AXAF HYPERVELOCITY IMPACT TEST RESULTS

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ABSTRACT

Today many spacecraft are using composite and honeycomb panels for key structural components. This paper will discuss the test results and analysis for six different composite and honeycomb combinations used on the Advanced X-Ray Astrophysics Facility (AXAF). Test results for a power and signal cable bundle will also be given. The tests planned for the multi-layer insulation (MLI) blanket, and four types of cable bundles will also be discussed. All four bundles will be tested with a MLI blanket in front of them and two will be tested behind composite/honeycomb spacecraft panels. Due to funding and scheduling problems this testing was not completed in time for the data to be included in this paper. Tests should be complete by the end of May and results available at the end of June.

1. INTRODUCTION

In August of 1988, TRW of Redondo Beach, California, was selected by the National Aeronautics and Space Administration (NASA) as the prime contractor for the development and initial operation of the Advanced X-Ray Astrophysics Facility.

AXAF consists of a highly sensitive x-ray telescope and the associated detecting devices attached to an octagonal spacecraft with an internal propulsion system. Weighing roughly 5,200 kg, AXAF will be approximately 11.9 m long by 4.2 m in diameter. It is scheduled to be launched aboard the Space Shuttle in August 1998. After being deployed from the orbiter, an inertial upper stage and then the internal propulsion system will be used to insert AXAF into a high elliptical orbit with a perigee of 10,000 km and an apogee of at least 100,000 km. The desired apogee is 140,000 km. The orbit was selected to provide increased observing time for capturing high-resolution images and spectra of X-ray sources during AXAF's five year mission life.

The spacecraft structural panels and optical bench are made of two different graphite fiber reinforced polyimides (GFRP) or composite panels bonded to the front and back of an aluminum honeycomb. Several variations of the M60J/954 material are used but all have the same density and ultimate tensile strength. The facesheet material and thickness, as well as, the honeycomb cell diameter and thickness varied with the location on AXAF and its application. Although composite panels, with and without honeycomb cores, are being more widely used for spacecraft structures and components, their ability to withstand the meteoroid and orbital debris environments is not well documented. Equations and models have not been developed yet to account for the differences in the behavior of composites and aluminum. As a result ballistic limit predictions are made using the New Cour-Palais or "Whipple" shield equation and a modified version of the Schmidt-Holsapple single plate equation (Ref.1) developed for aluminum.

AXAF is required to have a probability of no failure of any critical item due to meteoroids/debris of at least 0.92 for the five year mission. Since the observatory is only in low-earth orbit for the six hour duration of its orbital transfer maneuver, the orbital debris environment was determined to be negligible when compared to the meteoroid environment over the five year mission. In order to determine the probability of no failure, the ballistic limit of the material and the meteoroid flux for particles that size and larger must first be determined. The purpose of the hypervelocity impact testing of the composite panels was to determine the ballistic limit range and the extent of damage to the panels due to impact.

2. TESTS COMPLETED

The 0.17 caliber light gas gun at the NASA Johnson Space Center's (JSC) Hypervelocity Impact Test Facility was used to perform two types of tests for the AXAF program. The first set was done to determine the ballistic limit of six different composite facesheet and honeycomb combinations. The second set was to determine the amount of damage to unprotected power and signal wires due to a hypervelocity impact. For all of the testing, spherical projectiles of 2017 aluminum were used. Impact velocities were between 6.5 and 7.5 km/s at an impact angle of 0 degrees.

2.1 GFRP Tests

Seven different configurations of MLI, composite facesheets, and aluminum honeycomb were tested. The material and multi-layer insulation (MLI) type, the location on AXAF, the facesheet thickness, the honeycomb thickness, and the honeycomb cell diameter for each test sample configuration is shown (Table 1).

Material	MLI	Location	Facesheet Thickness (cm)	Honeycomb Thickness (cm)	Cell Diameter (cm)
M60J/954-2A	ABC	S/C Panels	0.0254	1.5875	0.3175
M60J/954-2A	ST	S/C Panels	0.0254	1.5875	0.3175
P100	ST	S/C Panels	0.0762	1.5875	0.3175
M60J/954	ABC	Optical Bench	0.0508	0.6350	0.3175
M60J/954	ABC	Optical Bench	0.1016	0.6350	0.3175
M60J/954	ABC	Optical Bench	0.1524	0.6350	0.3175
M60J/954-3	KF	TFTE	0.0406	0.6350	0.0254

ABC - Aluminized Beta Cloth ST - Silver Teflon KF - Kapton Film

Table 1. Test sample materials

The MLI was attached to the front facesheet of the sample with duct tape and at least one 0.1016 cm aluminum 2024-T3 witness plate was placed 2.54 cm behind the back face prior to testing (Fig. 1). The P100 samples also had a 0.00762 cm thick aluminum foil bonded to the back facesheet.

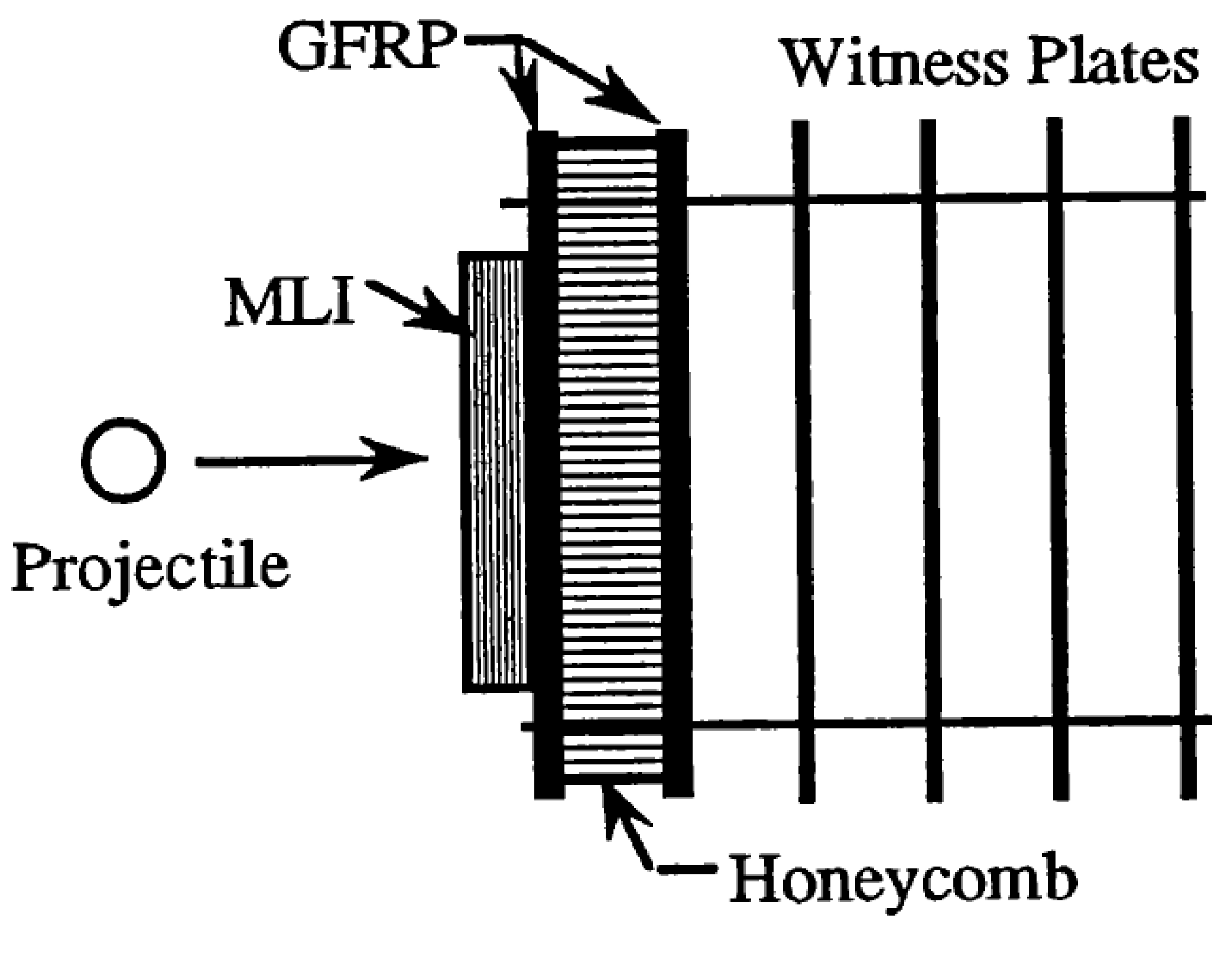

Figure 1. Test sample configuration

The AXAF external flight MLI blanket consists of a silver/teflon/inconel laminate cover layer bonded to an "outer" layer of aluminized kapton, 22 filler layers of aluminized kapton, 23 separator layers of dacron netting, and an inner layer of aluminized kapton. This blanket is used on all external spacecraft structure, however, due to the small quantity available for testing, aluminized beta cloth was substituted for the silver teflon cover layer for most of the tests. The remaining MLI blanket layers were the same. The telescope forward thermal enclosure (TFTE) is internal to the optical bench and used an MLI blanket of 24 layers of aluminized kapton separated by 22 layers of dacron netting. The optical bench is constructed of M60J/954 having three different facesheet thicknesses, the telescope forward thermal enclosure (TFTE) uses M60J/954-3, the spacecraft panels are made of P100 or T300, with M60J/954-2A being used for the forward and aft closeout panels.

2.1.1 GFRP test results

A ballistic limit range was determined for each of the material configurations tested. A sample was considered to have failed if the rear facesheet was penetrated and to have passed if the rear facesheet was not penetrated (Table 2). This allowed the range in which the ballistic limit occurs to be determined. However, due to the limited number of samples and the uncertainties of the initial calculations, the range is larger than desired for some of the materials (Table 2).

Shot Number	Facesheet Material	Facesheet Thickness (cm)	Projectile Diameter (cm)	Velocity (km/s)	Passed or Failed
A-2634	M60J/954-2A	0.0254	0.11906	7.04	Failed
A-2635	M60J/954-2A	0.0254	0.07938	7.04	Passed
A-2636	P100	0.0762	0.15875	6.65	Failed
A-2637	P100	0.0762	0.11906	6.80	Passed
A-2675	M60J/954-2A	0.0254	0.11906	7.26	Failed
A-2639	M60J/954	0.0508	0.15875	6.64	Failed
A-2640	M60J/954	0.0508	0.11906	6.66	Failed
A-2641	M60J/954	0.0508	0.07938	6.81	Passed
A-2642	M60J/954	0.1016	0.23813	6.63	Failed
A-2643	M60J/954	0.1016	0.19844	6.77	Failed
A-2644	M60J/954	0.1016	0.15875	6.81	Failed
A-2676	M60J/954	0.1016	0.07938	7.10	Passed
A-2646	M60J/954	0.1524	0.31750	6.38	Failed
A-2647	M60J/954	0.1524	0.28000	6.81	Failed
A-2648	M60J/954	0.1524	0.23813	6.55	Failed
A-2681	M60J/954	0.1524	0.07938	7.00	Passed
A-2673	M60J/954	0.0464	0.07938	7.19	Failed
A-2674	M60J/954	0.0464	0.03969	7.15	Passed

Table 2. Test sample status

In addition to determining the ballistic limit range the amount of damage to the samples was also documented. The hole size for the first and last layers of the MLI, the front facesheet, and rear facesheet for most of the samples are given (Table 3). The dimensions are in millimeters with dimensions for multiple holes being separated by commas or an ampersand. All holes are approximately round if only one dimension is given.

Shot Number	Multi-layer Insulation (MLI)		Front Facesheet	Rear Facesheet	
	Front Sheet	Back Sheet	Holes	Holes	Delam.
A-2634	1.5	14.4	~3.9	5.0 x 4.2	20.0 x 7.0
A-2635	1.0	12.0	3.0 x 4.0	none	none
A-2636	2.8	16.6	6.5	4.7	13.0
A-2637	1.9	40.0	4.53	none	none
A-2675	3.0	9.1	4.25 x 6.45	8.5 x 12.0	50.0 x 21.0
A-2639	3.1	~30.0		~9.6 x 9.6	~21
A-2640	1.17	10.0 & 5.0	4.52	6.0 x 5.0 &	8.36 x 5.9
				4.8 x 2.7	
A-2641	2.8	8.0	2.94 x 2.70	none	12.0 x 1.54
A-2642	3.0, 3.0, &	31.8	7.5	19.25 x 12.8	28.5 x ~9.1
	8.0 x 5.8				
A-2643	4.6		7.6	17.0 x 8.68	53.24 x 20.0
A-2644	2.0	7.5	5.7	10.0 x 3.0 &	17.0 x 49.0
				2.0	
A-2676	1.0	8.0	3.0	none	none
A-2646	17.0 x 17.0	16	11.0 x 9.2	20.0 x 13.0	22.0 x 80
A-2647	16.8 x 16.8	15.3	9.0	5.3 x 5.7	58.3 x 13.6
A-2648	14.0 x 14.0	27	8.05	21.78	67.8 x 21.78
A-2681	Data Unavailable			none	none
A-2673	1.0	8.0	3.3	4.0 x 2.0	6.5 x 6.0
A-2674	Data Unavailable			none	none

Table 3. Damage to test samples

As expected with composite materials the holes in the front facesheet are close to being round while those on the back facesheet tend to be irregularly shaped and have large areas of delamination around them. A drawing of a typical rear facesheet hole and the delamination resulting from penetration is shown (Fig. 2). The straight lines around the hole represent the delaminations which follow the angular orientation of the composite layer. The measurements given for the delamination are generally the maximum value along its length by the maximum with of the delaminated area perpinducular to the length.

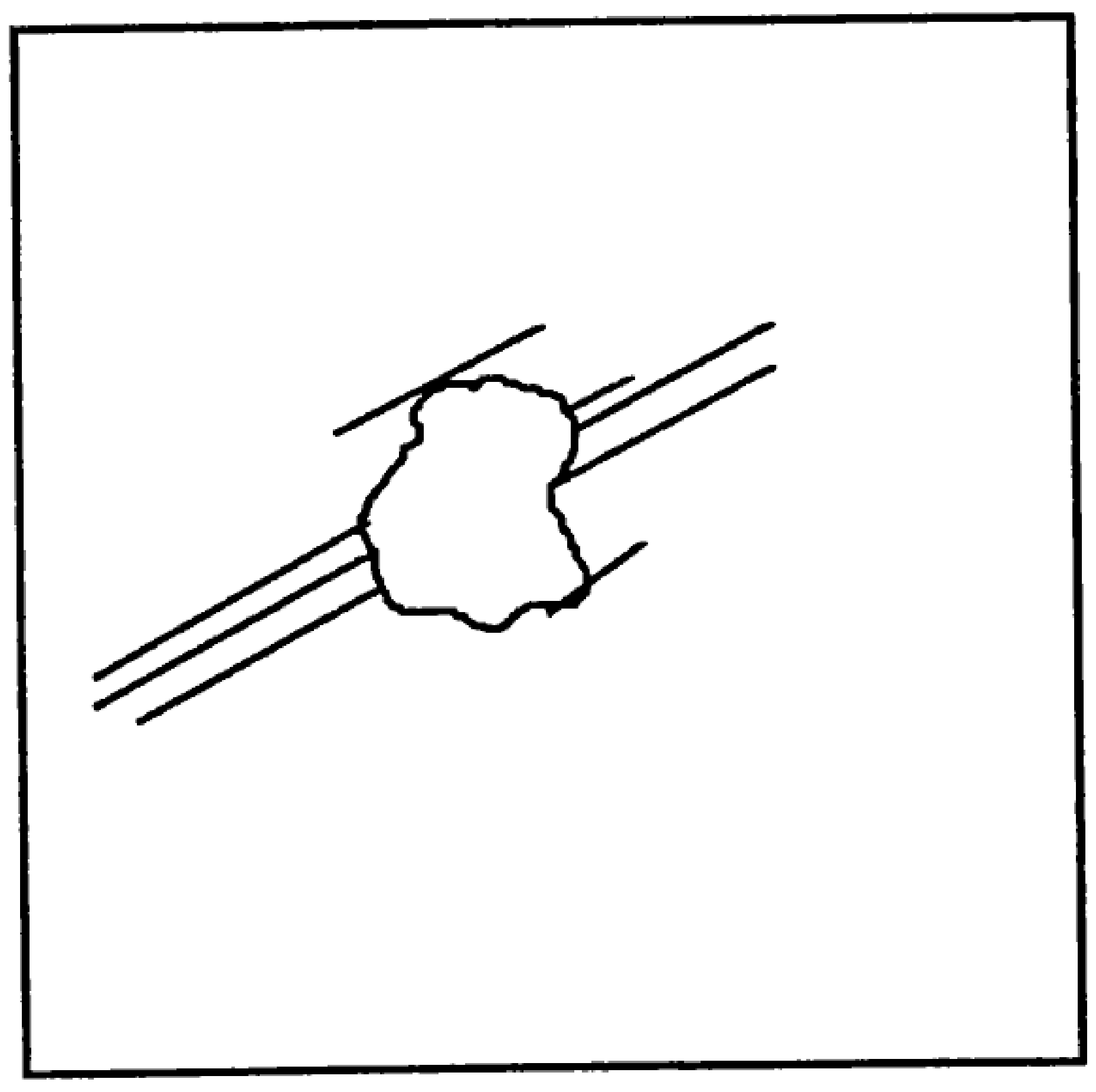

Figure 2. Drawing of a typical composite penetration

More detailed information on each of the material layers, drawings of the damage, and some photographs of the damage are contained in Ref. 2.

2.1.2 GFRP Analysis Results

Prior to performing the tests an initial ballistic limit was calculated using the aluminum whipple shield equation (Eq. 1) with the front facesheet as the bumper and the rear facesheet as the wall.

$$d_c = 3.918 t_w^{2/3} \rho_p^{-1/3} \rho_b^{-1/9} (V\cos\theta)^{-2/3} s^{1/3} (s/70)^{1/3} \qquad (1)$$

where: t_w = wall thickness (cm)
ρ_p = projectile density (g/cm3)
ρ_b = bumper thickness (cm)
V = normal velocity (km/s)
θ = impact angle (degrees)
s = separation distance between the bumper and the wall (cm)

Since the materials being used are composites separated by honeycomb the equation is not directly applicable. Two approaches were taken when solving Equation 1. One approach was to use the composite material properties and facesheet thickness in the equation as if they were aluminum. Another approach was to calculate what thickness of aluminum plate would stop the same size particle as the composite facesheet and use that thickness and the aluminum material properties for AL 6061-T6 to solve Equation 1. The equivalent thickness was calculated using Eq. 2, which is derived from the Schmidt-Holsapple single plate equation (Ref 1).

$$t_{AL} = t_{mat'l} (\rho_{AL}/\rho_{mat'l})^{-.159} (Y_{AL} / Y_{mat'l})^{-.236} \qquad (2)$$

where Y is the ultimate tensile strength in kilopounds per square inch, t is the wall thickness in inches, and ρ is the density in pounds per cubic inch.

The ballistic limit for both approaches above was calculated using twice the cell diameter as the separation distance and using the honeycomb thickness as the separation distance. For the materials on the optical bench there was no difference since the honeycomb thickness is twice the honeycomb cell diameter. For the other materials using the honeycomb thickness for the separation distance correlated better with the test data. The ballistic limit calculations for the composite and equivalent aluminum based on the honeycomb thickness, and the passing and failing shots for the configurations tested are shown (Table 4).

Facesheet Material	Facesheet Thickness	Projectile Diameter	Passed or Failed	Ballistic Limit for Composite	Ballistic Limit for Eq. AL
	(cm)	(cm)		(cm)	(cm)
M60J/954	0.0254	0.11906	Failed	0.07635	0.06122
M60J/954	0.0254	0.07938	Passed	0.07635	0.06122
P100	0.0762	0.15875	Failed	0.11932	0.11256
P100	0.0762	0.11906	Passed	0.11932	0.11256
M60J/954	0.0508	0.11906	Failed	0.08930	0.09719
M60J/954	0.0508	0.07938	Passed	0.08930	0.09719
M60J/954	0.1016	0.15875	Failed	0.14176	0.15429
M60J/954	0.1016	0.07938	Passed	0.14176	0.15429
M60J/954	0.1524	0.23813	Failed	0.18575	0.20216
M60J/954	0.1524	0.07938	Passed	0.18575	0.20216
M60J/954	0.0464	0.07938	Failed	0.08407	0.06171
M60J/954	0.0464	0.03969	Passed	0.08407	0.06171

Table 4. Calculated values vs. test data

The calculated critical diameter versus the facesheet thickness is shown plotted in Fig. 3. The lines are the calculated values for the two approaches and the points are the test data. As can be seen, both approaches fall within the predicted range for facesheet thicknesses above 1.0 cm, but are below the test data when the wall thickness is less than 0.05 cm. As can be seen the fidelity and quantity of data is insufficient to verify or disprove either approach although it does indicate that the approach is valid.

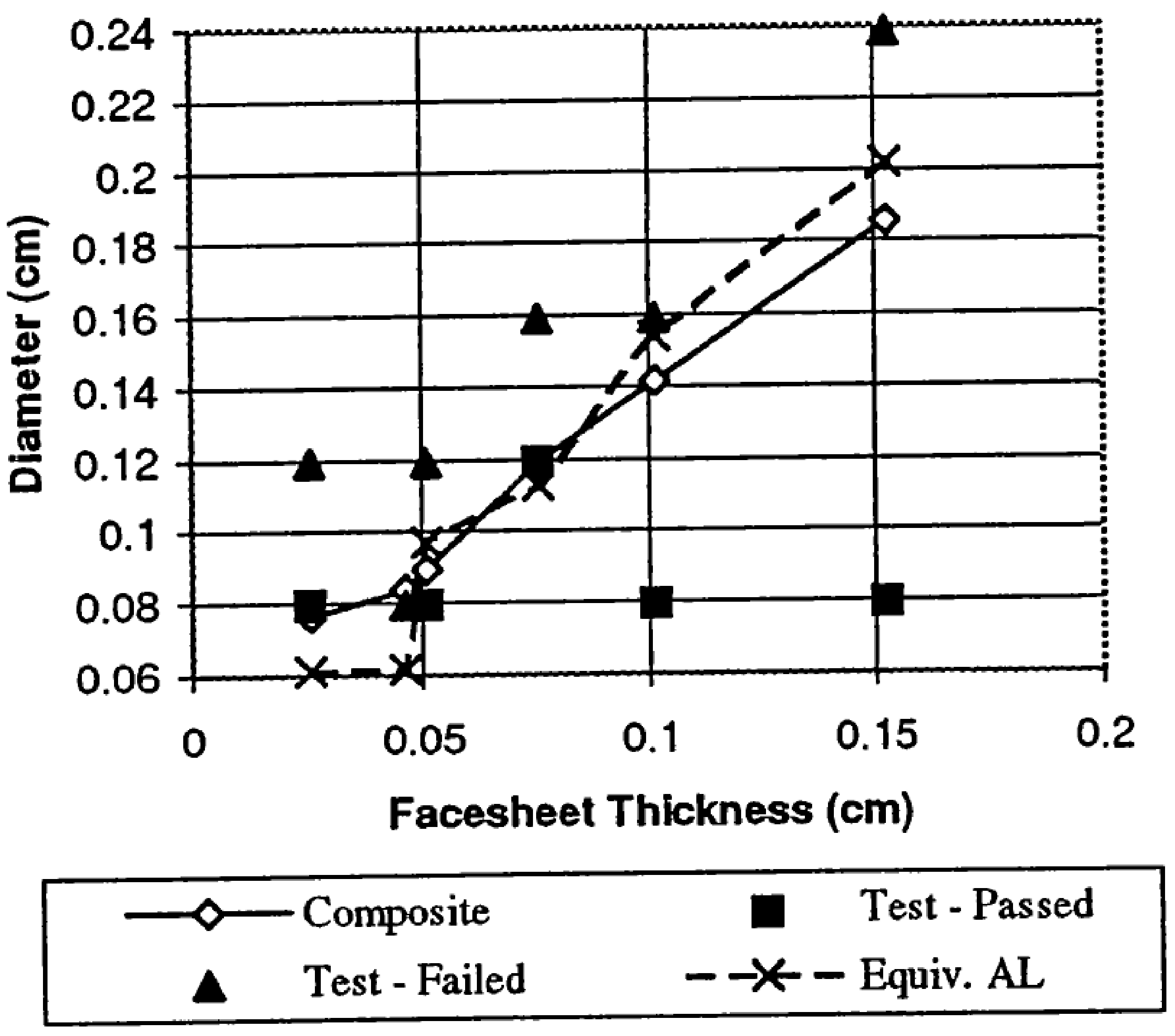

Figure 3. Critical diameter vs. facesheet thicknes

2.2 Cable tests

Hypervelocity impact tests were performed on a cable bundle approximately 0.6 meters long and containing 100 individual cables or wires. The bundle was made by combining a bundle of fifty white power cables with a bundle of fifty orange signal cables. One power cable is approximately 0.123 cm in diameter, is unshielded and has an ethylene-tetrafluoroethylene copolymer (ETFE) jacket. The signal wires are approximately 0.1 cm in diameter, are shielded with silver coated copper, and have jackets made of kapton. Three shots were done on each side of the cable bundle using the same projectile sizes for each side (Table 5).

Shot Number	Projectile Diameter	Projectile Velocity	Number of Wires Damaged	
	(cm)	(km/s)	Severed	Damaged
A-2650	0.1150	6.89	6	10
A-2652	0.0794	7.1	3	6
A-2655	0.0397	7.36	1	1
A-2656	0.1150	7.47	8	5
A-2659	0.0794	7.12	3	5
A-2660	0.0397	7.16	1	0

Table 5. Cable test results

As shown significant damage did occur. Testing to determine whether the cables were still operational were not performed. Additional hypervelocity testing of cables as they will be flown, followed by tests to determine if the cables are still functioning correctly will be performed.

3.0 ADDITIONAL TESTS PLANNED

Due to insufficient test data from the first test series to determine the best application of aluminum equations to non-aluminum materials, additional testing is planned.

This testing is also limited in scope but should help answer some AXAF specific, as well as, some general questions on the validity of equivalencing MLI to aluminum and its effectiveness as a bumper. The test series was originally much larger and planned to be done in October of 1996, but due to funding and procurement problems is now scheduled to start in early April 1997.

Testing of the MLI and the cables covered by MLI will be performed at Marshall Space Flight Center (MSFC) using the 0.07 caliber light gas gun. Testing of the cables behind the composite/honeycomb panels will be done by the White Sands Test Facility.

3.1 MLI tests

Test shots are planned to determine the ballistic limit, if possible, of the MLI blanket. The gun is capable of shooting projectiles in the 0.4 to 1.0 mm range. Preliminary calculations of the ballistic limit for the MLI blanket vary widely depending on the approach taken. Assuming the ballistic limit can be found, the same size projectiles will then be used on an equivalent thickness of aluminum. If the particle which does penetrate the MLI does not penetrate the aluminum, additional shoots with the next larger projectile will be done until the aluminum is penetrated. If the particle which does not penetrate the MLI does penetrate the aluminum, smaller projectiles will be used (if possible) to determine the ballistic limit of the aluminum. If the smallest projectile available penetrates both the MLI and the aluminum the amount and type of damage will be compared to see if the damage is similar enough to say they can be considered equivalent.

3.2 Cables behind MLI

The power and signal cables along the optical bench, and those exiting the spacecraft compartments, are covered only by MLI. This is of concern due to the thinness of these cables and their importance. The assumption made by TRW for analysis purposes is that all of the cables will still function if twenty-five percent or more of the conductor is still intact following impact. To help verify this assumption and the equivalencing to aluminum, hypervelocity impact tests will be performed followed by tests to determine the functionality of the cable. A side view of the test configuration for the MLI and cable bundles is shown (Fig. 4).

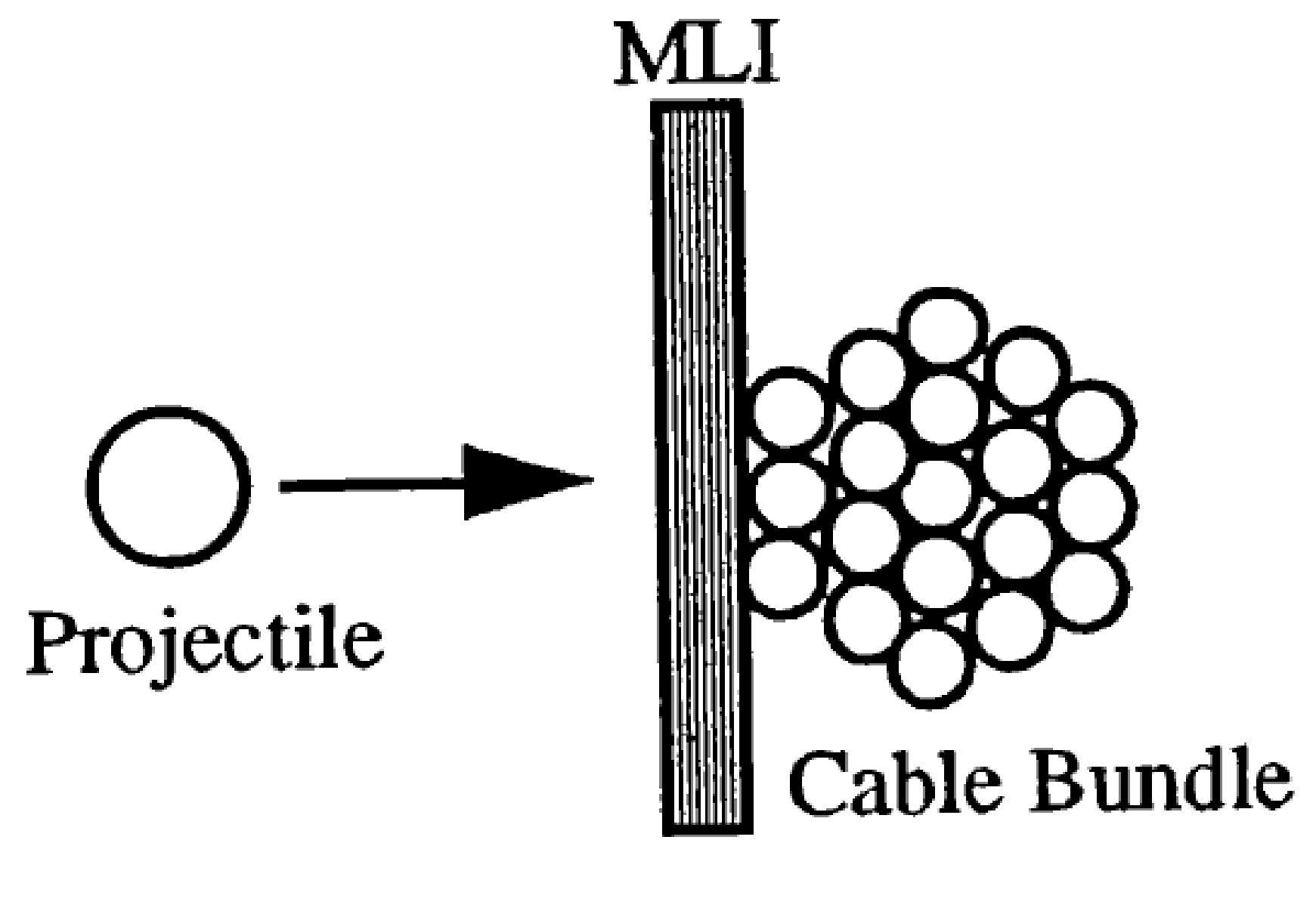

Fig. 4 MLI/cable test configuration

Four different types of cable bundles will be tested: the optical bench signal bundle; the optical bench power; a general power bundle; and a general signal bundle. All of the test bundles are approximately 1.27 cm in diameter and 0.6 m long. The signal bundle for the optical bench has a variety of cable sizes and types including shielded and coaxial. The cables for the optical bench power are unshielded 16 gage. The optical bench cable bundles are representative of the actual flight bundles since the power and signal cables are in separate bundles on AXAF. The other cable bundles on AXAF actually contain a mixture of power and signal cables however for testing purposes they are bundled separately. This was done to insure impact of the smallest cables. The power bundle consists of 20 gage, unshielded wires. Individually shielded 28 gage wire is used for the signal bundle. Following hypervelocity impact testing the cables will undergo electrical testing at MSFC to determine if they are still operating properly.

3.3 Cables behind GFRP panels

The same general power and signal bundles tested behind the MLI will also be tested behind spacecraft panels. There is concern that the honeycomb could cause additional damage to the cables or that arcing to the aluminum on the rear of the panels could occur. The tests panels to be tested are made of P100 with facesheet thicknesses of 0.0762 cm with 0.00762 cm of aluminum bonded to the rear facesheet. A side view of the test configuration, without the aluminum, is shown in Fig. 5.

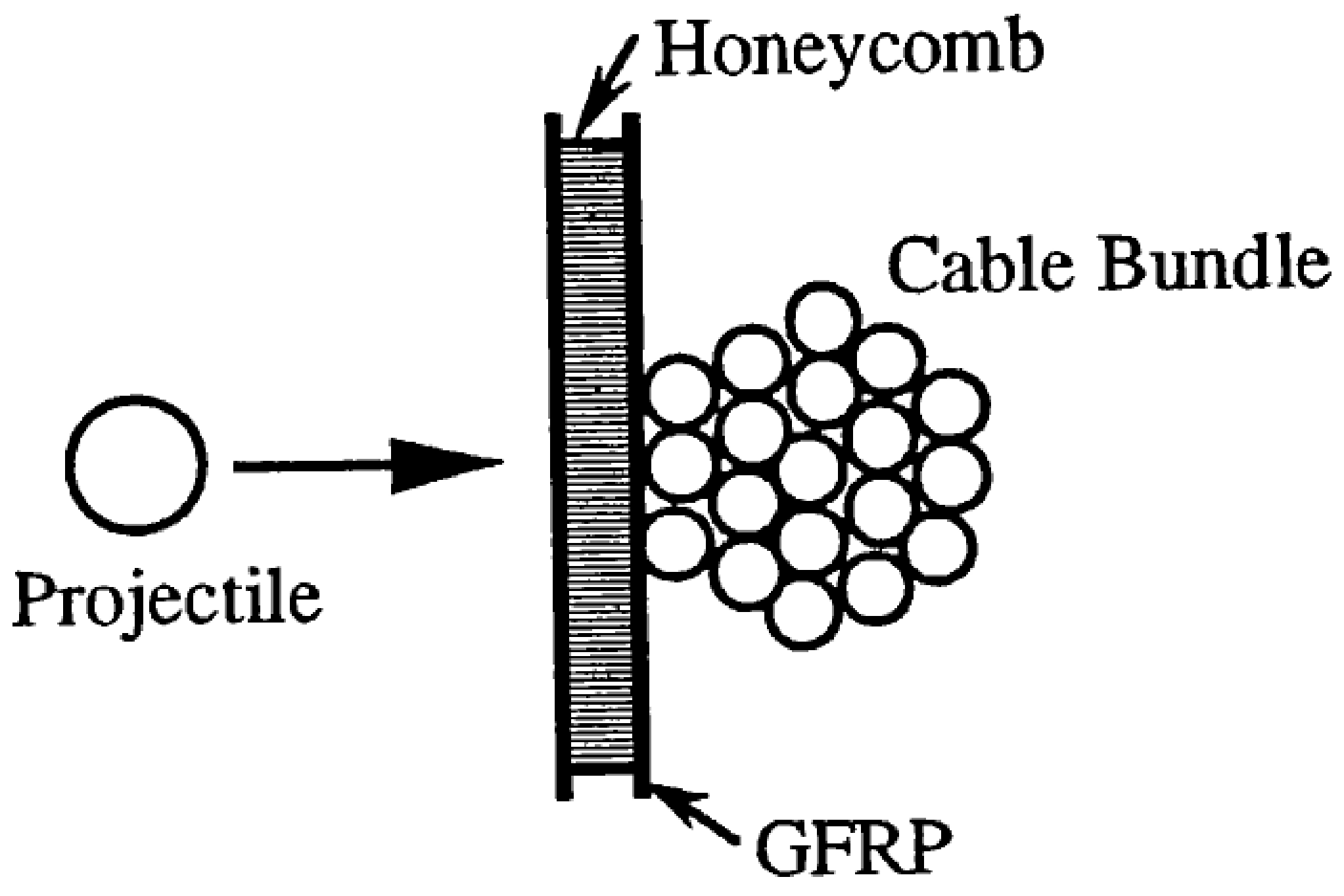

Fig. 5 Honeycomb and cable test configuration

Tests will be performed at the White Sands Test Facility and will use projectiles just above the ballistic limit so that both of the composite facesheets will be penetrated and cable damage will occur. After hypervelocity impact testing of the panels and cables is complete, testing to determine whether the cables are still operational will be performed at MSFC.

4. IMPORTANCE OF THE PLANNED TESTS

The data from the second test series is important to determine the validity of the assumptions made for the AXAF meteoroid analysis. They should give valuable insight into the validity of equivalencing the AXAF MLI blanket to aluminum, as well as, into the benefits, if any, of using MLI as a bumper. Valuable data on the amount of damage which can be sustained by power and signal cables and still function should also be obtained. This is useful not only for AXAF but for other spacecraft which are planned or being built using composite materials and/or minimally shielded cables.

5. REFERENCES

1. Hayashida, K. B. and Robinson, J. H., Single Wall Penetration Equations, *NASA TM-103565*, 1991.
2. Sanchez, G. A. and Kerr, J. H., *Advanced X-Ray Astrophysics Facility (AXAF) Meteoroid and Orbital Debris (M/OD) Test Report*, March 1996.