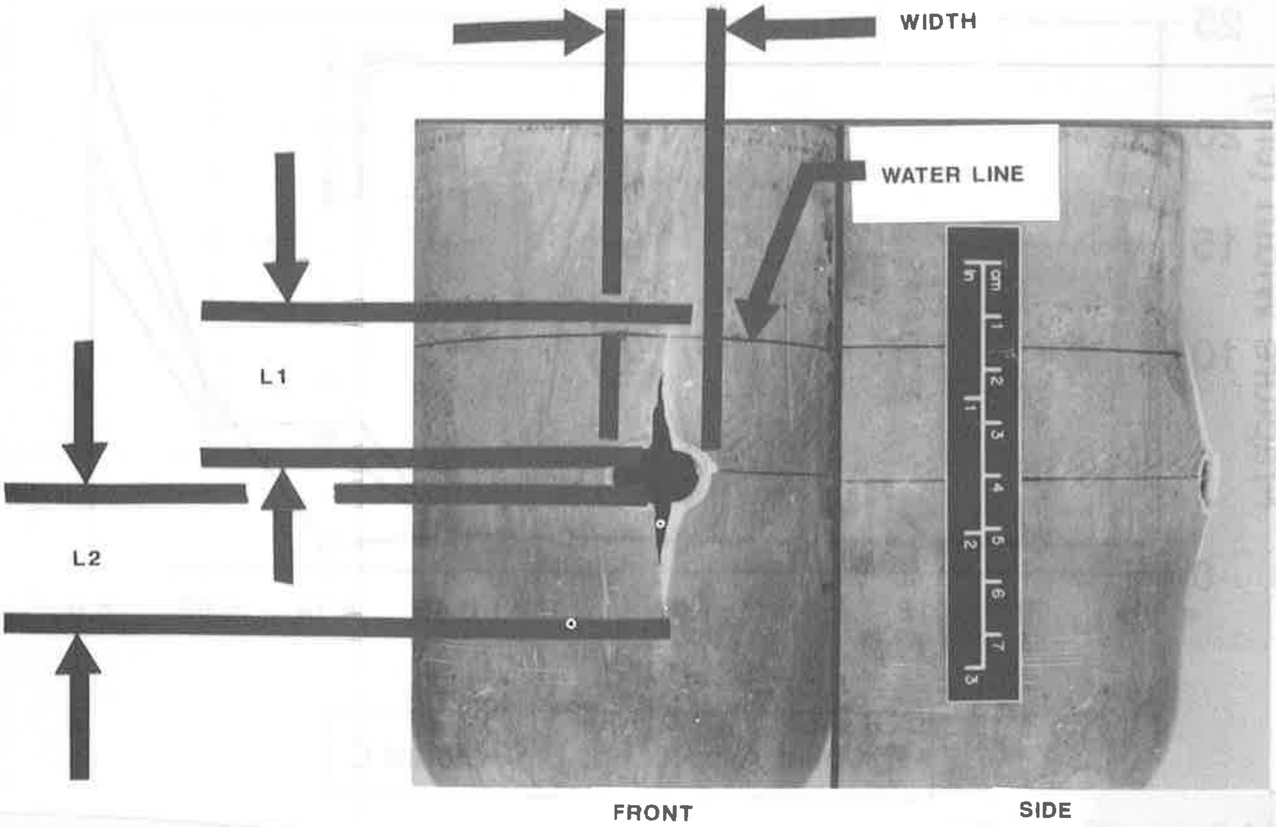


Figure 4. Typical low pressure impact damage.

propagation in the circumferential direction (Fig. 3), which was defined as catastrophic failure. In several instances at the higher test pressures, crack propagation was so severe that the impact surfaces swung back into the mounting frame (Fig. 3). None of the vessels showed visible signs of impact damage to the back wall; however, residual debris, which could easily be wiped off, was found on the back wall of some vessels.

Three impact damage measurements were made. The width of the impact hole was measured (Fig. 4) using digital calipers. The fracture lengths above (L1) and below (L2) the impact point were measured (Fig. 4). These damage measurements versus pressure are presented in Figures 5 through 7.

7. DISCUSSION

7.1 Damage mechanism

Rosenberg, Bless, and Gallagher (Ref. 7) proposed that projectile impact initiates a hydraulic ram effect (the shock pressure generated by the impact of the projectile at the liquid region of the pressure vessel). This hydraulic ram then initiates bulging and cracking around the impact hole. Two additional tests were performed at WSTF to verify the crack initiation mechanism. Tests on an evacuated pressure vessel (unstressed wall conditions) and a 6.9 MPa nitrogen-filled pressure vessel (138 MPa hoop stress) showed no signs of bulging or cracking around the projectile entry hole when viewed under the microscope. This supports the hydraulic ram crack initiation theory: cracking only occurred when liquid-filled vessels were impacted.

Once cracks are initiated, vessel internal pressure at the impact site promotes crack propagation. Because vessel axial stress is lower than hoop stress, cracks propagate along the vertical axis.

7.2 Effect of pressure

As shown in Figures 5 through 7, impact damage increased with test pressure. Impact hole width remained virtually constant at pressures below 3.45 MPa (Fig. 6), but increased dramatically at pressures above 3.45 MPa. At 6.9 MPa the vessel was split from end to end (Fig. 3) and hinged open. L1 and L2 measurements followed a similar trend (Figs. 6 and 7).

Because catastrophic failure usually occurred above but never below 3.45 MPa, this pressure was identified as a critical pressure. Above this critical pressure, L1 and L2 reached critical crack lengths (greater than 26 mm) resulting in unstable crack propagation and catastrophic failure.

7.3 Effect of mounting structure

Vessel impact damage was virtually identical for all three mounting configurations, at pressures up to 3.45 MPa (Figs. 5-7). At pressures above 3.45 MPa, impact damage varied with mount configuration, with a clear divergence occurring at 4.14 MPa and 6.9 MPa (Fig. 5).

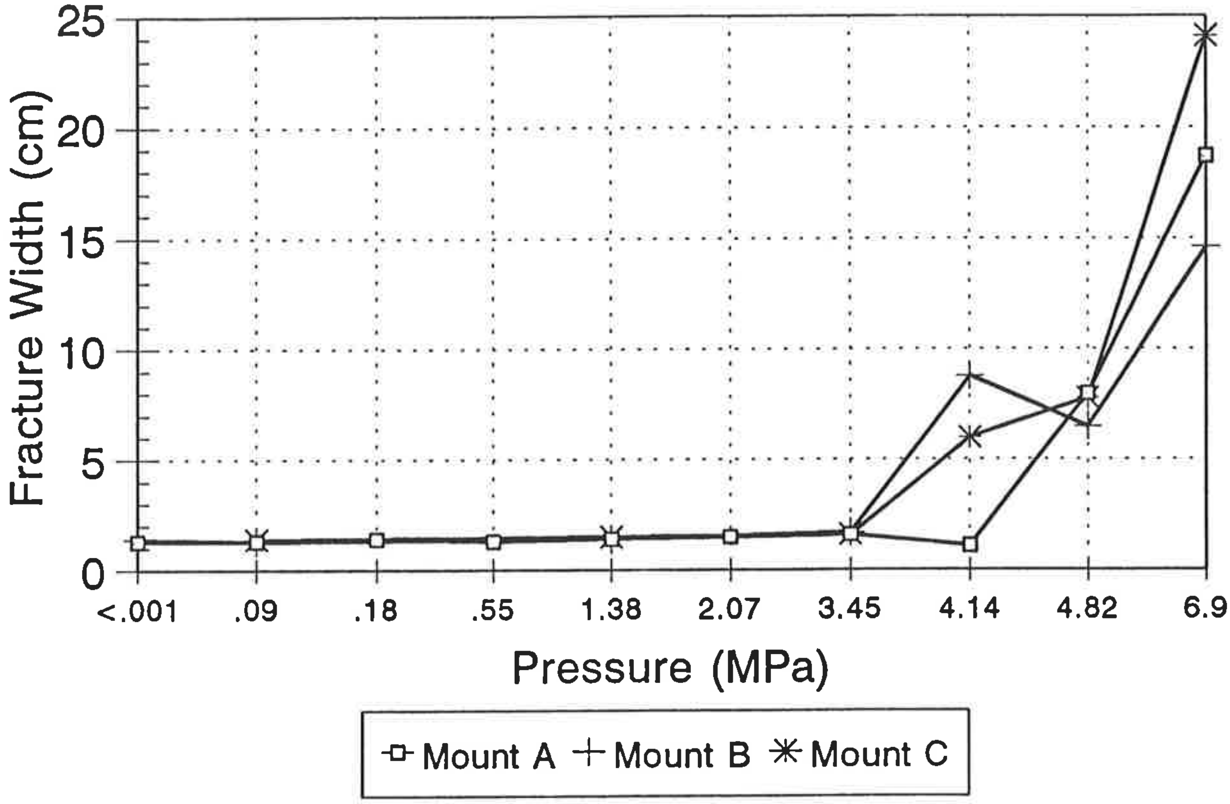


Figure 5. Fracture width vs. pressure.

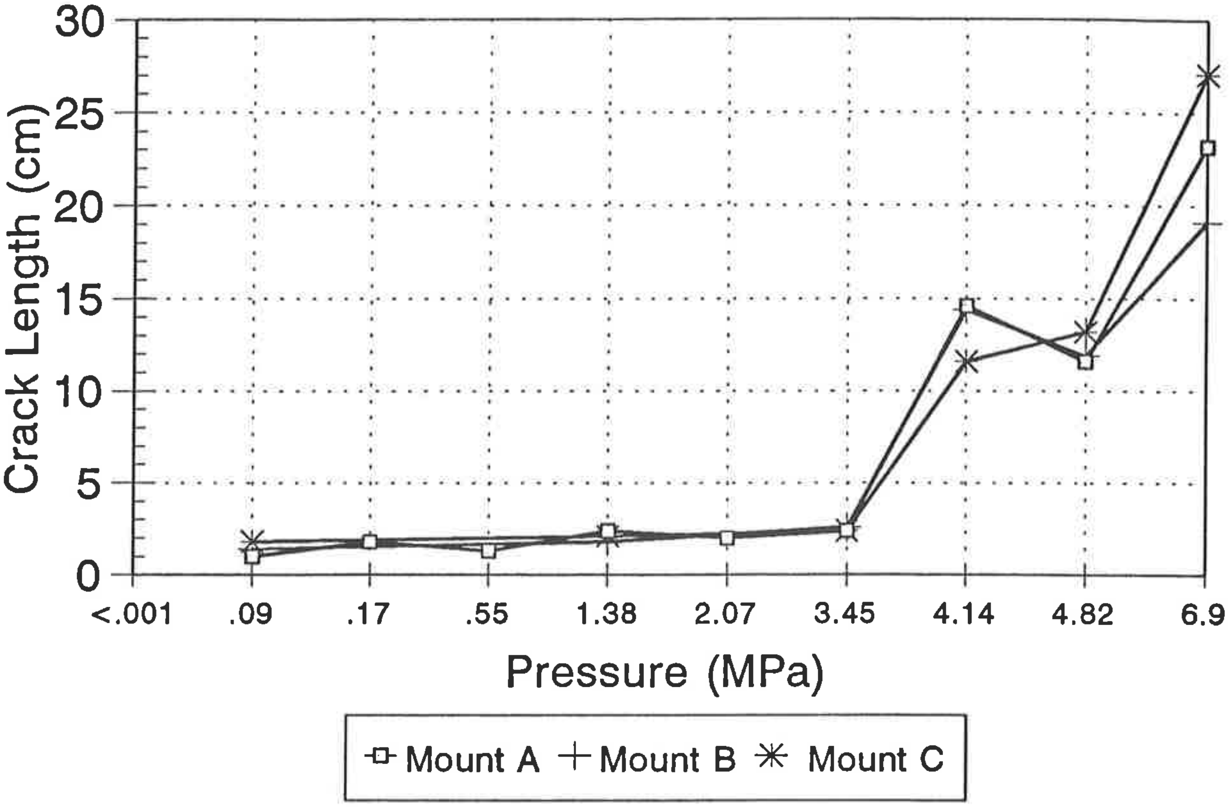


Figure 6. Crack length L1 vs. pressure.

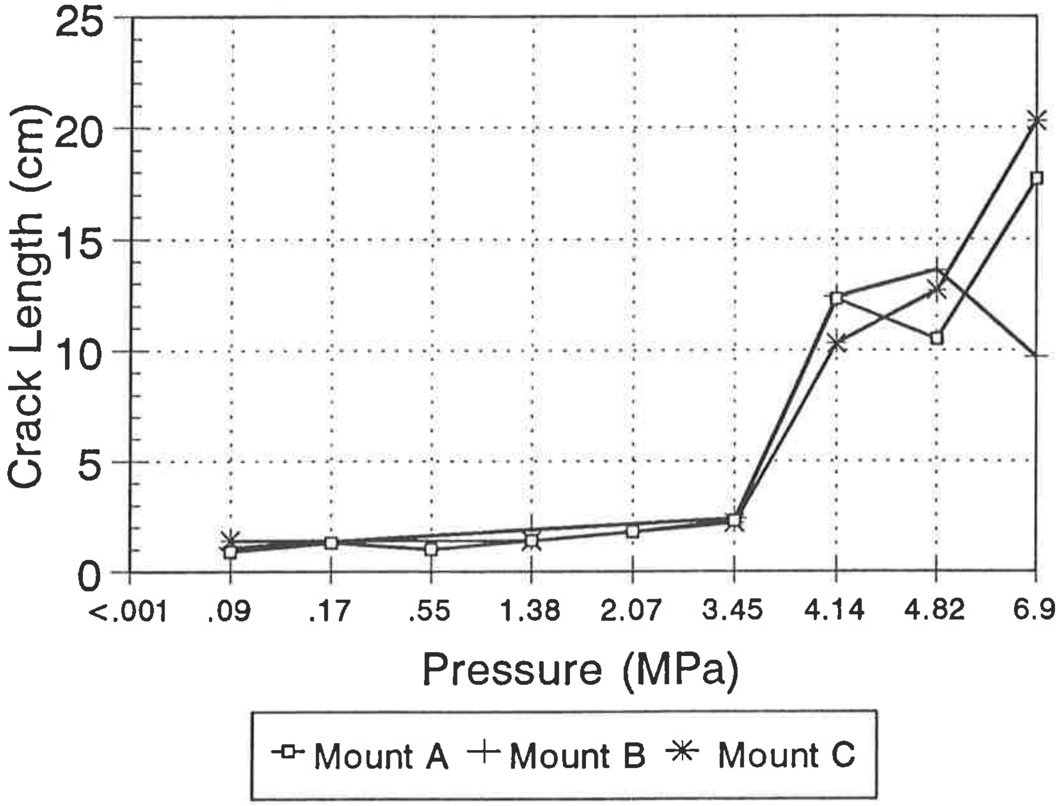


Figure 7. Crack length L2 vs. pressure.

Secondary damage to the mounting structure itself varied with mount configuration, particularly at the higher test pressures. Mounting plate "A" became badly twisted during vessel catastrophic failure (Fig. 3), allowing the vessel to swing backwards as much as 30°. Although the mounting plate used in configuration "B" did not sustain any damage, the fill port fitting was damaged beyond use. No damage to either the mounting plate or the fill port fitting occurred while using mount configuration "C."

In general, severe secondary mount damage corresponded to less severe vessel damage. The anomaly at 6.9 MPa, with configuration "B" (Fig. 7), was attributed to fill port o-ring seal failure following severe fitting deformation. The broken seal relieved gas pressure, providing additional stress relief at the crack front.

8. CONCLUSIONS

These results indicate that internal pressure has an effect on the severity of hypervelocity impact damage to a pressurized vessel. A critical pressure was identified, above which catastrophic failure usually occurred, and below which catastrophic failure never occurred. For these particular vessels, under the stated test conditions, this critical pressure was found to be near 3.45 MPa. By maintaining vessel pressure below this critical value, catastrophic failure can be minimized, thus reducing the risk of secondary damage to nearby personnel and equipment.

Mount configuration had no effect on the degree of vessel damage below the critical pressure. Mount configuration did affect the degree of vessel and secondary damage above the critical pressure, but this effect has not yet been fully investigated. These results indicate that a potential exists for mount designs which might minimize vessel catastrophic failure.

9. FUTURE WORK

Future tests will be repeated on the same type of aluminum liners, overwrapped with a graphite epoxy composite, to study the effects of vessel construction. These tests will then be repeated using various liquids to determine the vessel content's effect on catastrophic failure. A more thorough mount investigation is also planned.

10. REFERENCES

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ACKNOWLEDGEMENTS

The authors wish to thank Arnold Zamora for test support; Structural Composites Industries (SCI) for providing test articles; Jeanne Lee Crews, Manager of the HIT-F, for the use of her two-stage light gas gun; and Dr. Aaron Cohen, Director of the NASA Johnson Space Center, for discretionary funding to pursue this research.