Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 00 (2012) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

The 12th Hypervelocity Impact Symposium

Hypervelocity impact of explosive transfer lines

Michael D. Bjorkman[a],*, Eric L. Christiansen[b]

[a]Jacobs Technology, 2224 Bay Area Blvd, Houston, TX,77058 , USA
[b]NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX, 77058, USA

Abstract

Hypervelocity impact tests of 2.5 grains per foot flexible confined detonating chord (FCDC) shielded by a 1 mm thick 2024-T3 aluminum alloy bumper standing off 51 mm from the FCDC were performed. Testing showed that a 6 mm diameter 2017-T4 aluminum alloy 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.

Keywords: Hypervelocity; flexible confined detonating cord; HNS II

---

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 Flexible Confined Detonating Cord (FCDC) for an ETL to synchronize the actuation of pyrobolts during a contingency. The space constraints require placing the ETL 51 mm inside the 1 mm thick 2024-T72 aluminum alloy Whipple shield. A schematic diagram of the proposed layup is shown in Figure 1. A micrometeoroid or orbital debris (MMOD) particle perforating the layup would first impact the aluminum Whipple shield and the multilayer thermal insulation blanket (MLI)[3], which is in contact with the interior of the Whipple shield. The MMOD and Whipple shield fragments would then traverse a 51 mm space before impacting the 7.49 mm diameter FCDC. The proximity of the ETL to the thin shield prompted the authors to suggest testing was required and a 10 shot test program with surplused Shuttle ETL was performed at the NASA White Sands Test Facility.

2. Test 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 readily available 2024-T3 was substituted for the 2024-T72 used in the design for convenience. The 2024-T3 has an 8% larger tensile ultimate strength which should therefore lead to a slightly smaller hole in the shield and less shield fragment mass launched against the FCDC, thereby leading to a small under test.

---

* Corresponding author. Tel.: +1-281-244-6961 ; fax: +1-281-283-4212 .
E-mail address: michael.d.bjorkman@nasa.gov.

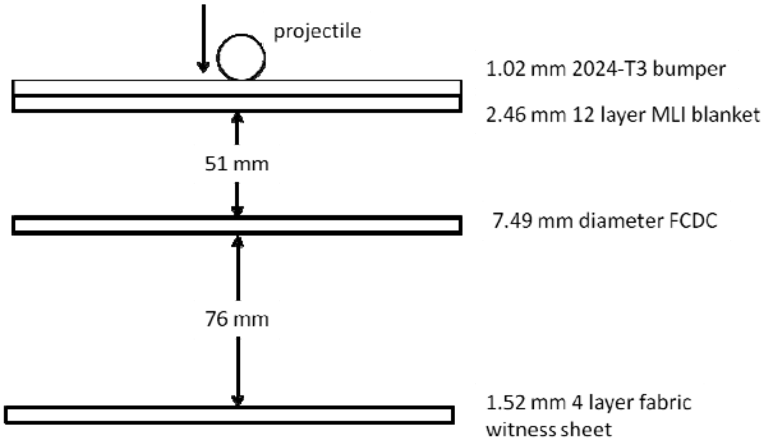
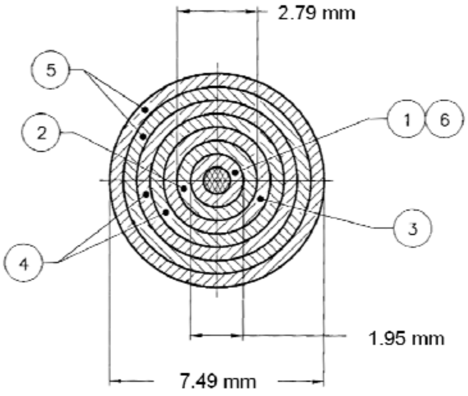


Fig. 1 Schematic diagram of the test article shot line.

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 formed tubing ends are shielded mild detonating cord; FCDC with the fabric overbraid replaced by a CRES tube. The very ends of the FCDC are the CRES transfer tips. (See the left hand side of Figure 4.) The ends of the transfer tips are covered by 2024-T351 aluminum alloy swell caps, which are used during testing to indicate whether the FCDC 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 explosive. HNS II has good thermal stability and has been used in a variety of spacecraft applications since Apollo[3]. HNS II is recrystallized HNS I. The larger grain size from re-crystallization improves the free-flowing characteristics of the powder making it especially suitable to packing the sheath of mild detonating fuse.[4] (For other HNS II physical properties and standard test results the reader is referred to [4] and [5].) The FCDC lead 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). (Nomex is a DuPont meta aramid product for

Fig. 2 Photograph of a Shuttle FCDC assembly (P/N 51009-2011)



Notes:

1. Metal sheath is seamless lead 6% ± 1% Antimony
2. Polyethylene Extrusion
3. Nomex Yarn, 1200 Denier, Natural
4. Fiberglass Yarn
5. Nomex Yarn, 2400 Denier, Natural
6. Explosive core is HNS (Type II, Grade A), core load is 2.50 ± 0.18 grains per foot

Fig. 3 FCDC cross section

high temperature applications.)

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 outline of 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[1].

3. Test Procedure

The tests were performed using 2017-T4 aluminum alloy 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 conditions. The initial projectile diameter at each test condition was 3.4 mm diameter. The next ball diameter tested was selected by traversing the decision tree shown in Figure 5 from top to bottom. This procedure will bracket the detonation/no detonation condition if a ball 6 mm or smaller in diameter can detonate the FCDC. 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 second column of Table 1 lists the vendor's advertised ball diameter.

The third column lists the ball mass measured in our lab using a Sartorius CP225D analytical scale. The test engineer sorts through the laboratory ball stock and picks out balls for each test campaign that weigh the expected amount for the desired diameter. Hence the tested ball masses are the same to ±0.1 mg for each size.

The fourth column lists the measured impact speed. 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[6] 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

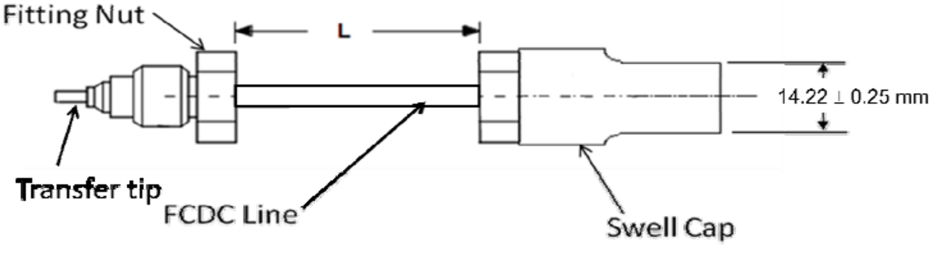


Fig. 4 FCDC assembly with swell cap.

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.

Table 1 Test matrix

Test Number	Nominal Projectile Diameter (mm)	Projectile Mass (mg)	Impact Speed (km/s)	Impact Angle (deg)	Cross range impact offset (mm)	detonation
HITF12025	3.4	57.78	6.81	0°	+4.0	no
HITF12028	3.4	57.77	6.80	45°	+2.5	no
HITF12031	3.4	57.77	3.96	0°	0.0	no
HITF12026	5.0	184.08	6.89	0°	+6.0	no
HITF12029	5.0	184.09	6.89	45°	-2.0	no
HITF12032	5.0	184.04	4.00	0°	+10.0	no
HITF12027	6.0	311.79	7.04	0°	+0.5	no
HITF12030	6.0	311.87	6.97	45°	-2.5	yes
HITF12033	6.0	311.89	4.06	0°	+7.0	no
HITF12034	5.8	285.86	7.02	45°	+12.5	no

The fifth column of Table 1 lists the cross range impact offset in mm. 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 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.

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.

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.

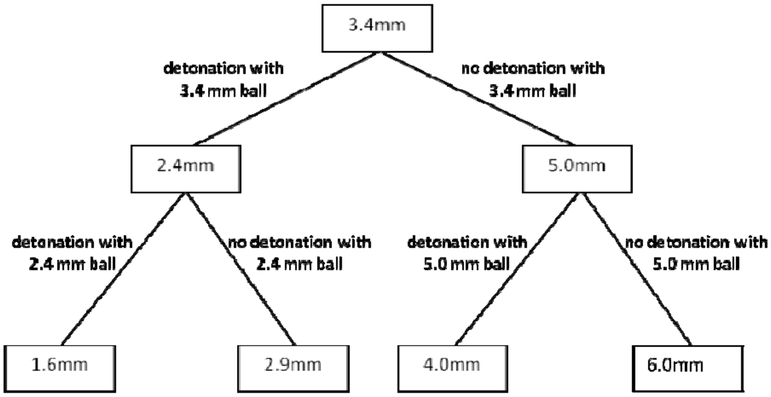


Fig. 5 Projectile diameter selection decision tree.

Table 2. Test results.

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.[a]
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.[b]
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:

[a]. Overbraids are counted from the exterior to the interior mild detonating chord.

[b] 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 FCDC was in the plane of the projectile trajectory and the Whipple shield normal.

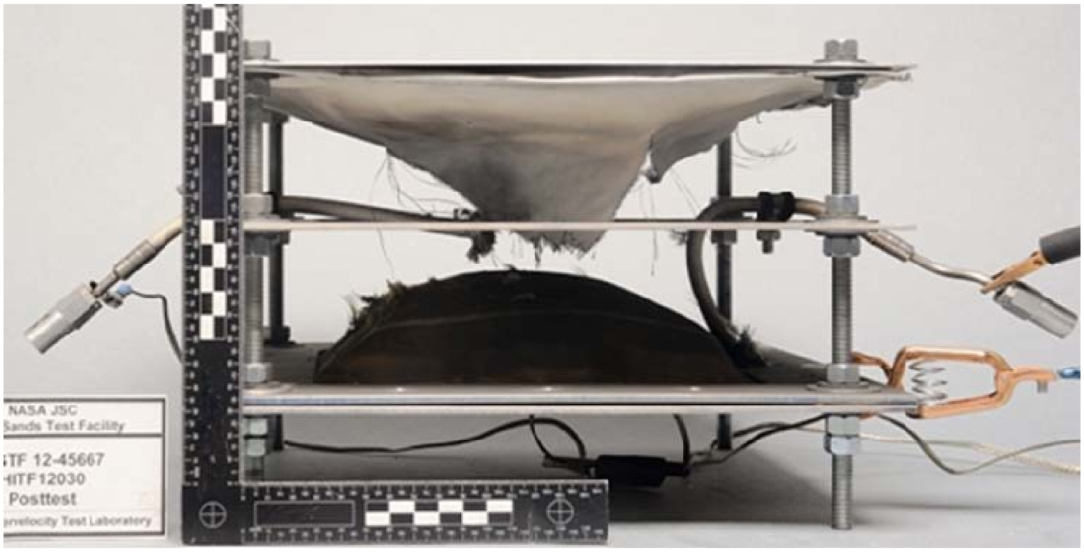


Fig. 6 HITF12030 test article, post-test. The projectile impacted at a 45 degree angle and was traveling from right to left in the photo. The bumper is at the top of the photo. The FCDC was severed by the impact. Detonation occurred in the left hand side of the FCDC, but not the right hand side.

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 aluminum alloy 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 HITF12030 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

Explosive transfer lines are typically categorized as impact insensitive. The vendor qualification report for the Shuttle ETL qualification cited that all tests with 22 long bullets and 38 caliber bullets failed to initiate the explosive transfer line[7]. However, these tests have demonstrated that a hypervelocity impact can initiate FCDC. Hence, while FCDC is insensitive to initiation from an impact it is 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 can occur and still initiate the FCDC. These tests are needed to determine the vulnerable area of the FCDC.

6. Conclusion

It was demonstrated by test that 2.5 grains per foot flexible confined detonating cord, protected by a Whipple shield, can be initiated by a hypervelocity impact. However, more testing is required to determine how the conditions for detonation vary with impact speed, angle and ball diameter before an assessment of the overall risk of initiation in the intended

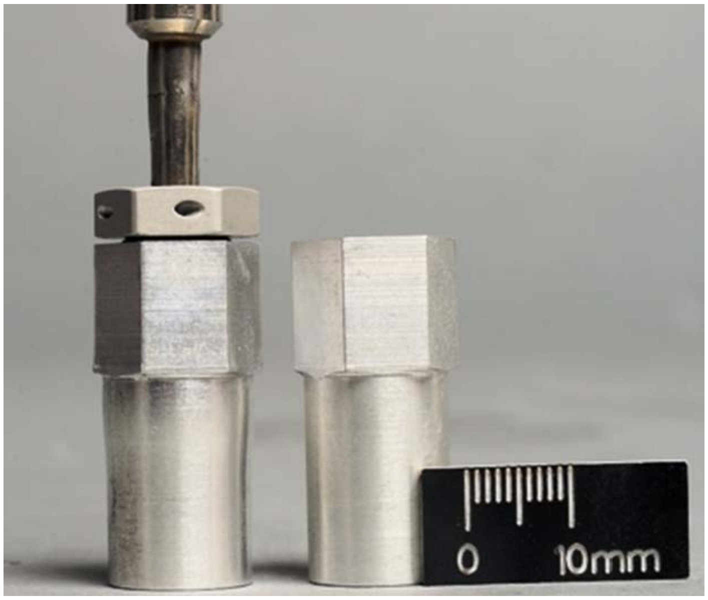


Fig. 7 The swell cap on the left is the cap from HITF12030 that indicated detonation.
The cap on the right is an unused swell cap for reference.

application is possible.

Acknowledgements

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

References

[1] A Manual for Pyrotechnic Design, Development and Qualification. NASA TM 110172. National Aeronautics and Space Administration. Washington DC, June 1995.
[2] Apollo Experience Report – Spacecraft Pyrotechnic Systems. NASA TN D-7141. National Aeronautics and Space Administration. Washington DC, March 1973.
[3] Reflective Superinsulation Materials. NASA CR-2507. National Aeronautics and Space Administration. Washington DC, January 1975
[4] Development of a High Temperature Resistant Mild Detonation Fuse. NASA CR-135472. National Aeronautics and Space Administration. Washington DC, January 1966.
[5] Application of Hexanitrostilbene (HNS) in Explosive Components. SC-RR-71 0673. Sandia Laboratories, Albuquerque, NM, May 1972.
[6] NASA-Remote Hypervelocity Test laboratory (RHTL) http://www.nasa.gov/centers/wstf/laboratories/hypervelocity/rhtl.html. Last accessed March 23, 2012.
[7] Shuttle Protechnic Devices Qualification Test Report. 3349(01)QTR(A). Explosive Technology, Inc., Fairfield, CA.