HYPERVELOCITY IMPACT INITIATION OF EXPLOSIVE TRANSFER LINES

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The Gemini, Apollo and Space Shuttle spacecraft utilized explosive transfer lines (ETL) in a number of applications. In each case the ETL was located behind substantial structure and the risk of impact initiation by micrometeoroids and orbital debris was negligible. A current NASA program is considering an ETL to synchronize the actuation of pyrobolts to release 12 capture latches in a contingency. The space constraints require placing the ETL 50 mm below the 1 mm thick 2024-T72 Whipple shield. The proximity of the ETL to the thin shield prompted analysts at NASA to perform a scoping analysis with a finite-difference hydrocode to calculate impact parameters that would initiate the ETL. The results suggest testing is required and a 12 shot test program with surplused Shuttle ETL is scheduled for February 2012 at the NASA White Sands Test Facility.

Explosive initiation models are essential to the analysis and one exists in the CTH library for HNS I, but not the HNS II used in the Shuttle 2.5 gr/ft rigid shielded mild detonating cord (SMDC). HNS II is less sensitive than HNS I so it is anticipated that these results using the HNS I model are conservative. Until the hypervelocity impact test results are available, the only check on the analysis was comparison with the Shuttle qualification test result that a 22 long bullet would not initiate the SMDC. This result was reproduced by the hydrocode simulation. Simulations of the direct impact of a 7 km/s aluminum ball, impacting at 0 degree angle of incidence, onto the SMDC resulted in a 1.5 mm diameter ball initiating the SMDC and 1.0 mm ball failing to initiate it. Where one 1.0 mm ball could not initiate the SMDC, a cluster of six 1.0 mm diameter aluminum balls striking simultaneously could. Thus the impact parameters that will result in initiating SMDC located behind a Whipple shield will depend on how well the shield fragments the projectile and spreads the fragments. An end-to-end simulation of the impact of an aluminum ball onto a Whipple shield covering SMDC is problematic due to the hydrocode fracture models. Regardless, two simulations were performed resulting in a 5 mm ball initiating the SMDC and a 4 mm ball failing to initiate the SMDC.

Hypervelocity impact tests are being planned to confirm the findings of the simulations, and/or to provide data to update the simulations. The results from the tests will be provided in the paper.

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ABSTRACT

Hypervelocity impact tests of 2.5 grains per foot flexible confined detonating chord (FCDC) shielded by a 1 mm thick 2024-T3 bumper standing off 51 mm from the FCDC were performed. Testing showed that a 6 mm diameter 2017-T4 ball impacting the bumper at 6.97 km/s and 45 degrees impact angle initiated the FCDC. However, impact by the same diameter and speed ball at 0 degrees angle of impact did not initiate the FCDC. Furthermore, impact at 45 degrees and the same speed by a slightly smaller diameter ball (5.8 mm diameter) also did not initiate the FCDC.

1. Introduction

The Gemini, Apollo and Space Shuttle spacecraft utilized explosive transfer lines (ETL) in a number of applications.[1,2] In each case the ETL was located behind substantial structure and the risk of impact initiation by micrometeoroids and orbital debris was negligible. A current NASA program is considering an ETL to synchronize the actuation of pyrobolts in a contingency. Shielded Mild Detonating Cords (SMDC) and Flexible Confined Detonating Cords (FCDC) were considered for the ETL. The space constraints require placing the ETL 50 mm below the 1 mm thick 2024-T72 Whipple shield. The proximity of the ETL to the thin shield prompted the authors to perform a scoping analysis with a finite-difference hydrocode to calculate impact parameters that would initiate the ETL. The results suggested testing was required and a 10 shot test program with surplused Shuttle ETL was performed at the NASA White Sands Test Facility.

The scoping analysis was performed with the Sandia National Laboratory, Albuquerque, finite difference Eulerian hydrocode CTH. CTH contains an initiation model for HNS I in its materials library, but no model of the HNS II used in the Shuttle 2.5 grains per foot rigid shielded mild detonating cord (SMDC) and flexible confined detonating cord (FCDC). HNS II is less sensitive than HNS I so it was anticipated that the scoping analysis results using the HNS I model would be conservative.

Computation of the sizes of the fragments produced by projectile impact onto a bumper at 7 km/s is problematic. Therefore the first series of computations was performed with single spherical projectiles directly striking the SMDC and the size projectiles required to initiate the SMDC compared with the known sizes of projectile and bumper fragments from prior tests of aluminum balls striking aluminum bumpers at 7 km/s. The simulations of the direct impact of a 7 km/s aluminum ball at 0 degree angle of impact onto the SMDC resulted in a 1.5 mm diameter ball initiating the SMDC and 1.0 mm ball failing to initiate it. However, a bumper impact will result in a cloud of fragments so some computations with an array of six balls were performed as the second series of calculations. It was found that where one 1.0 mm ball could not initiate the SMDC, a cluster of six 1.0 mm diameter aluminum balls striking at 7 km/s simultaneously could. One mm diameter fragments are well within the realm of possibility from 7 km/s impacts, particularly if the impact is oblique, so impacts at 45 degrees obliquity were recommended for the test program.

The third series of scoping computations was an end-to-end simulation of the impact of an aluminum ball onto an 1 mm thick aluminum bumper standing off by 51 mm from the SMDC. The balls struck the bumper at 7 km/s with a 0 degree angle of impact. The two simulations resulted in a 5 mm ball initiating the SMDC and a 4 mm ball failing to initiate the SMDC.

The scoping analyses suggested that the test program include tests with 4 to 5 mm diameter balls impacting at 0 and 45 degrees angle of impact. The ETL application of interest has a small presented area, so 4 to 5 mm diameter orbital debris particles will have a small probability of impact. Therefore smaller diameter balls were added to the test program to confirm that the probability of initiation is small. The final factor to affect the test design was when the project switched the hardware design from SMDC to FCDC. All of the modeling was dependent on shock wave initiation of the explosive core and the fabric overwrap of the FCDC will propagate shock waves poorly compared with the stainless steel tubing confinement of the SMDC. Therefore, larger diameter projectiles were added to the test matrix to increase the likelihood that some test would initiate the FCDC.

2. Target Article Description

The test article configuration is comprised of the four components shown in Figure 1: a 2024-T3 aluminum alloy bumper, a multi layer thermal insulation (MLI) blanket positioned flush against the inside of the bumper, the flexible confined detonating cord (FCDC) secured to an aluminum frame with ¼ inch wire clamps, and a four layer aramid cloth (Zylon/PBO) witness plate.

The Shuttle program provided 10 surplused FCDCs for this test campaign. Eight of the test articles were part numbers 51009-2011 (serial numbers 1, 3, 4, 6 – 10) with an overall length 478 mm and two were part numbers 51009-2003 (serial numbers 8 and 14) with an overall length 563 mm. A photo of a 51099-2011 assembly is shown in Figure 2. The white fabric is the outer fabric layer of the FCDC. The two ends are rigid, shielded mild detonating cord that end in transfer tips. The ends of the transfer tips are covered by swell caps, which are used during testing to indicate whether the SMDC detonated. The swell caps are discussed below. The 10 cm scale at the bottom of the photo is for reference.

The FCDC cross section is shown in Figure 3. The central explosive core of the FCDC is 2.5 grains per foot HNS II high explosive. HNS II has good thermal stability and has been used in a variety of spacecraft applications since Apollo. The HNS is confined by a lead sheath to help sustain the detonation. The sheath is indicated by flag note 1 in Figure 3. The lead sheath is encapsulated in a polyethylene extrusion to improve the mild detonating cord formability. The remaining layers of the FCDC are there to contain the detonation products. The polyethylene extrusion is wrapped in a 1200 denier yarn Nomex fabric jacket (flag note 3), then two layers of fabric made from fiberglass yarn (Flag note 4), and finished off with two layers of fabric made from 2400 denier Nomex yarn (Flag note 5).

Swell caps are used during FCDC development and qualification to indicate detonation. If the FCDC detonates during test, then the 14.22 mm diameter swell cap will expand by 0.5 mm or more. Deflagration of the mild detonating cord results in less expansion. Swell caps are on both ends of the FCDC shown in the photograph in Figure

2. The line drawing in Figure 4 illustrates the transfer tips that are covered by the swell caps in the photograph. The right hand side of the FCDC in Figure 4 has a swell cap threaded on to the transfer tip and the left side of the figure shows an exposed transfer tip. The transfer tips thread into initiators, junctions, etc., to build up the explosive transfer line.

3. Test Procedure

The tests were performed using Aluminum 2017-T4 balls. Projectile diameter and mass were measured and reported prior to the test. Three impact conditions were tested: 7 km/s at 0 deg impact angle, 7 km/s at 45 deg impact angle, and 4 km/s at 0 deg impact angle. Three projectile diameters were used at each of the 3 impact-speed/impact-angle test condition. The initial projectile diameter at each test condition was 3.4 mm diameter and projectile diameter for subsequent tests were increased or decreased based on the criteria shown in Figure 4. The resulting test matrix from the application of the decision tree during the testing is shown in Table 1. The largest diameter ball at the largest impact angle was required to detonate the FCDC.

The targets were positioned in the test chamber so that the impact would be directly over the FCDC. However, not all impacts occurred at the aim point. The cross range miss distances measured to the nearest 0.5 mm are listed in Table 1, column 7. A positive value missed to the right from the point of view along the projectile velocity vector, and a negative value missed to the left. The FCDC is 7.49 mm in diameter, so the average miss distance was 0.51 diameters, with a standard deviation of 0.67 diameters.

The test articles were built up at the NASA Johnson Space Center and shipped to the NASA White Sands Test Facility Remote Hypervelocity Test Laboratory[3] for testing.

The 17 caliber range was used for launching the 3.4 mm balls and the 50 caliber range was used for the larger sizes.

Impact speed was measured using laser velocity gates. Upper bound uncertainty on the 17 caliber speed measurement ranges from 0.6% to 1.8%, depending on which laser stations are used. The upper bound uncertainty on the 50 caliber speed measurement ranges from 0.43% to 1.63%, again dependent on which laser stations are used for the measurement.

The projectile integrity is confirmed before impact using ultra high speed imagining system cameras. The typical setup captures a shadowgraph of the projectile before impact.

The flight range and target chamber pressures were maintained below 2.5 torr in the 17 caliber range and 14 to 16 torr in the 50 caliber range.

4. Test Results

The test conductor's summary of the FCDC condition following the tests are summarized in Table 2. As noted in the table, the largest size projectile at the largest impact angle planned for these tests was required to initiate the FCDC.

A photograph of the post-test condition of the test article that detonated (HITF12030) is shown in Figure 6. The bumper is at the top of the photograph and the witness sheet at the bottom. The 6 mm diameter 2017-T4 projectile was traveling at 6.97 km/s and impacted at 45 degrees from the bumper normal. The projectile trajectory was in the plane of the photo and was traveling from right to left. The FCDC was severed and two parts can be seen on the left and right hand sides of the photograph. The left hand (down range) side of the severed FCDC detonated and the right hand side did not. The

FCDC was not disturbed prior to the taking of the photograph and the curled back position of the right hand side of the FCDC is the final rest position following the impact.

The swell cap from the detonating end of the HIT12030 FCDC is shown on the left hand side of Figure 7. The swell cap on the right hand side of Figure 7 is unused and is shown for reference. The final diameter of the swell cap was 15.21 mm. The initial diameter of the swell cap was 14.22 mm for a change in diameter of 0.99 mm. Remember that the diameter change used during qualification testing to indicate detonation is 0.5 mm or larger. So the observed change in diameter is well within the range of that indicating detonation.

5. Discussion

Vendor qualification testing of the Shuttle SMDC included a ballistic test campaign using 22 long bullets. The SMDC failed to initiate in every ballistic qualification test. However, these tests have demonstrated that hypervelocity impacts that result in sufficiently large amplitude shocks for sufficiently long durations will initiate FCDC. Hence, while FCDC is resistant to impact initiation, and by analogy SMDC, theey are not immune.

These tests were intended to aid the assessment of the risk of FCDC initiation by MMOD impact. However, that assessment is hampered by the small data set. More testing is required to resolve two issues. First, tests are needed that initiate the FCDC at a variety of impact angles and speeds to complement the tests reported here that did not initiate the FCDC. These tests are need to determine the impact conditions leading to failure for the risk assessment. Second, testing is needed to determine how far cross range the impact may be and still initiate the FCDC. These tests are needed to determine the vulnerable area of the FCDC when projected onto the bumper.

6. Conclusion

It was demonstrated by test that 2.5 grains per foot flexible confined detonating cord may be initiated by hypervelocity impact when shielded by a bumper. However, insufficient testing was performed to assess the overall risk of initiation in the intended application.

Acknowledgements

B. Alan Davis of the NASA Johnson Space Center Hypervelocity Impact Technology group was the test conductor.

References

1. NASA TM 110172. A Manual for Pyrotechnic Design, Development and Qualification. National Aeronautics and Space Administration. Washington DC, June 1995.
2. NASA TN D-7141. Apollo Experience Report – Spacecraft Pyrotechnic Systems. National Aeronautics and Space Administration. Washington DC, March 1973.
3. NASA-Remote Hypervelocity Test laboratory (RHTL) http://www.nasa.gov/centers/wstf/laboratories/hypervelocity/rhtl.html. Last accessed March 23, 2012.

Table 1 Test Matrix

Test Number	Projectile Diameter (mm)	Projectile Mass (g)	Actual Velocity (km/s)	Impact Angle (deg)	Cross range impact offset (mm)	detonation
HITF12025	3.4	0.05778	6.81	0°	+4.0	no
HITF12028	3.4	0.05777	6.80	45°	+2.5	no
HITF12031	3.4	0.05777	3.96	0°	0.0	no
HITF12026	5.0	0.18408	6.89	0°	+6.0	no
HITF12029	5.0	0.18409	6.89	45°	-2.0	no
HITF12032	5.0	0.18404	4.00	0°	+10.0	no
HITF12027	6.0	0.31179	7.04	0°	+0.5	no
HITF12030	6.0	0.31187	6.97	45°	-2.5	yes
HITF12033	6.0	0.31189	4.06	0°	+7.0	no
HITF12034	5.8	0.28586	7.02	45°	+12.5	no

Test Number	Detonation cord damage
HITF12025	Outermost Nomex overbraid was perforated exposing a 20.9 x 7.5 mm area of the second Nomex overbraid. Within this exposed area was a 3.9 x 3.5 mm area of severed strands on the second Nomex overbraid. The diameter of the swell caps was unchanged. (note 1)
HITF12028	Outermost Nomex overbraid was perforated exposing a 14.1 x 8.7 mm area of the second Nomex overbraid. Within this exposed area was a 4.4 x 3.5 mm perforation of the second Nomex overbraid exposing the first fiberglass overbraid. The diameter of the swell caps was unchanged.
HITF12031	All three Nomex overbraids and all two fiberglass overbraids were perforated exposing a 2.4 x 2.2 mm area of the polyethylene extrusion. The polyethylene extrusion was not perforated. The diameter of the swell caps was unchanged.
HITF12026	All three Nomex overbraids and all two fiberglass overbraids were perforated exposing a 4.3 x 3.0 mm area of the polyethylene extrusion. Within the exposed area a 1.4 x 0.8 mm area of the polyethylene extrusion was perforated, exposing the lead sheath beneath. The diameter of the swell caps was unchanged.
HITF12029	FCDC completely severed with HNS visible on the severed ends of the lead sheath. The diameter of the swell caps was unchanged.
HITF12032	The outermost Nomex overbraid was perforated exposing a 24.0 x 7.2 mm area of the second Nomex overbraid. Within this exposed area were several severed areas of the second Nomex overbraid with the largest being 4.5 x 4.1 mm. The diameter of the swell caps was unchanged.
HITF12027	FCDC completely severed with HNS visible. The diameter of the swell caps was unchanged.
HITF12030	FCDC completely severed with HNS visible on the exposed up range end. The down range end had no HNS visible in the severed end of the lead sheath. The swell cap diameter on the up range end was unchanged and the swell cap diameter on the down range end grew from 14.22 mm to 15.21 mm. (note 2)
HITF12033	Perforation of the Nomex and fiberglass overbraids down to the third Nomex overbraid occurred. This exposed 24.0 mm of the third Nomex overbraid. The third Nomex overbraid had multiple severed strands throughout this area with the most significant damage a 2.6 x 1.9 mm perforation that exposed the polyethylene extrusion and the lead sheath. The diameter of the swell caps was unchanged.
HITF12034	All three Nomex overbraids and all two fiberglass overbraids were perforated exposing a 2.4 x 1.9 mm area of the polyethylene extrusion. The diameter of the swell caps was unchanged.
Notes: 1. Overbraids are counted from the exterior to the interior mild detonating chord. 2. Up range and down range refers to the direction of travel of the projectile, with	

down range being the projectile direction of travel. The axis of the SMDC was in the plane of the projectile trajectory and the bumper normal.

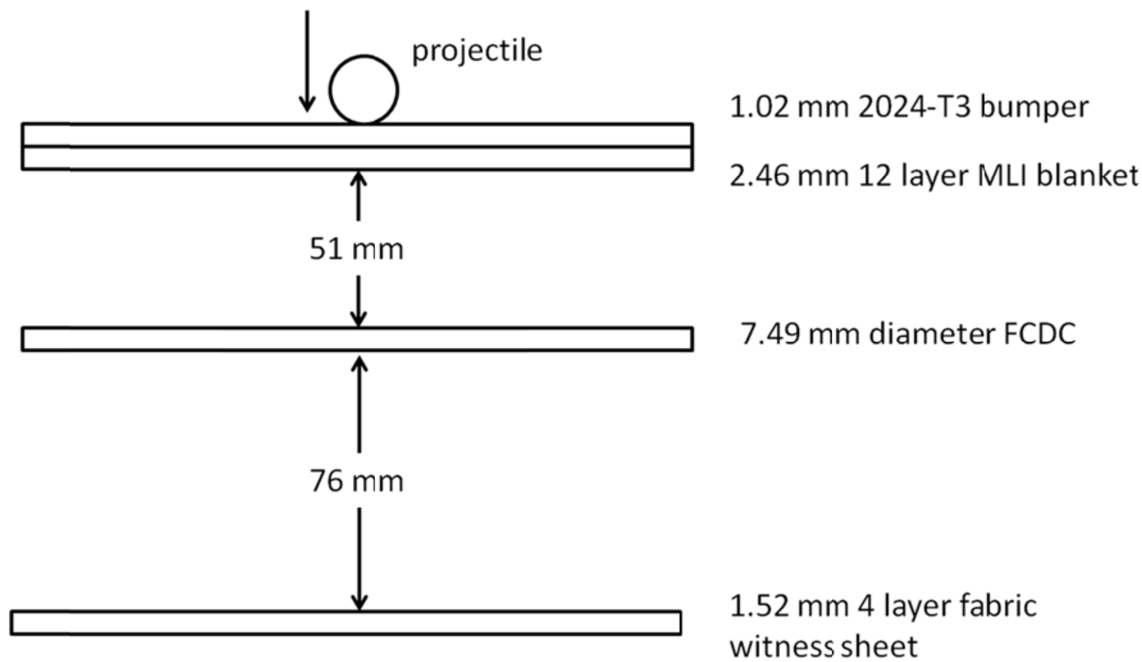

Figure 1. Schematic diagram of the test article shot line.

Figure 2. Photograph of FCDC assembly tested (P/N 51009-2011)

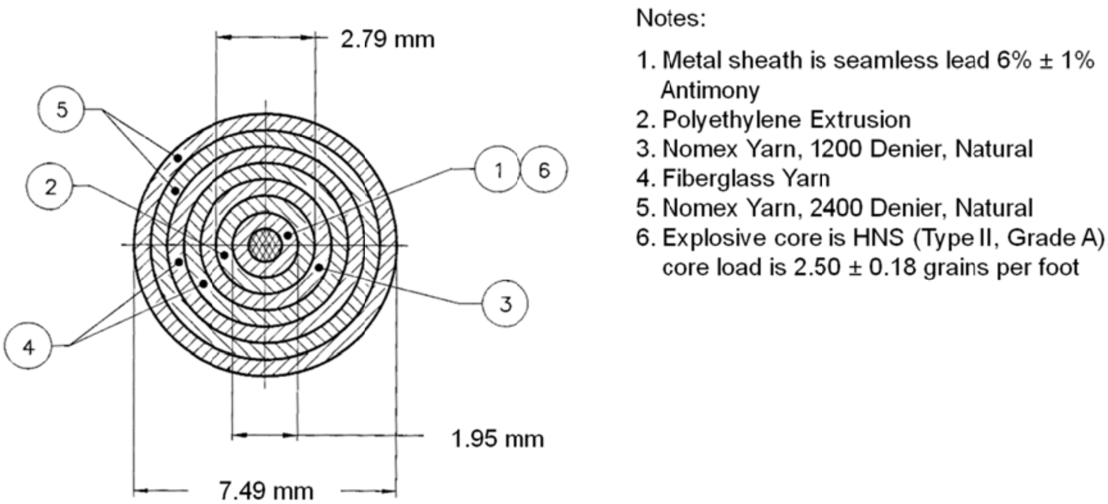

Figure 3. FCDC cross section.

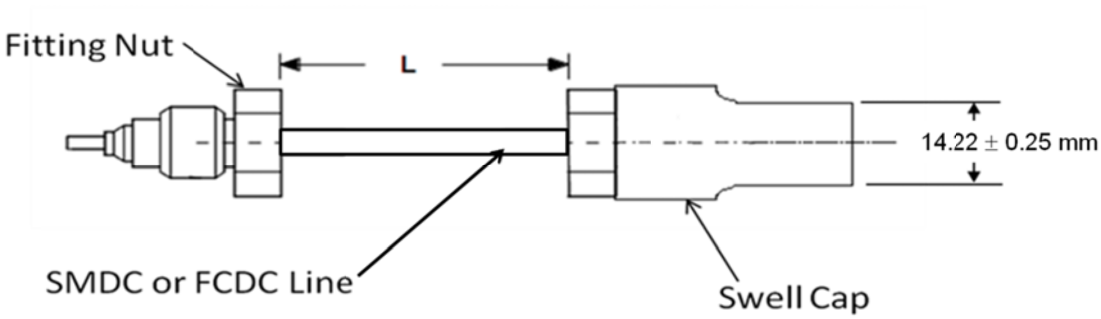

Figure 4. FCDC assembly with swell cap.

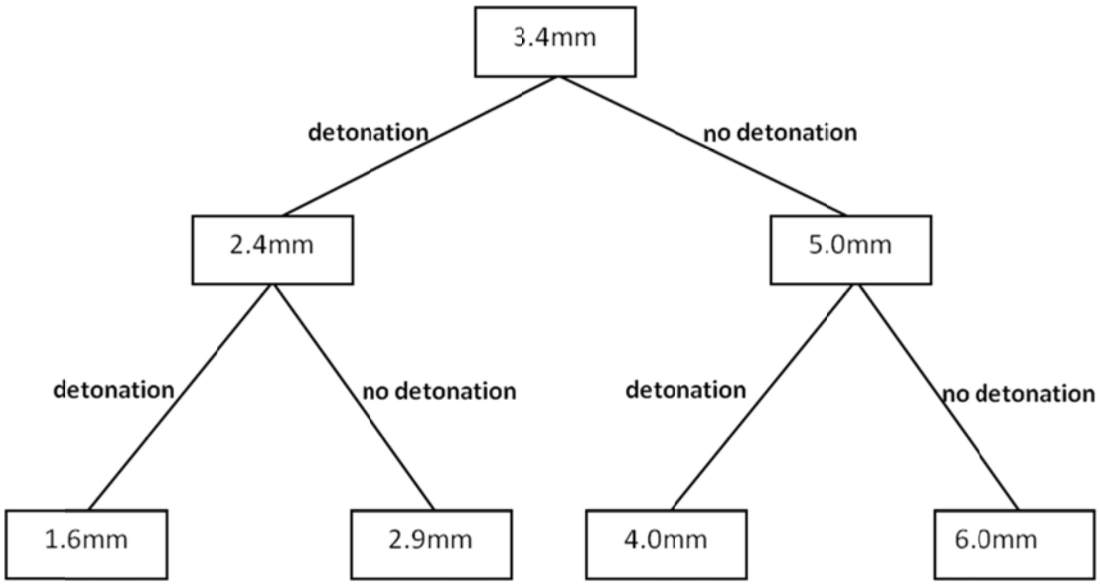

Figure 5. Projectile diameter selection decision tree.

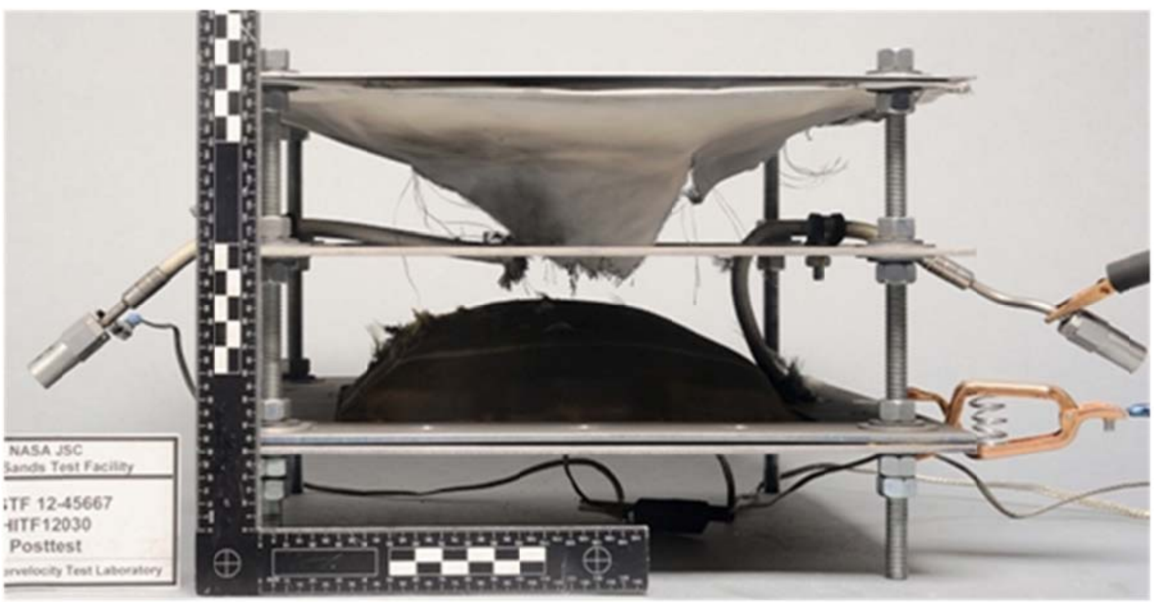

Figure 6. HITF12030 test article, post-test. The projectile impacted at a 45 degree angle and was traveling from right to left in the photo. The bumper is at the top of the photo. The FCDC was severed by the impact. Detonation occurred in the left hand side of the FCDC, but not the right hand side.

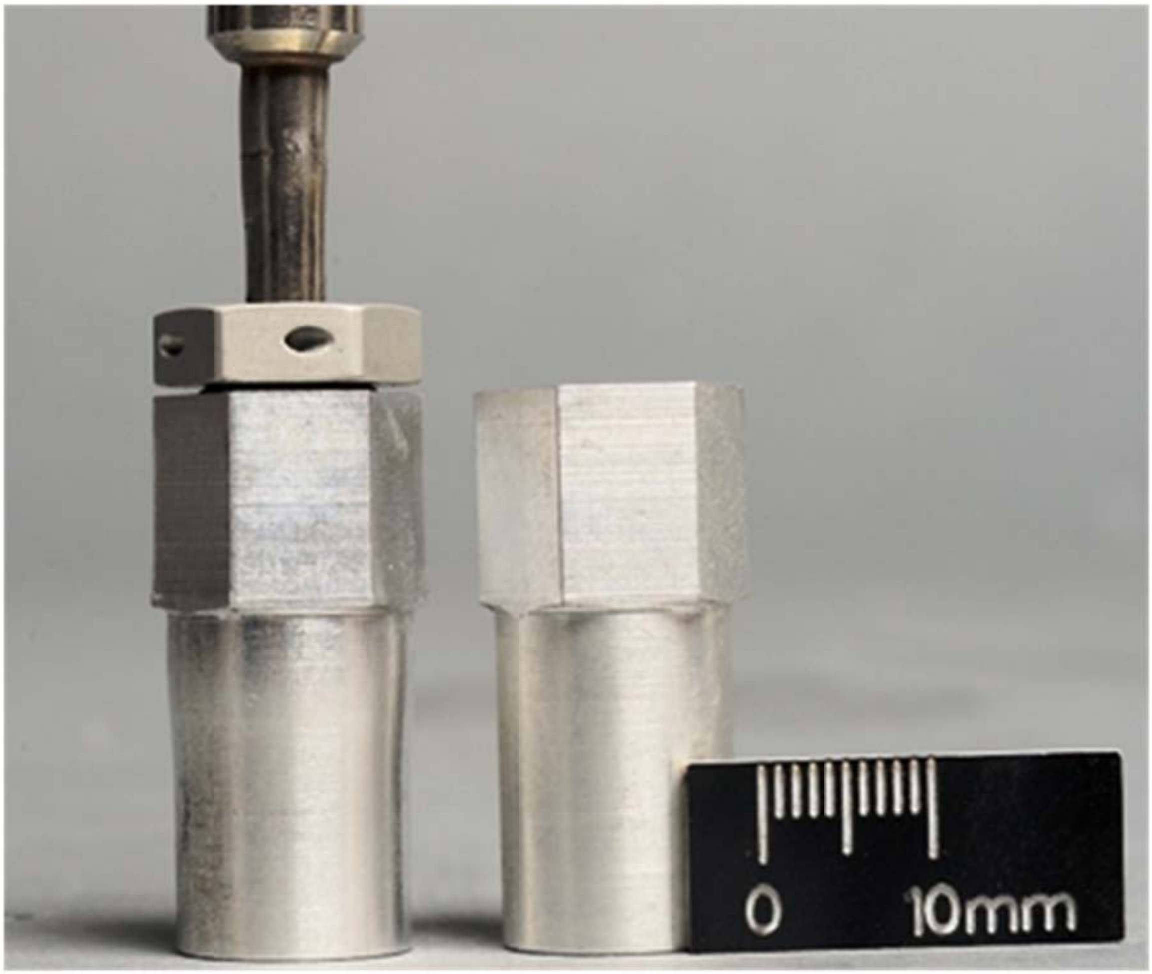

Figure 7. The swell cap on the left is the cap from HITF12030 that indicated detonation. The cap on the right is an unused swell cap for reference.