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Hypervelocity Impact Testing of Nickel Hydrogen Battery Cells

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HYPERVELOCITY IMPACT TESTING OF NICKEL-HYDROGEN BATTERY CELLS

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Abstract

Nickel-Hydrogen (Ni/H₂) battery cells have been used on several satellites and are planned for use on the International Space Station. In January 1992, the NASA Lewis Research Center (LeRC) conducted hypervelocity impact testing on Ni/H₂ cells to characterize their failure modes. The cell's outer construction was a 24 mil-thick Inconel 718 pressure vessel. A sheet of 1.27 cm thick honeycomb was placed in front of the battery cells during testing to simulate the on-orbit box enclosure. Testing was conducted at the NASA White Sands Test Facility (WSTF). The hypervelocity gun used was a 7.6 mm (0.30 caliber) two-stage light gas gun. Tests were performed at speeds of 3, 6, and 7 km/sec using aluminum 2017 spherical particles of either 4.8 or 6.4 mm diameter as the projectile. The battery cells were electrically charged to about 75 percent of capacity, then back-filled with hydrogen gas to 900 psi simulating the full charge condition. High speed film at 10 000 frames/sec was taken of the impacts. Impacts in the dome area (top) and the electrode area (middle) of the battery cells were investigated. Five tests on battery cells were performed. The results revealed that in all of the test conditions investigated, the battery cells simply vented their hydrogen gas and some electrolyte, but did not burst or generate any large debris fragments.

Test Articles

Four Ni/H₂ cells manufactured by Gates Aerospace Batteries were used for these tests. The cell exterior was an Inconel 718 cylindrical pressure vessel, 3.5 in. in diameter,

with hemispherical domes welded on both ends. The cylindrical portion of the pressure vessel had a nominal thickness of 24 mils while the dome sections were approximately 19 mils. The cells were surrounded by a 0.148 in. thick anodized aluminum 6063-T6 thermal sleeve. This sleeve was insulated from the pressure vessel by a 9 mil thick fiberglass cloth-reinforced silicone rubber sheet. The thermal sleeve extends from below the top dome down past the lower dome. The cells had a nameplate rating of 81 Ampere-hours (A-hr) with an actual capacity of 94 to 100 A-hr at 10 °C.

The positive electrodes were nickel screens containing sintered carbonyl nickel powder electrochemically impregnated with nickel hydroxide and cobalt hydroxide. The negative electrodes were nickel screens with Gortex Teflon backing coated with a platinum catalyst. The circular electrodes, having a hole in the middle, were stacked on a polysulfone core along with woven zirconium oxide cloth separators and polypropylene gas screens. All these components were held in compression by two nickel endplates. The electrolyte was a potassium hydroxide (KOH) solution of weight percent varying between 24 and 31 percent.

An aluminum 5056-H39 honeycomb with a cell size of 0.188 in. sandwiched between two 0.016 in. thick aluminum 7075-T73 face sheets was used to simulate an on-orbit box enclosure that would be used in space to protect the battery cells from direct impacts. The total thickness of the honeycomb sandwich was 0.5 in.

Prior to the Ni/H₂ cell impact tests, cell mockup tests were performed to determine the particle size/velocity combination that would be necessary for penetration. The cell mockups consisted of empty, unpressurized Inconel

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718 vessel forms, aluminum sleeve mockup plates, and the honeycomb sandwich mentioned above.

Test Facility

The hypervelocity impact tests were performed at the NASA White Sands Test Facility (WSTF). A 7.6 mm (0.30 caliber) two-stage light gas gun was used for all testing. The gun was capable of shooting projectiles up to 6.4 mm in diameter at 6 km/sec. For particles of 4.8 mm diameter or less, a velocity of 7 km/sec was obtainable. The projectiles used for all tests were aluminum 2017 spheres. The 4.8 mm particles had a mass of 0.16 g and the 6.4 mm particles were 0.38 g. A Lexan sabot, a two-piece structure that positions and supports the projectile while it is in the launch tube, was used for each test. The target chamber used had a volume of 0.37 m³.

The Ni/H₂ cells that were used for this testing were equipped with fill tubes and valves on both terminals which allowed for filling with hydrogen gas. A remotely-operated hydrogen gas fill and drain system was constructed for this purpose. A thermocouple was attached to each cell to monitor temperature. The cell voltage and current was also monitored during the electrical charging of the cells, during the hypervelocity impact, and afterwards. Flash x-rays and a laser intervalometer were used to measure the particle velocity for all tests. A high speed camera filmed each test at 10 000 frames/sec. Still photographs of the battery cells were taken before and after the impact tests.

Test Procedures

Initially, tests were performed with the mockup test articles to determine the particle sizes that would be necessary for penetration into the cell domes and sides at 3 and 7 km/sec. The resulting mockup test and actual battery test parameters are shown in Table I. These particle size/velocity combinations were at the upper limit of facility capabilities, but were sufficient for meeting our objectives of determining failure modes after penetration. During two of these mockup shots, x-rays were taken of the particle as it exited the honeycomb, prior to impacting the cells, to characterize the debris cloud. It showed that the particles broke up while going through the honeycomb and became a cone of debris. The debris appeared to be more concentrated for the 3 km/sec shot. These x-rays are shown in Fig. 1.

There were two types of mockup tests. The side shot mockup tests (1A, 2A, and 3A) consisted of a 6 by 6 in. piece of honeycomb separated by 0.9 in. from a 0.148 in. thick aluminum 6063-T6 plate (simulating the battery cell thermal sleeve). This plate was directly in front of a piece of insulator and an empty Inconel 718 vessel (simulating the battery cell). The dome shot mockup tests (1C and 2C) consisted of

TABLE I.

Test ID	Impact location	Velocity	Mockup or cell	Particle size
1A	Side	6.79 km/sec	Mockup	4.8 mm
1B	Side	6.80 km/sec	Cell	4.8 mm
1C	Dome	6.96 km/sec	Mockup	4.8 mm
1D	Dome	6.72 km/sec	Cell	4.8 mm
2A	Side	3.06 km/sec	Mockup	6.4 mm
2B	Side	3.20 km/sec	Cell	6.4 mm
2C	Dome	3.31 km/sec	Mockup	4.8 mm
2D	Dome	3.23 km/sec	Cell	4.8 mm
3A	Side	5.85 km/sec	Mockup	6.4 mm
3B	Side	5.88 km/sec	Cell	6.4 mm

a 6 by 6 in. piece of honeycomb separated by 2.0 in. from an empty Inconel 718 dome. All of these materials were weighed before and after the impacts, photographed after the impacts, and a high speed camera filmed the impacts.

For the actual cell side impact tests (1B, 2B, and 3B) a 9 by 9 in. piece of honeycomb was placed 0.9 in. from the side of the battery cell as shown in Fig. 2. The side impact shots were simulating a particle impact on the side of the honeycomb enclosure box which then impacted the battery cell. For the actual cell dome impact tests (1D and 2D) a 6 by 6 in. piece of honeycomb was placed 2.0 in. from the battery cell dome as shown in Fig. 3. This test simulated a particle impact on the top of the enclosure box which then impacted the cell dome. Due to the location of the fill tubes and valves on the cell terminals, we could not put the battery cell perpendicular to the honeycomb. It was positioned at a 45° angle. For all tests, the honeycomb face sheet was positioned perpendicular to the particle flight path. This was thought to be a worst case because the particle's path through the honeycomb is the shortest. For all the battery cell tests a 16 by 6 in. witness plate of 25 mil thick Inconel 718 was placed 2.0 in. behind the battery cell and 2.0 in. next to the battery cell parallel to it and at right angles to each other. There was also a piece of honeycomb 0.9 in. away from the cell in front of the side Inconel witness plate. The objective of these witness plates was to simulate a nearby battery cell and the enclosure box to determine if there was any secondary debris from the impact that could possibly damage other battery cells or escape from the enclosure box. All of the materials were weighed before and after the impact tests.

Prior to the start of the cell impact tests, a resistance measurement was made between the battery cells and the test fixture to insure isolation. The target tank was secured and the lines leak checked. Next, the chamber was filled with nitrogen. The cells were then electrically charged to approximately 75 percent state of charge (85 A-hrs and 750 psia). The cell voltage, current, pressure, and temperature were monitored and recorded from cell charging through post-impact. After the electrical charge was completed, the cell was filled with hydrogen to 900 psia to simulate a full charge. This was done because it would

have been difficult to fully electrically charge the battery efficiently without any cooling. After the cell filling, the chamber and flight range was evacuated to 0.4 to 0.6 psia and the shot was made. The shot was recorded using high speed film.

After the test, cell resistance measurements were made of the battery cell. Photos were taken of the test setup and individual pieces of hardware. The hardware was also individually weighed after the impact tests.

Results and Discussions

Test 1B: Side Shot at 7 km/sec

In this test a 4.8 mm diameter projectile traveling at 6.80 km/sec penetrated the honeycomb and the battery cell thermal sleeve, but did not penetrate the battery pressure vessel. The impact resulted in a dimple in the pressure vessel but the pressure integrity was maintained (as proven by a post-test helium leak check). The dimple did result, however, in the cell going into a slow self-discharge which was due to an internal short developing between some of the electrodes and the dimple in the pressure vessel. This was supported by terminal to vessel resistance readings of 0.1 and 11.4 Ω and post-test x-rays of the battery cell. The cell self-discharged and rose in temperature to 74 °C before reaching 75 psia. This cell was later retested with a larger projectile for Test 3B.

The honeycomb had a 6.6 mm diameter entrance hole. The exit hole was roughly 4.6 by 6.4 cm and was accompanied by 7 petals of varying length and curl. On the aluminum thermal sleeve, the impact area was one large crater of approximately 12.7 mm diameter with many smaller craters within a 2 cm radius. At the bottom of the large crater there was one hole of 3.3 mm diameter with two smaller holes nearby. The pressure vessel had a dimple 12.7 mm wide by 1.8 cm high and 0.345 cm deep. The Inconel witness plates had no signs of damage or debris.

The high-speed film showed that the honeycomb face sheets did not delaminate. It also showed that there was some debris traveling forward and backward at roughly 64 to 100 m/sec.

Test 3B: Side Shot at 6 km/sec

This test was performed with the same cell that was used in Test 1B. In this test, the cell was rotated 180° from the Test 1B configuration. Since the cell was electrically damaged but not penetrated in that test, the cell was not electrically charged prior to the test, but was backfilled with hydrogen to 900 psia. The projectile size was increased to 6.4 mm diameter and the corresponding velocity obtained was 5.88 km/sec.

There was complete penetration of the honeycomb, thermal sleeve, and pressure vessel in this test. The impact of the projectile on the honeycomb left a clean entrance

hole of 7.6 mm diameter. There was a tear 1.5 cm long and 4.6 mm wide 10.2 mm above the entrance hole indicating particles came back through the honeycomb and front face sheet. Figure 4 shows the inside of the delaminated front facesheet and the damage done to the interior honeycomb. The front face sheet was completely delaminated from the honeycomb which bowed toward the cell. This is shown in Fig. 5. The exit hole had a diameter of roughly 6.1 cm with 8 petals. Figure 6 shows the exit hole on the back side of the rear facesheet. There was liquid KOH on the cell side of the honeycomb.

The aluminum sleeve had a heart-shaped hole of roughly 2.0 cm in diameter with several other impacts within a radius of 2.0 cm. There was also KOH residue and black residue on the aluminum sleeve. A close-up of the impact area is shown in Fig. 7. The cell pressure vessel had a 10.2 mm diameter hole with 4 cracks between 10.2 and 17.8 mm in length emanating from it. The impact area on the bare cell after removal of the thermal sleeve can be seen in Fig. 8.

The honeycomb witness plate to the side of the cell was sprayed with a dull gray and metallic residue, along with flecks of metal. There was one 3.0 mm diameter dent and several pinhole size dents on the honeycomb. The Inconel witness plates had gray and black residue on them but were not damaged.

The high speed film and pressure data showed that the vessel vented hydrogen and KOH lasting 200 msec. The film also showed that the force of the impact caused the front face sheet of the honeycomb to delaminate. The entire piece of honeycomb whipped back and forth about 2.5 cm around the original centerline, hitting the cell and coming loose from its support structure. Several pieces of debris were also visible moving radially outward as a result of the initial rebound of the honeycomb.

Test 1D: Dome Shot at 7 km/sec

In this test a 4.8 mm diameter projectile traveling at 6.72 km/sec penetrated the battery cell dome with a series of small holes, which appeared to cause a crescent-shaped rupture 3.0 cm long formed by several holes. The ruptured section lifted 3.8 mm above the surface of the dome as a result of the cell venting. The dome impact area is shown in Fig. 9.

A clean 6.4 mm diameter hole was made in the front face sheet of the honeycomb. There were also two pinholes indicating small particles had come back through the honeycomb. The front face sheet delaminated from the honeycomb near the middle but was attached at the edges. The exit hole was about 5.08 cm high and 4.32 cm wide with 6 large petals. There was evidence of KOH on the rear face sheet.

There was also KOH on the battery cell dome and thermal sleeve. On the dome, besides the rupture, there were about a dozen small holes and some metal spattering around the impact area. The honeycomb and Inconel

witness plates had some black residue and some splashed KOH on them, but there were no signs of particle impacts.

The high speed film showed the honeycomb front face sheet delaminate and the entire sheet moved back and forth about 1.3 cm from its original position. A white vapor, presumably KOH, could be seen venting from the cell and impacting the honeycomb causing it to bend 10^0 3.9 msec after impact. A few pieces of debris were seen flying at steep angles backward and radially outward. The KOH vapor masked any further details on the debris.

Test 2B: Side Shot at 3 km/sec

In this test a 6.4 mm diameter particle traveling at 3.2 km/sec penetrated the honeycomb, the thermal sleeve and the battery pressure vessel.

The entrance hole in the front honeycomb face sheet was 7.1 mm in diameter with back-petalling around the edges indicating debris had come back through. The exit hole in the back face sheet was approximately 2.5 cm by 4.6 cm in size with 7 petals. There was liquid KOH on the rear face sheet of the honeycomb and on the cell thermal sleeve.

The aluminum thermal sleeve was bulged inward from the impact which also left a crater-like hole approximately 15.2 mm in diameter. The hole at the bottom of the crater was irregularly shaped varying from 6.1 to 12.7 mm in diameter. An area 4.1 cm wide by 3.0 cm high surrounding the crater was covered with about 2 dozen small craters and pinhole-size dents. This area was covered with deposits of residue and liquid. An energy-dispersive x-ray spectroscopic analysis (EDS) of the black deposit on the exterior of the aluminum sleeve indicated oxygen, aluminum, zirconium, potassium, iron, cobalt, nickel, platinum, and yttrium. All of these materials are found in the battery cell construction.

The impact made a dent and a fissure-like penetration into the pressure vessel. The main crack was 1.8 cm long with 1.0 and 0.8 cm long secondary cracks. At its widest point the main crack was 2.5 mm wide. A close-up of the cell penetration is shown in Fig. 10.

The honeycomb side witness plate had some gray and black residue on the front half, along with some liquid and small particles. The Inconel plates had less residue on them. There were no signs of dents or damage to either witness plate.

The high speed film showed that the honeycomb only wavered back and forth slightly and the face sheets did not delaminate. Some small debris could be seen moving outward and upward, but once again, the KOH spray masked any further details.

Test 2D: Dome Shot at 3 km/sec

In this test a 4.8 mm diameter particle traveling at 3.23 km/sec penetrated both the honeycomb and the battery pressure vessel.

The entrance hole in the honeycomb front face sheet was 5.8 mm in diameter and very clean with no signs of particles coming back through the honeycomb. The exit hole in the back face sheet was 2.0 by 1.5 cm with 5 petals.

The pressure vessel dome was penetrated in three places. Two holes approximately equal in size were closely spaced and about 5.1 mm in diameter. A third hole about 12.7 mm from the other two was 2.5 mm in diameter. White residue, presumable KOH, was splattered around the holes and it also dripped down the side of the cell. The dome impact area can be seen in Fig. 11.

The honeycomb witness plate to the side of the dome was sprayed with black and gray powder and flecks of metal, but it was not damaged by any particles. The Inconel witness plates behind and to the side of the cell showed no signs of damage.

The high speed film showed a few pieces of debris were visible which seemed to originate from the honeycomb. Approximate velocities were 37 to 42 m/sec. Nine milliseconds after the impact, the honeycomb and support structure had bent 10^0 from the force of escaping gas and liquid from the cell. A simplified thrust calculation for KOH and hydrogen emanating from the dome was performed and yielded a maximum force on the order of 210 N which would logarithmically decay over about 50 msec. This assumed an ideal, uniform, isentropic gas mixture traveling at sonic velocity and should only be considered an order of magnitude calculation.

In all of the tests, a black residue was seen on the front honeycomb face sheet and to a lesser degree on the witness plates. This seemed to come from the gas gun and the churning up of "dust" in the target chamber. Also during each test, almost immediately after impact, the cell voltage dropped to near 0 V and there was a slight temperature increase, approximately 5^0 C.

Conclusions

Ni/H₂ battery cells were impact tested at both 3 and 6 to 7 km/sec in both the dome area and the central cell stack area. During these tests the cells were fully charged with hydrogen gas at 900 psia. All of the impact tests showed that the cell responded in a benign manner. The impact simply resulted in one or more holes in the pressure vessel causing the hydrogen gas and KOH electrolyte to vent. The vessels did not rupture or burst in any way. Several secondary debris particles were seen in the high speed film but none of them damaged any of the Inconel or honeycomb witness plates. There were a few cases where some particles of debris came back through the initial impact area in the honeycomb. Based on these test results, it appears that a hypervelocity impact on a Ni/H₂ cell used in space would result in the loss of functionality of the battery of which it

was part of, but would not result in a catastrophic failure that would cascade to other cells or nearby hardware.

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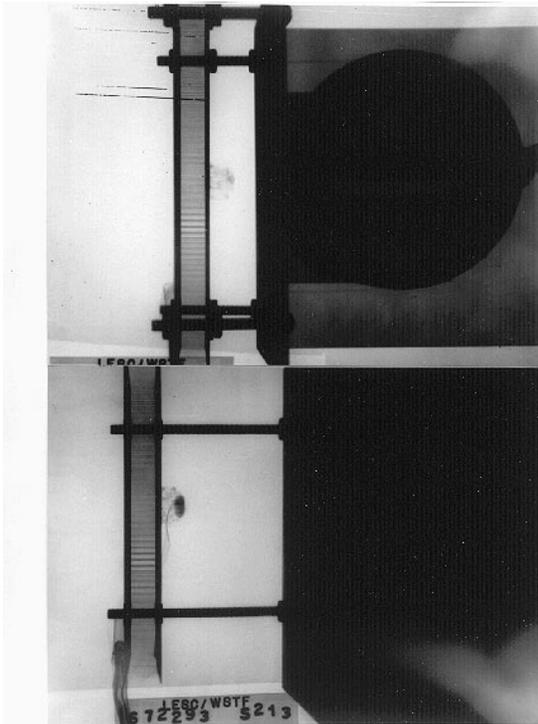


Figure 1.—X-rays of projectile after exiting the honeycomb at 7 km/sec (top) and 3 km/sec (bottom).

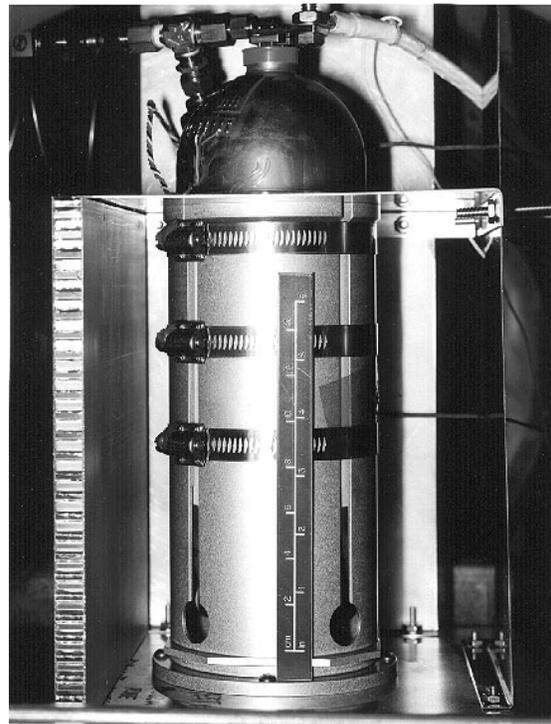


Figure 2.—Test configuration for Ni/H₂ cell side impact test. Particle approached the cell from the left impacting the honeycomb at a 90° angle.

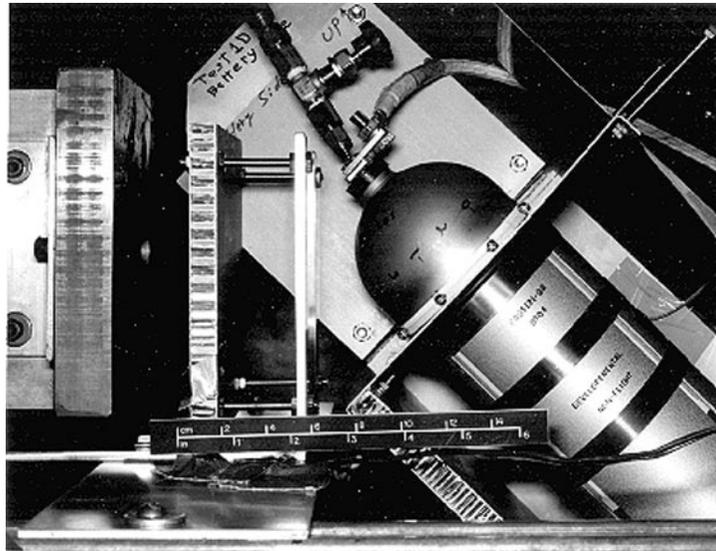


Figure 3.—Test configuration for Ni/H₂ cell dome impact test. Particle approached the cell from the left impacting the honeycomb at a 90° angle.

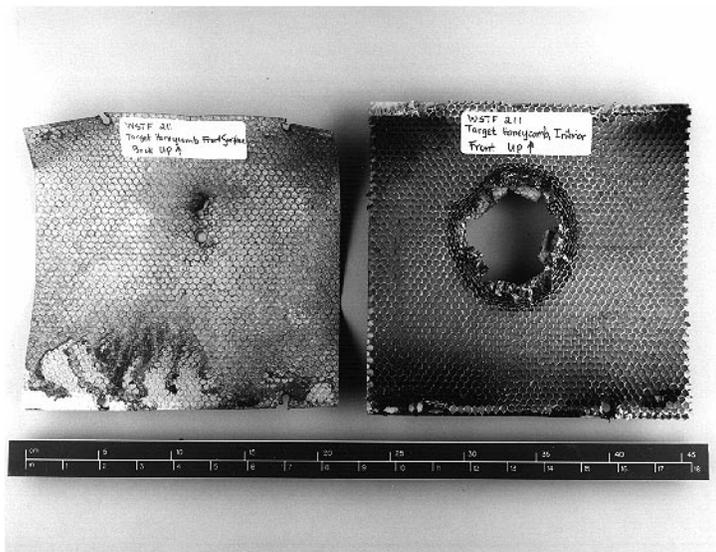


Figure 4.—The inside of the delaminated front face sheet (left) and the honeycomb (right) after the impact from Test 3B.

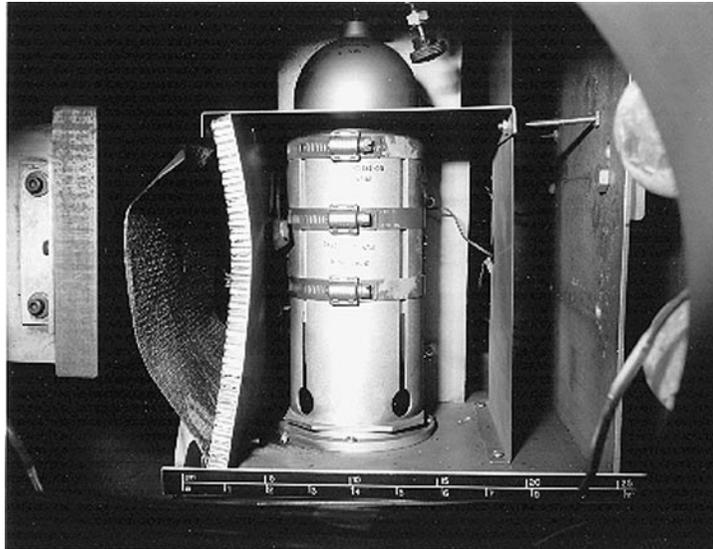


Figure 5.—Post-impact view of Ni/H₂ battery cell and honeycomb in Test 3B.

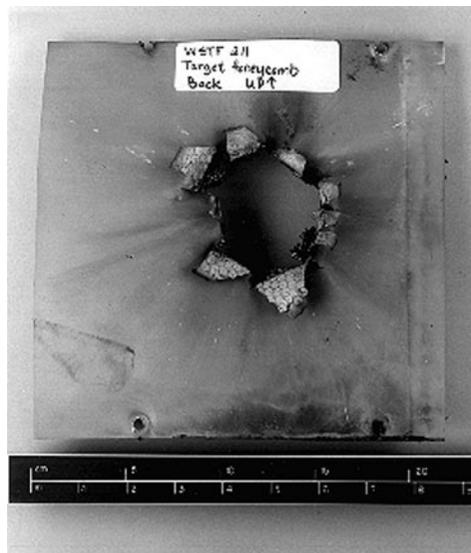


Figure 6.— The back side of the honeycomb rear face sheet from Test 3B.

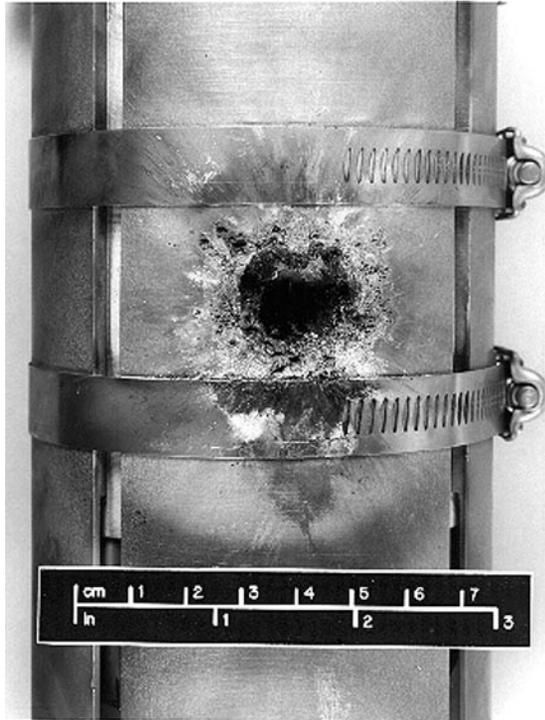


Figure 7.—Close-up of impact area on Ni/H₂ cell aluminum thermal sleeve after Test 3B.

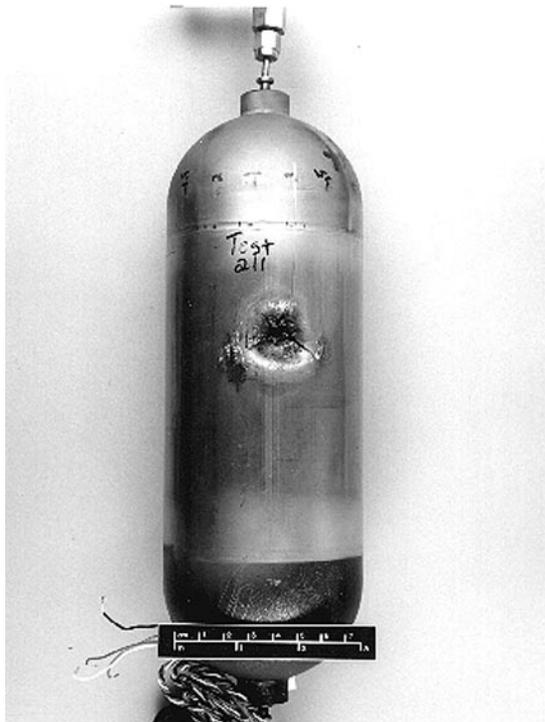


Figure 8.—Ni/H₂ battery cell without thermal sleeve after a 6 km/sec impact in Test 3B.

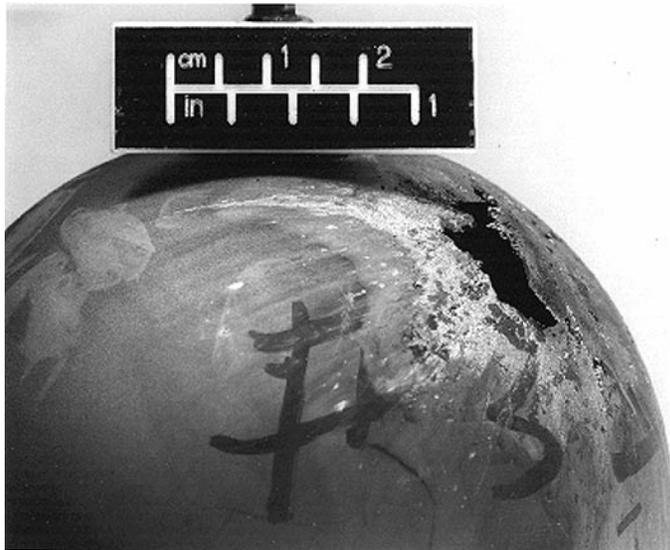


Figure 9.—Ni/H₂ battery dome from Test 1D after a 7 km/sec impact to the dome area.



Figure 10.—Close-up of Ni/H₂ battery pressure vessel (without thermal sleeve) from Test 2B after a 3 km/sec impact.



Figure 11.—Ni/H₂ battery cell from Test 2D after a 3 km/sec impact to the dome area.

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