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TSS TETHER CABLE METEOROID/ORBITAL DEBRIS DAMAGE ANALYSIS

By K.B. Hayashida and J.H. Robinson

Structures and Dynamics Laboratory
Science and Engineering Directorate

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This report summarizes the damage analyses performed on the tether cable used for the tethered satellite system (TSS), for the damage that could be caused by meteoroid or orbital debris impacts. The TSS consists of a tethered satellite deployer and a tethered satellite. The analytical studies were performed at Marshall Space Flight Center (MSFC) with the results from the following tests: (1) hypervelocity impact tests to determine the "critical" meteoroid particle diameter, i.e., the maximum size of a meteoroid particle which can impact the tether cable without causing "failure"; (2) electrical resistance tests on the damaged and undamaged tether cable to determine if degradation of current flow occurred through the damaged tether cables; and (3) tensile load tests to verify the load carrying capability of the damaged tether cables. Finally, the HULL hydrodynamic computer code was used to simulate the hypervelocity impact of the tether cable by particles at velocities higher than can be tested, to determine the extent of the expected tether damage.

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TSS TETHER CABLE METEOROID/ORBITAL DEBRIS DAMAGE ANALYSIS

I. INTRODUCTION

This report summarizes the damage analyses performed on the tether cable of the tethered satellite system (TSS) for the damage that could be caused by a meteoroid or orbital debris impact. The TSS consists of a tethered satellite deployer and a tethered satellite. The analytical studies were performed at Marshall Space Flight Center (MSFC) with the results from the following tests: (1) hypervelocity impact tests to determine the "critical" meteoroid particle diameter, i.e., the maximum size of a meteoroid particle which can impact the tether cable without causing "failure"; (2) electrical continuity tests on the damaged and undamaged tether cable to see whether a degradation of current flow occurred through the damaged tether cable; and (3) tensile load tests to verify the load carrying capability of the damaged tether cables. To aid in the analysis efforts, the HULL hydrodynamic computer code was used to simulate the hypervelocity impact of the tether cable by particles at velocities higher than can be tested to determine the extent of the expected tether damage.

II. BACKGROUND

The TSS is a joint project with the Italian Space Agency, the Agenzia Spaziale Italiana (ASI). It was developed to be a reusable orbital flight facility for a wide variety of scientific investigations in low-Earth orbit (LEO). The TSS will be used to checkout, deploy, maintain, and retrieve scientific payloads away from or toward the Earth from the space shuttle on either a conducting or nonconducting tether. The TSS is capable of deploying a satellite using a conducting tether for electrodynamic missions to a distance of not less than 20 km above the orbiter (away from the Earth) with the shuttle operating in a nominal 297-km circular orbit. For atmospheric/geodynamic missions, the TSS is capable of deploying a satellite using a nonconducting tether to a distance of not less than 100 km below the orbiter (toward the Earth) with the shuttle operating at a nominal 230-km circular orbit. For the nominal TSS mission, a duration of 38 h is subject to the limitations of the satellite electrical energy and operational profile selected. The first mission for the TSS, called TSS-1, was launched in July 1992, and was an electrodynamic mission. A series of TSS missions are planned throughout the 1990's.

III. EVALUATION OF PREVIOUS TSS-1 METEOROID IMPACT ANALYSES

A major concern with the tether was the effect of the meteoroid and orbital debris environment definitions on its survivability. The previous analyses used median material densities as 0.5 g/cm^3 for meteoroids and 2.5 g/cm^3 for orbital debris. The most common practice accepted by the space station program for the meteoroid and orbital debris damage analysis uses the constant densities 0.5 g/cm^3 for meteoroids and 2.8 g/cm^3 for orbital debris. These values are used in this report for the TSS meteoroid and orbital debris damage analysis.

In addition to difference in environment definitions, previous analyses may not have accounted for effects of the gravitational defocusing and body shielding factors for the meteoroid environment. The space shuttle, tether, and satellite altitudes are necessary to determine these factors and may not have been defined until recently. The gravitational defocusing and body shielding factors are calculated by using the following equations:[1]

$$\text{Gravitational defocusing factor, } G_E = 0.568+0.432\left(\frac{R_E}{r}\right) ,$$

where

R_E = Earth radius (km)

r = orbit radius (km).

$$\text{Body shielding factor, } \xi = \frac{1+\cos\theta}{2} ,$$

where

$\sin\theta = \frac{R}{R+H}$

R = Earth radius (km)

H = altitude above surface (km).

These factors affect the meteoroid flux, i.e., the number of meteoroid particles expected to impact a given area in a given amount of time. These factors are therefore very important for accurate analyses.

Previous analyses used data from hypervelocity impact tests[2 3] performed several years ago and determined the "critical" meteoroid particle diameter to be 0.04 cm. Since these tests did not use the actual tether cable as the target, the calculation of the "critical" particle may have been affected. The "critical" particle is defined as the meteoroid particle diameter, velocity, and average density which results in damage that will cause 50 percent loss of the tether cable strength. Analyses were performed by MSFC to determine the probability of mission failure, with the updated meteoroid environment, to compare to previous results. Another possible "critical" failure not yet considered was the degradation of the tether cable that may cause loss of mission due to loss of current flow resulting in little or no scientific data obtained.

To begin the MSFC comparison, the final configuration of the tether cable was obtained (fig. 1). To check the previously estimated 0.04-cm "critical" particle, this meteoroid particle diameter was analytically tested to see if it would penetrate through the Nomex braided jacket and Kevlar strength member to damage the insulation of the tether cable without losing half of the tether cable strength (fig. 2). The combined density for the Nomex braided jacket and Kevlar strength member was estimated as 1.403 g/cm^3 with a total thickness of 0.05 cm. An empirically developed penetration equation for a "thick plate" was used to determine the penetration depth of the 0.04-cm particle into the tether cable. This penetration equation, shown below, assumes the penetration depth would be less than half of the total target thickness: [4]

$$p = Km^{0.352}\rho^{\frac{1}{6}}V^{\frac{2}{3}} \ ,$$

where

K = a constant for target material

p = depth of penetration (cm)

m = particle mass (g)

ρ = particle density (g/cm^3)

V = impact velocity (km/s).

Table 1 shows the constant, K, for two target materials. Since material constants are not provided in the literature for nonmetallic materials, the material constant from the Nomex/Kevlar combined density (1.403 g/cm^3) was estimated as 0.47 by interpolating from these data points (fig. 3).

Next, the number of hours between expected critical impacts and the probability of no mission loss for meteoroids was calculated using the 0.04-cm diameter "critical" meteoroid particle. A 30-h exposure time (the lifetime defined for the aeroassist flight experiment) was assumed to be applicable for the TSS mission. It was concluded that the 0.04-cm diameter particle would impact the tether cable every 48 days and would penetrate half of the tether diameter. The probability of no mission loss from meteoroids only was calculated as 97.43 percent. Any change to the assumptions made here could dramatically change the final results.

IV. ADDITIONAL METEOROID/ORBITAL DEBRIS ANALYSES ON TETHER CABLES

The main objective of these analyses was to determine the integrity of the tether cable after the damage caused by meteoroid or orbital debris impacts. The Kevlar strength member of the tether is designed to provide 400 lbf (1,780 N) of break load. Also, from IRAD test results,[2 3] the damage from a hypervelocity impact of the 0.04-cm diameter meteoroid particle was estimated to decrease the tether strength by half, i.e., reduce its capability to 200 lbf (890 N). The expected maximum operational load for the TSS-1 is 25 lbf (111 N), and the nominal operational load is 13 lbf (58 N). Thus, it was concluded that the tether cable should meet the design requirements for structural integrity if impacted by a 0.04-cm diameter meteoroid.

To verify this conclusion, first an analytical and then an experimental determination of the meteoroid particle which would degrade the tether strength by half was made. The "critical" particle diameter was determined which would just penetrate through the Nomex braided jacket and Kevlar strength member thicknesses, and cause possible degradation of the insulation capability. The thick plate penetration depth equation[4] was again used to calculate the particle diameters which would penetrate this depth into the tether cable. The "critical" particle diameters were calculated for meteoroids and orbital debris as 0.0348 cm and 0.0244 cm, respectively. Two different particle sizes were expected, due to differences in the average velocities and average material densities of meteoroids and orbital debris. Figure 4 shows the expected tether damage caused by these particles. The overall probability of no mission loss (or no impact of these particle sizes or any larger ones) was calculated as ~93.68 percent.

The assumption for the material constant, as discussed in the previous section, increases the uncertainty in the calculated values for the meteoroid and orbital debris particle sizes, but it is the best estimate currently available. To increase confidence in the analysis, tests to simulate impact of hypervelocity particles on the actual tether cable were planned and completed.

V. TEST RESULTS FROM HYPERVELOCITY IMPACT, TENSILE LOAD AND ELECTRICAL RESISTANCE TESTS, AND COMPUTER CODE SIMULATION RESULTS

A. Hypervelocity Impact Tests

Since hypervelocity impact tests were never performed using the actual tether cable, this became the next step in the analysis. This would disprove or verify the MSFC analysis done to this point. In addition, an analysis for the effects of the manmade orbital debris was needed, and these tests could contribute valuable information to complete such an analysis.

At the request of MSFC personnel, hypervelocity impact tests on the tether cable were performed at Johnson Space Center (JSC). Approximately 15 ft (457.20 cm) of tether cable was supplied by Martin Marietta Corporation, the prime contractor. The cable was cut into 15-in (38.10-cm) long samples. Each test article had three cables mounted on a 6-inch (15.24-cm) square frame, to assure at least one would be impacted by the tiny test particle (fig. 5). Four hypervelocity impact tests were performed. Pyrex and aluminum spheres were used to model the meteoroid and orbital debris particles, respectively. Two particle sizes, 1/64-in (0.0397-cm) and 0.0341-cm diameter spheres, which were the smallest sizes within the facilities launch capability, were used for these tests. These also happen to be very near the estimated 0.04-cm predicted "critical" particle diameter. MSFC's assessment of the tether from the impact tests is shown in table 2 with the test results and conditions on each tether cable. Figures 6 and 7 are photos of the impacted tethers for tests No. 1951 and 1956. For tests No. 1951 and 1958, the No. 2 cable, located at the middle of the test article, received the worst damage and lost about a half of the Kevlar strength member due to impact. These impacts appear to be in dead center of the cables. An interesting side result is that the Kevlar seemed to turn black from the heat of impact. The right side of the No. 3 cable for test No. 1951, located on the right side of the test article, was grazed by one half of the sabot used to propel the particle down the gun barrel (equivalent to approximately 2 mg of nylon). For test No. 1954, the particle slightly grazed the outer side of the No. 3 cable. Only the Nomex jacket, the outermost layer of the cable, was damaged. Finally, for test No. 1956, the particle hit the left side of the No. 2 cable, located at the middle of the test article, causing some damage to the Nomex and Kevlar. Also, one half of the sabot hit the right side of No. 1 cable, located at the left side of the test article, causing extensive damage.

B. Computer Code Impact Simulations

Current hypervelocity impact test technology limits projectile velocities to below 8 km/s. Some facilities under development can reach velocities up to 12 km/s, but the projectile shapes and sizes are random, and costs for operation are too high. To verify impact reactions of the tether at the higher velocities, the HULL hydrodynamic computer code was used for impact simulation. The HULL computer code is currently used by the U.S. Army Corps of Engineers through an agreement with NASA for the Space Station *Freedom* program to evaluate candidate orbital debris shields. Two cases were chosen to simulate hypervelocity impacts: one with an 8 km/s aluminum particle for comparison with the hypervelocity impact test result, and the other with a 19 km/s ice projectile, the average meteoroid velocity, to simulate a meteoroid impact. The particle sizes used were 0.0348 cm, simulating a meteoroid impact and 0.0244 cm simulating a debris impact. The results from these code runs, shown on figures 10 and 11, show that the meteoroid impact traveling at 19 km/s is less damaging than the orbital debris impact traveling at 8 km/s. For both cases, at least half of the Kevlar strength member remains to carry the expected maximum load. These results complement the previous test results and analyses.

C. Tensile Load Test on Damaged Tether Cables

After the hypervelocity impact tests were completed, tensile load tests were performed for the damaged tether cables. These tests determined whether the 50-percent loss of the Kevlar strength member would cause a 50-percent reduction of the tether's design load. Three tests were performed and were recorded on high-speed film. The film of these tests is available for viewing from the authors or from the TSS project office. Table 3 shows the test results. All the damaged tether cables tested held at least 160-lb tensile load, this was about 40 percent of the design break load and 640 percent of the expected maximum operational load.

D. Electrical Continuity Tests on Damaged Tether Cables

As an aside, to determine if the current flow through the tether cable would be affected by a meteoroid or orbital debris impact, electrical continuity tests were performed on the damaged and undamaged tether cables, before the tensile load tests were performed. The test results are shown in table 4. It was found that the damaged tether cables did not show any measurable degradation of current flow compared to the undamaged cables. Thus, it was concluded that the chance of aborting the mission or losing scientific data from a meteoroid or orbital debris impact causing loss of electrical continuity is insignificant.

VI. RECOMMENDATIONS/CONCLUSIONS

It is extremely important to have the accurate mission information and correct meteoroid and orbital debris environments for a true representative analysis. Changing the values for these parameters by a fraction can influence the analysis results dramatically. Variations in the "critical" particle diameter for both meteoroids and orbital debris will be misleading and result in wrong conclusions. It is always recommended to perform the verification tests using the actual configuration of the flight hardware.

For the tether cable, it was concluded that the tether cable can sustain operation during a 30-h mission, given the nominal environment definitions. A particle larger than the 0.04-cm diameter meteoroid particle would be required to damage the cable to a break point. This corresponds to a probability of no encounter of less than 97.43 percent, for meteoroids alone. To be more precise, the overall probability of no mission failure for the combined meteoroid and orbital debris environments is ~93.68 percent. The series of tests performed indicate that the damaged tether cable can operate nominally and hold more than the expected maximum operational load without degrading the current flow. Although this study was not exhaustive, it is believed that the chance of a TSS-1 mission failure from a meteoroid or orbital debris particle impact is very low.

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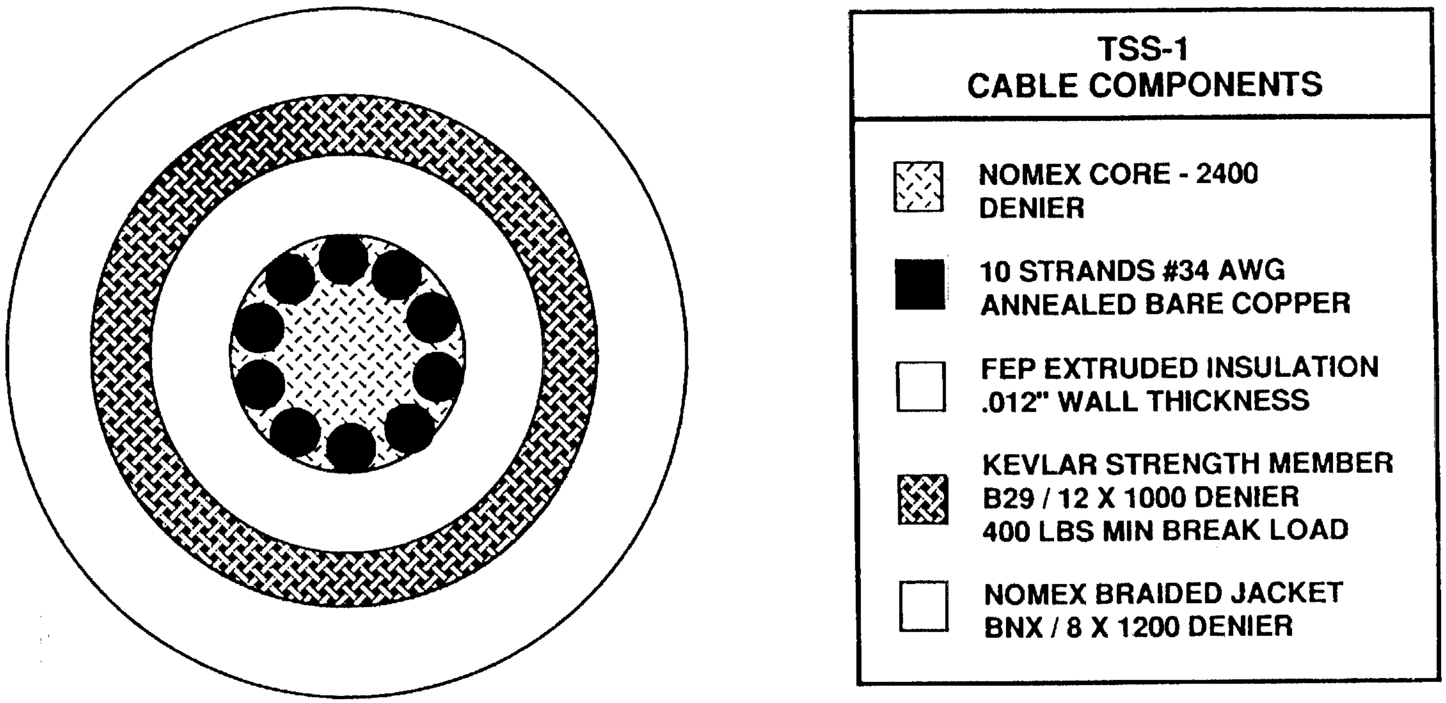
2. Crouch, D.S.: "Shuttle/Tethered Satellite System" Martin Marietta Report Number D80-48721-001, Project Number D-21D, June 1981.

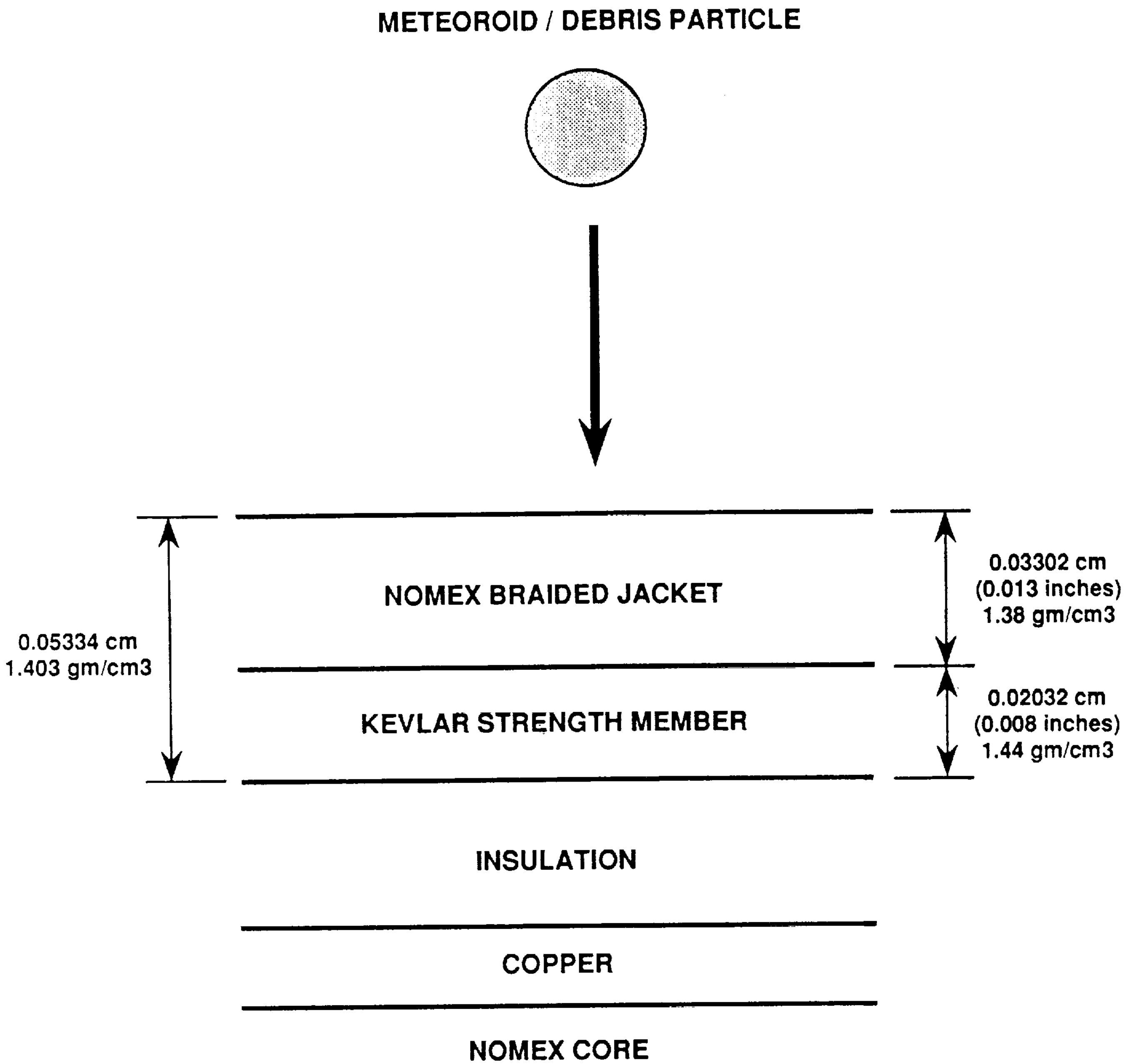
3. Tallentire, F.I.: "Space Tether Materials Study." Martin Marietta Report Number S86-61567-001, Project Number D67-S, February 1987.

4. Frost, V.C.: "Meteoroid Damage Assessment." Aerospace Corporation, NASA SP-8042, May 1970.



	CUMULATIVE DIAMETER	DENSITY (g/cm3)
(1) Nomex Core	0.020" (0.05080 cm)	1.38
(2) Copper	0.034" (0.08636 cm)	8.91
(3) Insulation	0.058" (0.14632 cm)	2.12 - 2.17
(4) Kevlar Strength Member	0.074" (0.18796 cm)	1.44
(5) Nomex Braided Jacket	0.100" (0.25400 cm)	1.38

Figure 1. Configuration and material properties for tether cable.



The "critical" plate thickness which the projectile can penetrate is assumed as the total thickness of the Nomex Braided Jacket and the Kevlar Strength Member, i.e. 0.05334 cm.

Figure 2. Assumptions made to predict the "critical" projectile diameter.

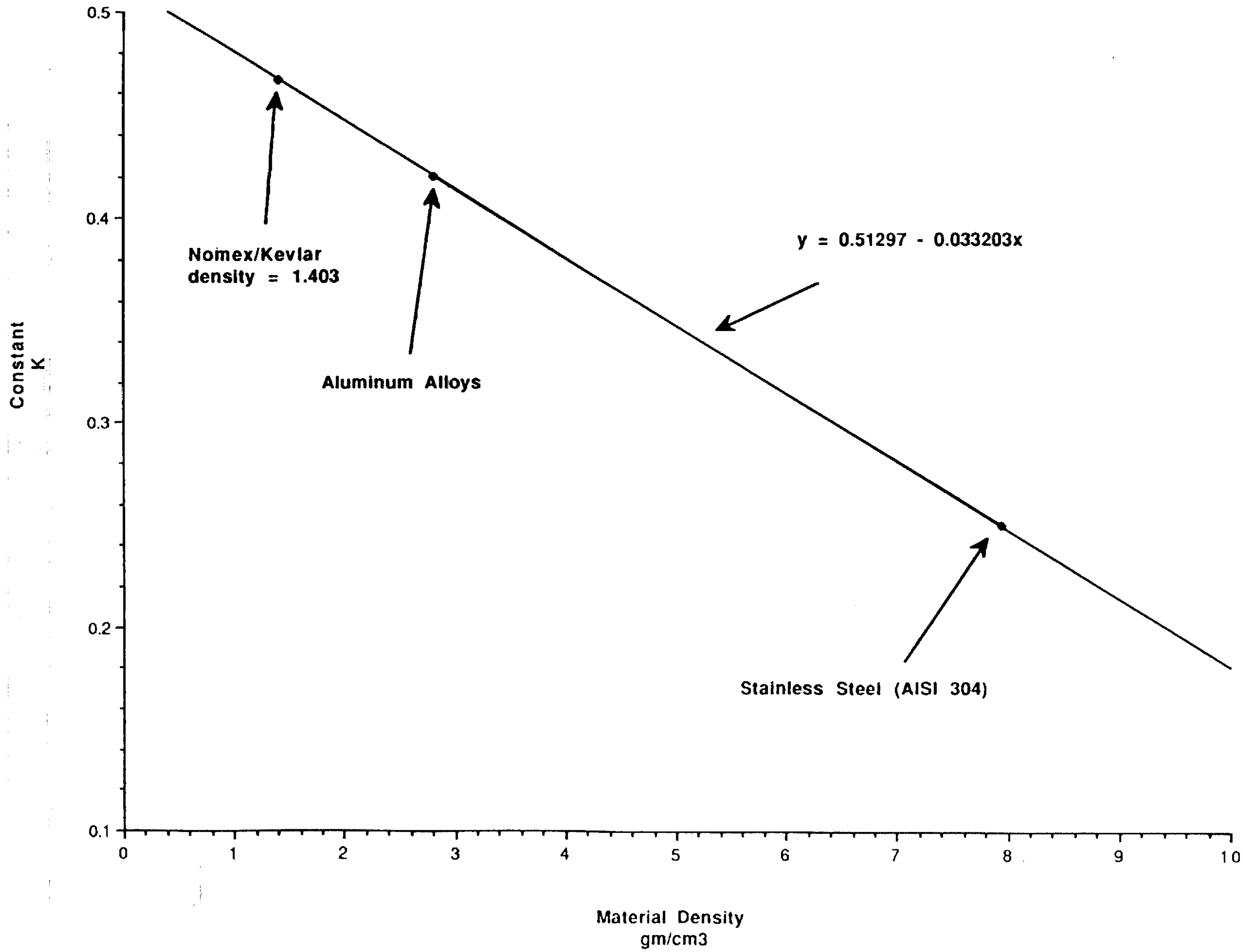


Figure 3. Curve of material constant, K, versus material density (gm/cm^3).

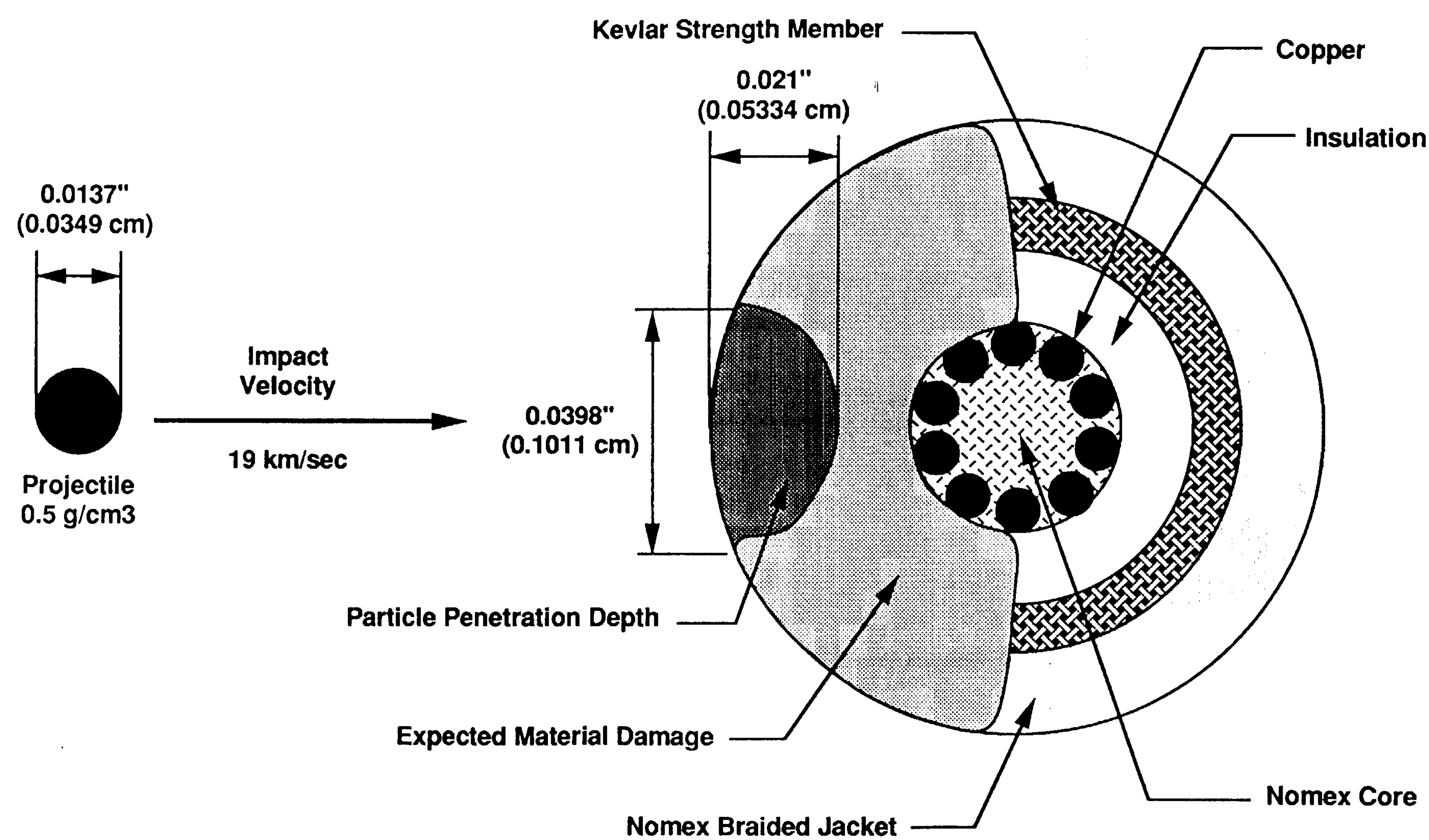


Figure 4. Expected damage caused by hypervelocity impact.

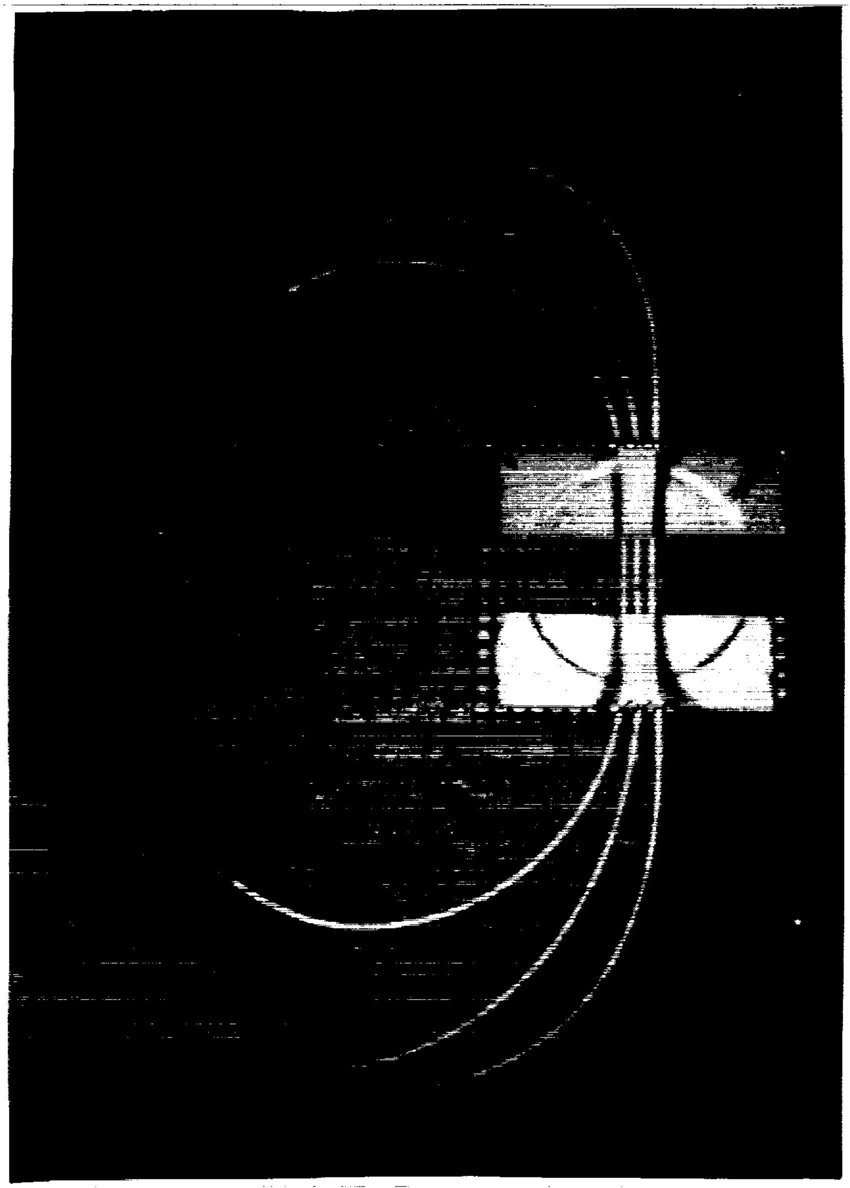


Figure 5. Test article setup for hypervelocity impact test.

Figure 6. Hypervelocity impact test results for test No. 1951.

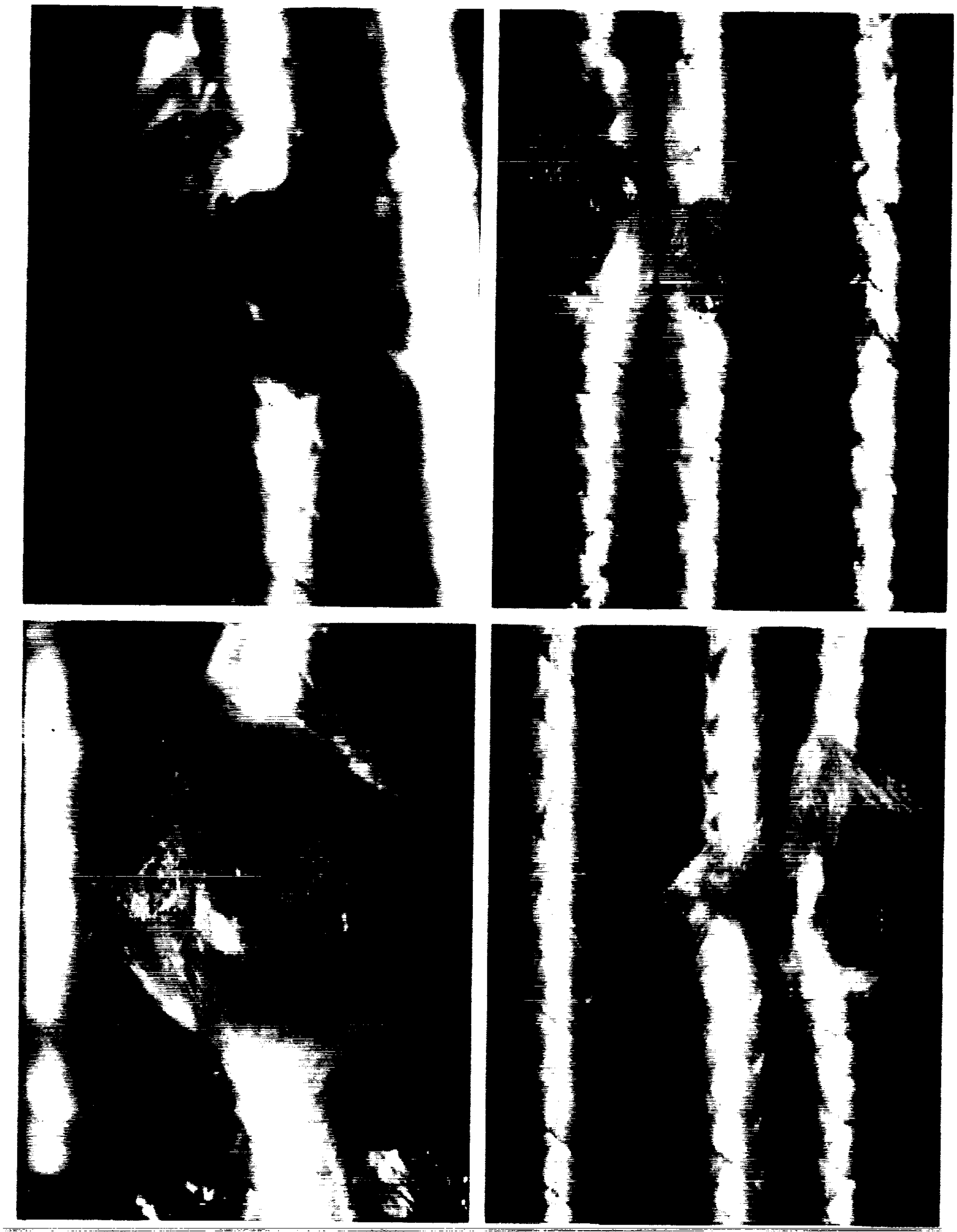


Figure 7. Hypervelocity impact test results for test No. 1956.

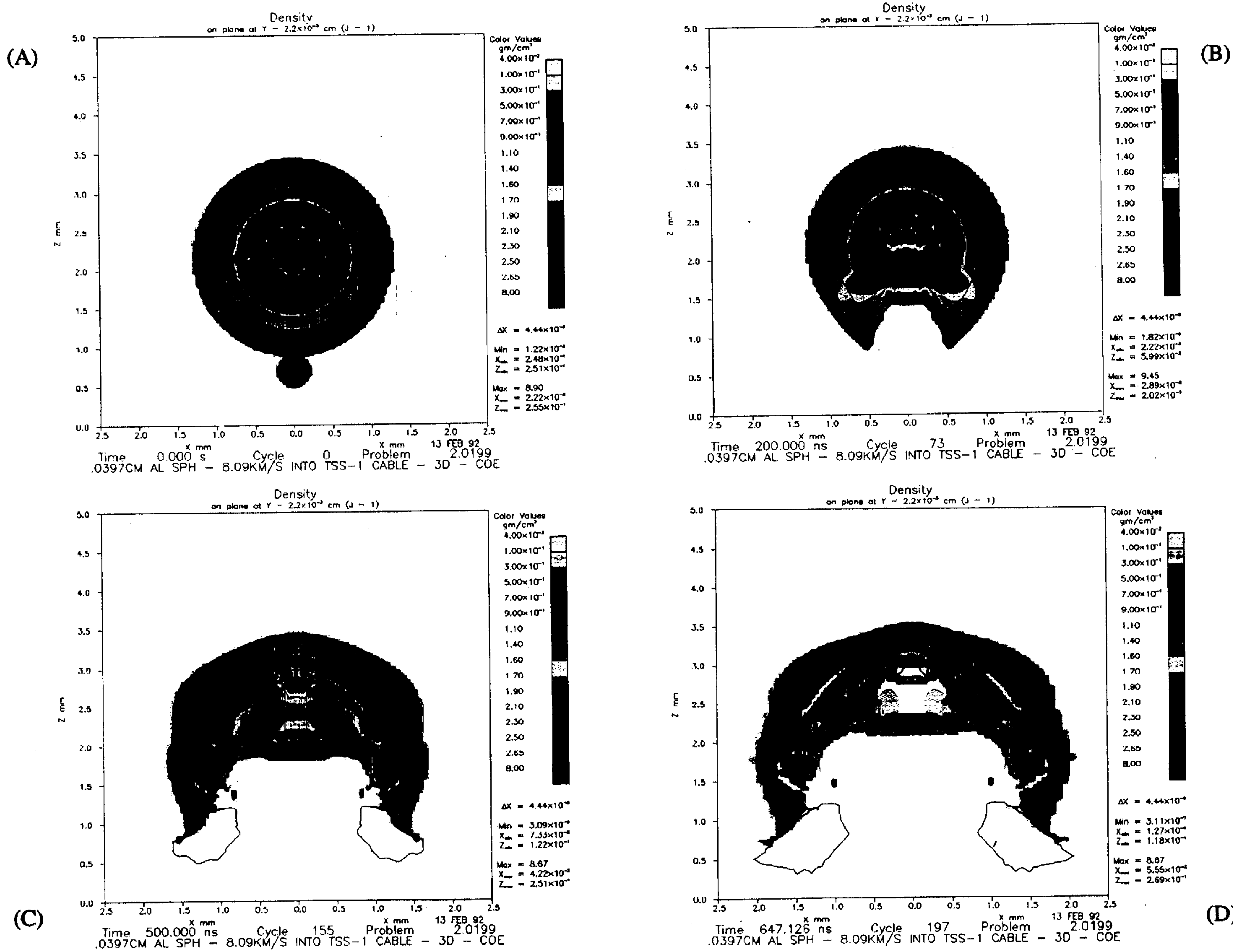


Figure 8. HULL code time step simulation for debris impact.

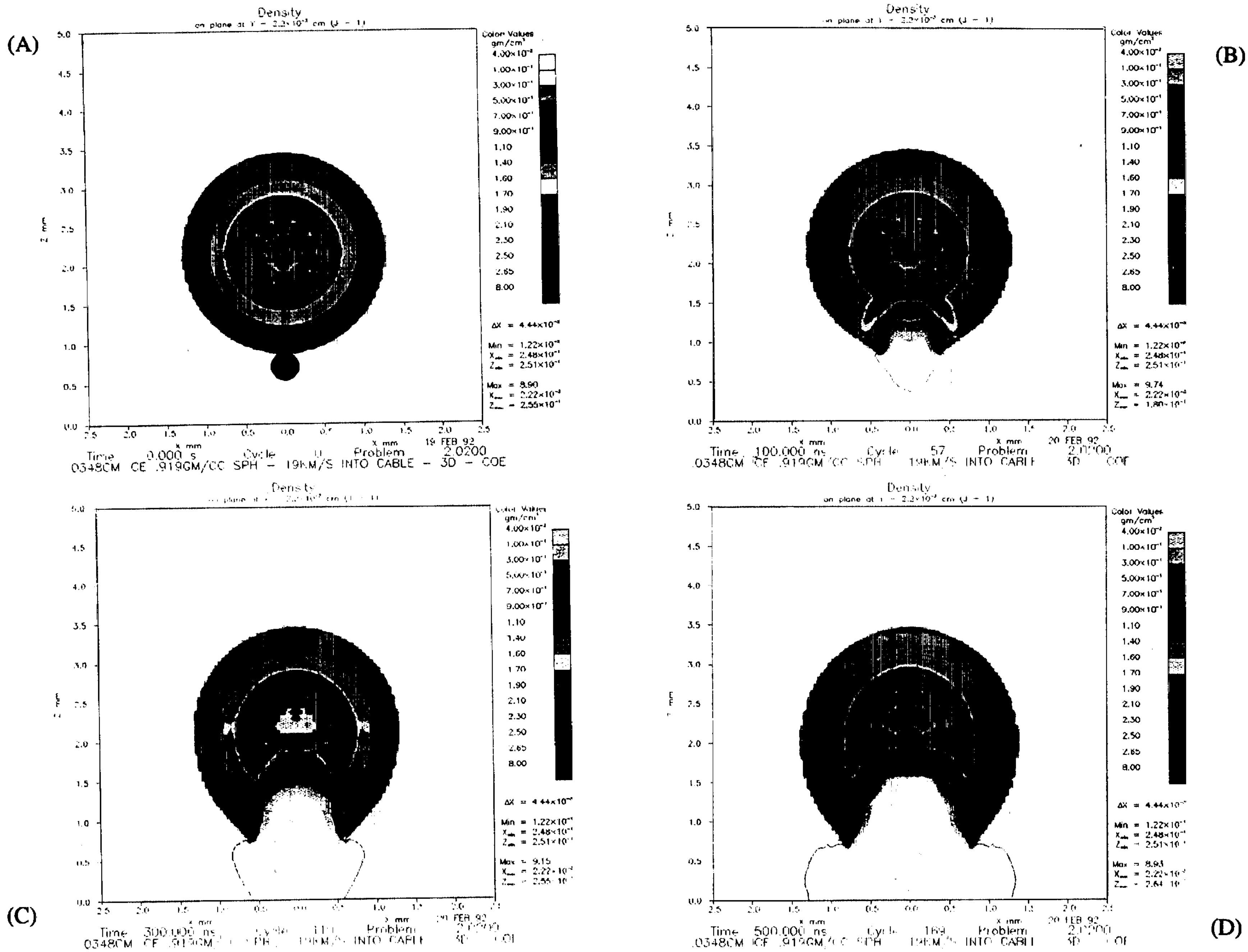


Figure 9. HULL code time step simulation for meteoroid impact.

Table 1. A constant, K, and density for different materials.

Material	Constant (K)	Density (gm/cm^3)
Aluminum alloys	0.42	2.80
Stainless steels	0.25	7.92

NOTE: From "Meteoroid Damage Assessment," NASA SP-8042), May 1970, Table III, Constants for Crater Depth in a Semi-infinite Body (Room Temperature).

Table 2. TSS tether hypervelocity impact test results.

Test No.	Projectile			Impact Velocity (km/s)	Tether Damage			Witness Plate Damage
	Diam. (cm)	Material	Weight (mg)		One	Two	Three	
1951	0.0397	2017 AL	0.11	8.09	Very slight blackening of outer threads of Nomex jacket, next to impact sight on tether two. Can be reused for more testing. Original Mass: 3.78056 gms Posttest Mass:	Impact appears to be in dead center of the tether. One-half to three-quarters of the Nomex jacket is frayed. Possible similar damage to Kevlar strength member. Kevlar has turned from yellow in color to black; appears to have burned from the heat impact. Original Mass: 3.45086 gms Posttest Mass:	Right side grazed by one-half sabot (~2 mg Nylon) Original Mass: 3.45233 gms Posttest Mass:	Complete penetration by each half of the sabot; one hole is circular with a clear hole diameter = 1.7 mm and a lip-lip average diameter = 25 mm; elliptical penetration has a clear hole dimension = 2.0 mm by 1.4 mm, and a lip-lip dimension of 2.7 mm by 2.3 mm. A few nonpenetrating craters are also present. The largest is 0.9 mm diameter, and resulted in a dimple on the back of the witness plate. Original Mass: 23.87309 gms Posttest Mass:
1954	0.0397	Pyrex	0.07	7.27	None; reused for later test. Original Mass: not recorded Posttest Mass:	None; reused for later test. Original Mass: not recorded Posttest Mass:	Slight grazing by the particle on outer side of tether. Only Nomex jacket seems to be damaged. Original Mass: 3.41899 gms Posttest Mass: 3.41489 gms	Hundreds of tiny craters from particle and tether debris spray. Largest crater is approximately hemispherical and 0.5 mm diameter, from outer lip edge to outer lip edge. Hundreds of smallest craters are less than 0.05 mm diameter. A black coating covers about half of the area of concentrated craters. Original Mass: 23.86944 gms Posttest Mass: 23.87017 gms

Table 2. TSS tether hypervelocity impact test results (continued).

Test No.	Projectile			Impact Velocity (km/s)	Tether Damage			Witness Plate Damage
	Diam. (cm)	Material	Weight (mg)		One	Two	Three	
1956	0.0397	Pyrex	0.07	7.88	Extensive damage on right side caused by one-half sabot (~2 mg Nylon). Approximately three-quarters of the outer Nomex jacket is frayed. Possible similar damage to Kevlar strength member. Kevlar has turned from yellow in color to black; appears to have burned from the heat of impact. Original Mass: 3.35336 gms Posttest Mass:	Left side grazed by Pyrex. Less than one-half of the outer Nomex jacket is frayed. Possible similar damage to Kevlar strength member. Kevlar has turned from yellow in color to black; appears to have burned from the heat of impact. Original Mass: 3.42121 gms Posttest Mass:	Very slight blackening of outer threads of Nomex jacket, next to impact sight on tether two. Original Mass: 3.44604 gms Posttest Mass:	Complete penetration by half of the sabot; several holes are circular with a clear hole diameter = 1.0 mm and a lip-lip average diameter = 1.7 mm; a large elliptical penetration has a clear hole dimension = 3.0 mm by 1.4 mm, and a lip-lip dimension of 3.8 mm by 2.5 mm. Several nonpenetrating craters are also present. The largest is 1.0 mm diameter, and resulted in a dimple on the back of the witness plate. Original Mass: 23.83142 gms Posttest Mass: See Note 2
1958	0.0341	Pyrex		7.36	None; reused for later test. Original Mass: 3.36179 gms Posttest Mass:	Impact appears to be in dead center of the tether. Similar but less damage than test No. 1951. Approximately one-half of the outer Nomex jacket is frayed. Possible similar damage to Kevlar strength member. Kevlar has turned from (continued)	None; reused for later test. Original Mass: 3.37588 gms Posttest Mass:	Tens of tiny craters from particle and tether debris spray. Largest crater is approximately hemispherical and 0.5 mm diameter, from outer lip edge to outer lip edge. Original Mass: 23.88599 gms Posttest Mass:

Table 2. TSS tether hypervelocity impact test results (continued).

Test No.	Projectile				Tether Damage			
	Diam. (cm)	Material	Weight (mg)	Impact Velocity (km/s)	One	Two	Three	Witness Plate Damage
1958 (cont.)						yellow in color to black; appears to have burned from the heat of impact. Original Mass: 3.30722 gms Posttest Mass:		

NOTES:
1. Witness plates for these tests are 0.022-in (0.05588-cm) thick 1100 aluminum alloy and placed 4 inches behind tethers.
2. Numbers for tethers were not identifiable and it was assumed, based on the tether's length and weight measured before test.

Table 3. Tensile load test results for damaged tether cables.

	Cable No.	Load at Start (lb)	Approximate Time at End (s)	Load at Failure (lb)	Loading Rate
Test 1	1954-T3	12	180	160*	Constant 1 lb/s load rate was used.
Test 2	1956-T2	10	80	202	Constant 3 lb/s load rate was used.
Test 3	1951-T2	48	84	190*	Constant 4 lb/s load rate was used up to approximately 150 or 160 lb, then load rate was increased.

* Load was not increased past this point; cable slipped in the test fixture.

Table 4. Electrical continuity test results for damaged/undamaged tether cables.

	Cable No.	Test 1 Measured Voltage (mV)	Test 1 Calculated Resistance (mΩ)	Test 2 Measured Voltage (mV)	Test 2 Calculated Resistance (mΩ)	Comments
1	1958-T1	66.41	66.41	67.00	67.00	Not impacted.
2	1958-T2	55.62	55.62	64.00	64.00	Damaged by impact.
3	1958-T3	69.00	69.00	67.00	67.00	Not impacted.
4	1956-T1	84.00	84.00	169.00	84.50*	Badly damaged by impact.

	Cable No.	Continuity (Yes/No)	Comments
5	1956-T2	Yes	Damaged by impact.
6	1956-T3	Yes	Not impacted.
7	1954-T3	Yes	Not impacted.
8	1951-T1	Yes	Not impacted.
9	1951-T2	Yes	Damaged by impact.
10	1951-T3	Yes	Not impacted.

NOTES:

1. For test cases 1 through 3, currency used was 1 A.
2. For test case 4, currency used was 2 A.
3. For test cases 5 through 10, only continuity was evaluated; resistance was not recorded.

APPROVAL

TSS TETHER CABLE METEOROID/ORBITAL DEBRIS DAMAGE ANALYSIS

By K.B. Hayashida and J.H. Robinson

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

J.C. BLAIR
Director, Structures and Dynamics Laboratory

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