SIMULATED METEOROID PENETRATION OF REUSABLE SURFACE INSULATION

by

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OVERVIEW

(Figure 1)

Meteoroid impact simulation tests of Reusable Surface Insulation (RSI) tiles were conducted at McDonnell Douglas Astrophysics Laboratory, El Segundo, California. Results of tests were used to determine penetration resistance of RSI attached to simulated Shuttle Structure. Probability of no meteoroid damage to a typical Shuttle Orbiter was determined. Specimens were plasma jet tested to determine effects of various size meteoroid cavities on thermal performance of RSI.

OVERVIEW

- METEOROID TESTS OF SIX RSI SPECIMENS
- PENETRATION RESISTANCE OF RSI
- PENETRATION RESISTANCE OF RSI PLUS STRUCTURE
- APPLICATION TO SHUTTLE
- THERMAL DEGRADATION OF IMPACTED RSI

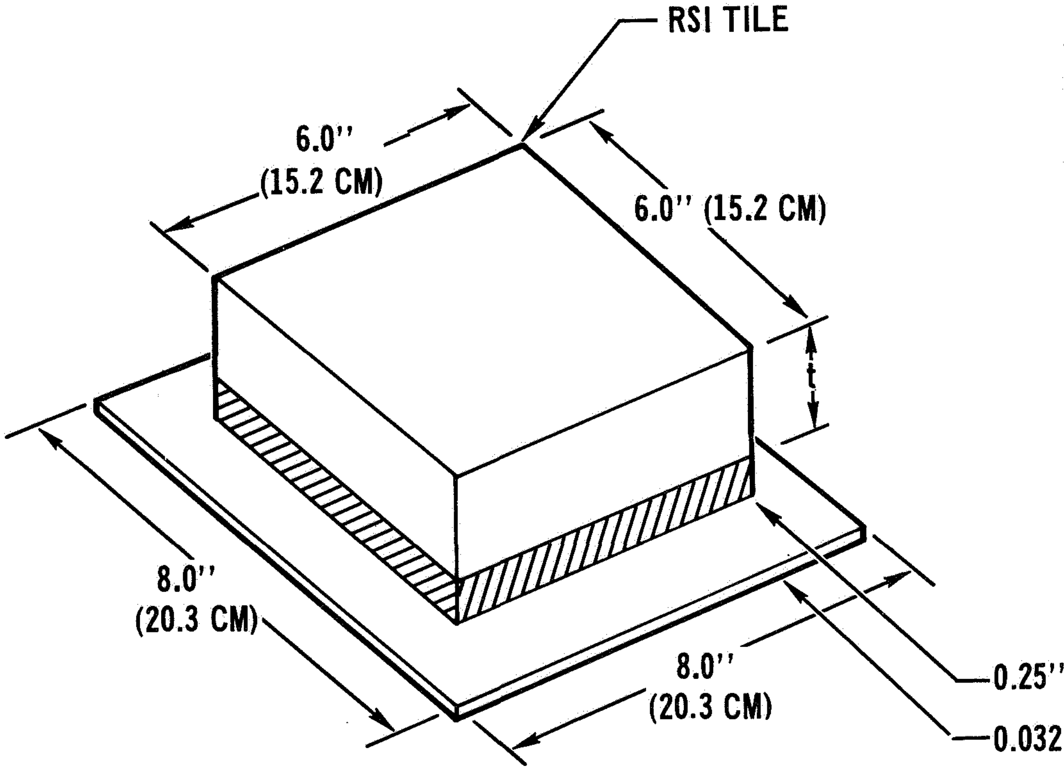
Figure 1

RSI SPECIMENS FOR METEOROID TESTS

(Figure 2)

RSI tiles were bonded to aluminum skin panels representative of the Space Shuttle primary structure. Specimens consisted of a 20.3 cm x 20.3 cm x 0.081 cm (8.0" x 8.0" x 0.032") aluminum plate, a 15.2 cm x 15.2 cm x 0.64 cm (6.0" x 6.0" x 0.25") sponge pad, and a 15.2 cm x 15.2 cm (6.0" x 6.0") RSI tile. Thickness of tiles ranged from 1.90 cm (0.75") to 11.4 cm (4.5"). The RSI material used in these tests was 240 kg/m^3 (15.0 lb/ft^3) Hardened Compacted Fibers (HCF) produced by McDonnell Douglas Astronautics Company - East. Rasbestos Manhatten S105 sponge with a density of approximately 480 kg/m^3 (30 lb/ft^3) was used as the strain isolator. Spherical aluminum particles were propelled from a light gas gun at a velocity of about 7.3 km/sec (23,000 ft/sec).

RSI SPECIMENS FOR METEOROID TESTS



NO. SPECIMENS	RSI TILE THICKNESS IN. (a)
1	4.5 (11.4)
3	1.75 (4.4)
2	0.75 (1.9)

(a) UNITS IN PARENTHESIS ARE CM

Figure 2

PREVIOUS POLYURETHANE FOAM TESTS

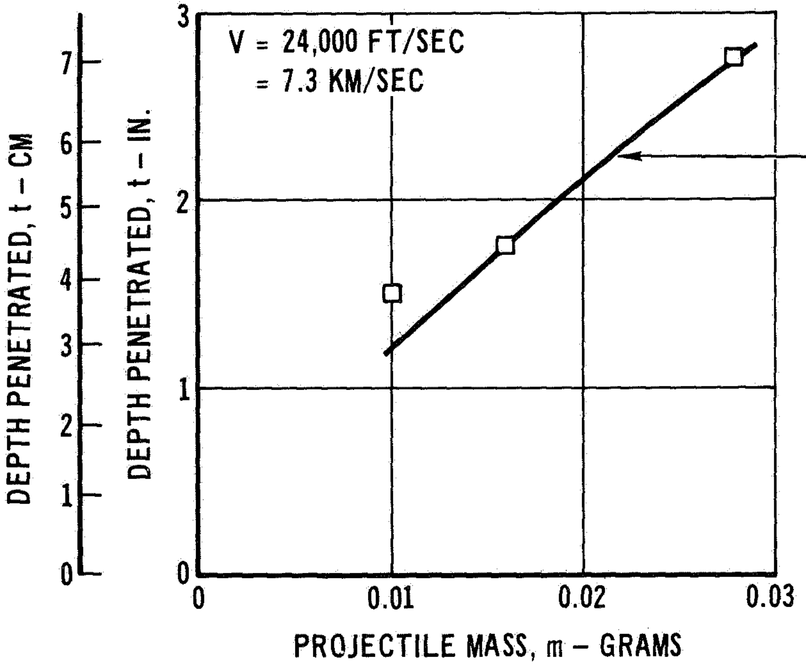
(Figure 3)

Results of previous meteoroid tests of polyurethane foam aided in developing empirical functions for predicting penetration resistance by assuming a similar penetration mechanism. Penetration depths into polyurethane foam for three different projectile masses are shown on this chart. Summers' equation for penetration into a semi-infinite solid was used as a basis for establishing an equation relating depth of penetration (t) into foam to projectile mass (m) and velocity (v). This equation is,

$$t = Km^{X}v^{2/3}$$

Constants K and X were determined from tests. Since velocity was not a test variable, the exponential value recommended by Summers was used.

PREVIOUS POLYURETHANE FOAM TESTS



FOAM DENSITY = 1.2 PCF (19.2 KG/M^3)

ASSUME $t = Km^x V^{2/3}$

THEN BASED ON TEST DATA

$K = 124.5$
$x = 0.805$

THEREFORE, $t_{FOAM} = 124.5 m^{0.805} \left(\frac{V}{7.3}\right)^{2/3}$

t_{FOAM} = cm

m = GRAMS
V = KM/SEC

Figure 3

PRELIMINARY RSI ANALYSIS BASED ON FOAM TESTS

(Figure 4)

To obtain a penetration equation for RSI, it was assumed that the penetration mechanisms of RSI and foam are similar. This is reasonable because their densities are low relative to metallic materials. Therefore, it follows that the weight of RSI penetrated (ρ_{RSI}) (t_{RSI}) is some factor (ϕ) times the weight of foam penetrated (ρ_{FOAM}) (t_{FOAM}). Substitution of this equation into the empirical penetration equation for foam results in the penetration equation for RSI. The parameter ϕ was then obtained from tests.

PRELIMINARY RSI ANALYSIS BASED ON FOAM TESTS

$$(\rho_{RSI})(t_{RSI}) = \Phi(\rho_{FOAM})(t_{FOAM})$$

t = THICKNESS PENETRATED BY GIVEN MASS AT GIVEN VELOCITY

ρ = MATERIAL DENSITY

ρ_{FOAM} = 0.0194 GRAM/CC (1.2 pcf)

ρ_{RSI} = 0.2420 GRAM/CC (15 pcf)

THEREFORE $t_{RSI} = 9.98\ \Phi\ m^{0.805} \left(\frac{V}{7.3}\right)^{2/3}$

t_{RSI} = cm

m = GRAMS

V = Km/SEC

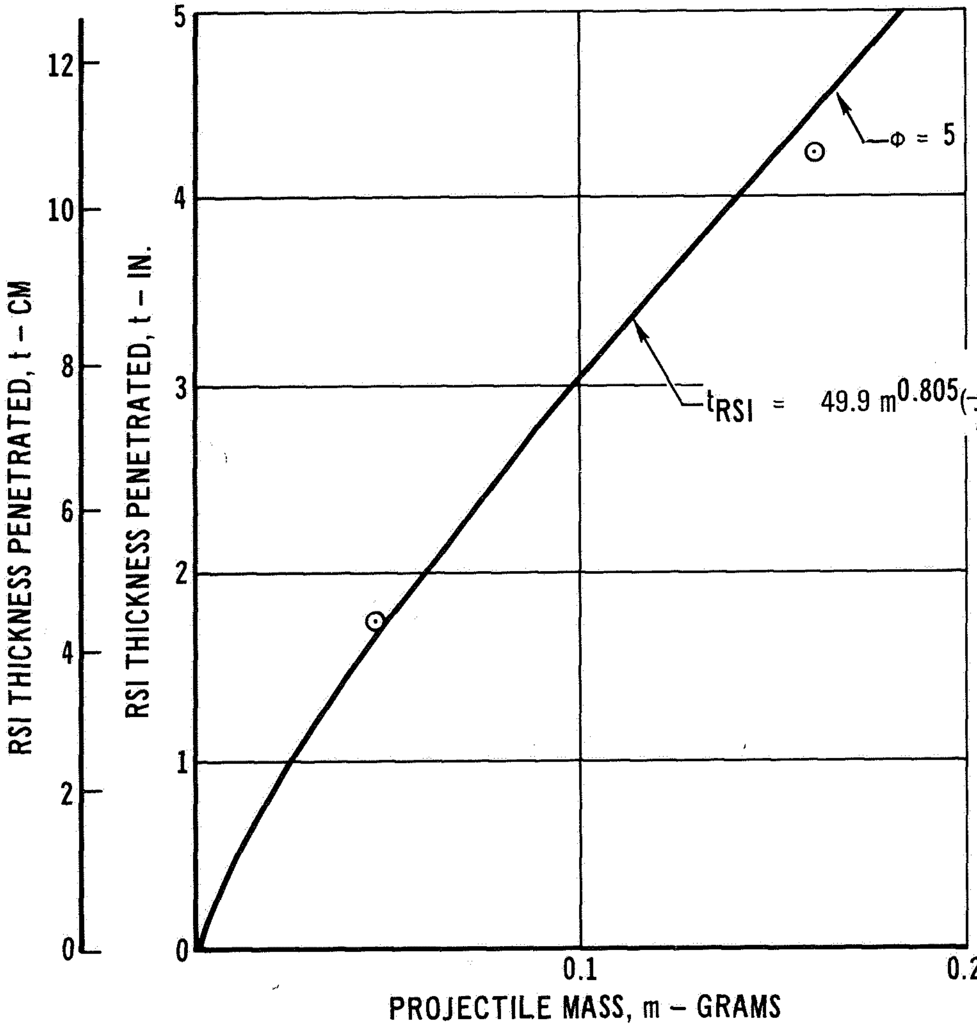
Figure 4

PENETRATION RESISTANCE OF RSI

(Figure 5)

The first two data shots were used to establish the penetration resistance of RSI. Spherical aluminum particles were propelled from a light gas gun at a velocity of about 7.3 Km/sec (23,000 ft/sec). Two projectile diameters were used and depths of penetration are shown on this chart. Also shown is a plot of the empirical penetration equation for RSI using $\phi = 5$. Test results best fit this curve. The resulting penetration equation can then be used to calculate depth of penetration into RSI.

PENETRATION RESISTANCE OF RSI



$t_{RSI} = 49.9\ m^{0.805}\left(\frac{V}{7.3}\right)^{2/3}$

RSI THICKNESS CM (IN)	PROJECTILE DIA (CM)	PROJECTILE MASS (GRAMS)	DEPTH OF PENETRATION CM (IN)
11.4 (4.5)	0.48	0.1589	11.8 (4.25)
4.45 (1.75)	0.32	0.0469	4.45 (1.75)

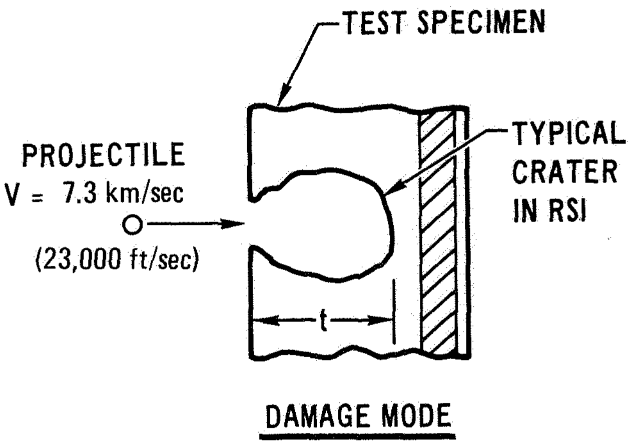


Figure 5

TYPICAL RSI DAMAGE DUE TO METEOROID IMPACT

(Figure 6)

Photos were taken of all specimens after testing to provide a permanent record of the degree of damage. This is a cutaway view of a 4.45 cm (1.75 inch) thick specimen showing typical simulated meteoroid damage. The projectile penetrated the full thickness of RSI in this test and created a large egg-shaped cavity.

TYPICAL RSI DAMAGE DUE TO METEOROID IMPACT

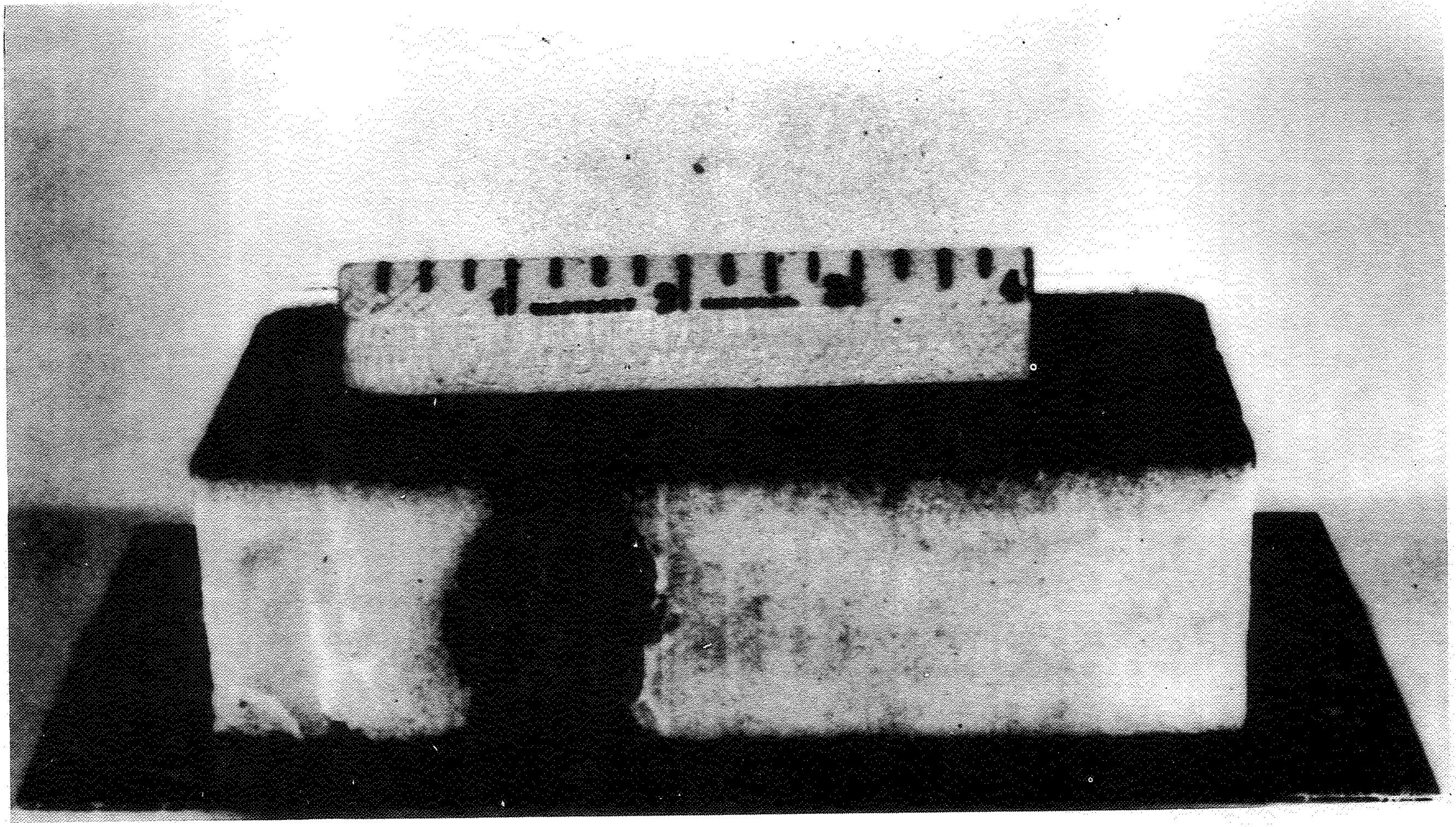


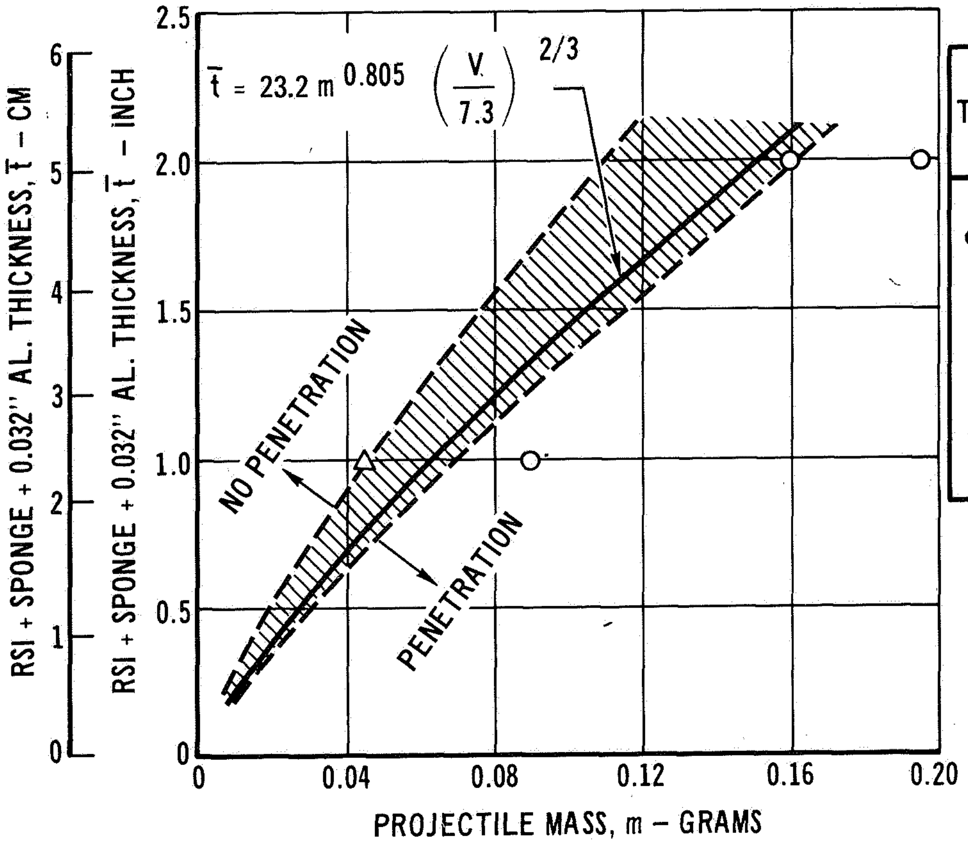
Figure 6

STRUCTURAL PENETRATION DATA

(Figure 7)

Four meteoroid shots were used to yield structural penetration data. Results of tests are shown on this chart. Three shots, denoted by circles, completely penetrated HCF, sponge, and aluminum panel. One projectile penetrated the HCF and sponge and made a large dent in the aluminum plate. A structural penetration equation was developed from these data based on the empirical equation developed for penetration into RSI only. The shaded area represents the region of uncertainty which could be reduced with further testing.

STRUCTURAL PENETRATION DATA



RSI* THICKNESS CM (IN)	PROJECTILE** DIA (CM)	MASS (GRAMS)	TEST RESULTS
4.45 (1.75)	0.48	0.1593	JUST PENETRATED
4.45 (1.75)	0.52	0.1978	COMPLETE PENETRATION
1.90 (0.75)	0.32	0.0467	BIG DENT IN ALUMINUM SHEET
1.90 (0.75)	0.40	0.0919	COMPLETE PENETRATION

*TOTAL SPECIMEN THICKNESS IS RSI THICKNESS + 0.64 cm (0.25") SPONGE + 0.081 cm (0.032") AL.

** V = 7.3 km/sec (23,000 ft/sec)

Figure 7

RSI SPECIMEN METEOROID DAMAGE--COMPLETE PENETRATION

(Figure 8)

None of the RSI tiles failed catastrophically, but large, egg-shaped craters did result from meteoroid penetration. This chart shows the metallic side of a specimen that was completely penetrated. The petalled hole is typical of thin gage shielded structures.

RSI SPECIMEN METEOROID DAMAGE—COMPLETE PENETRATION

Figure 8

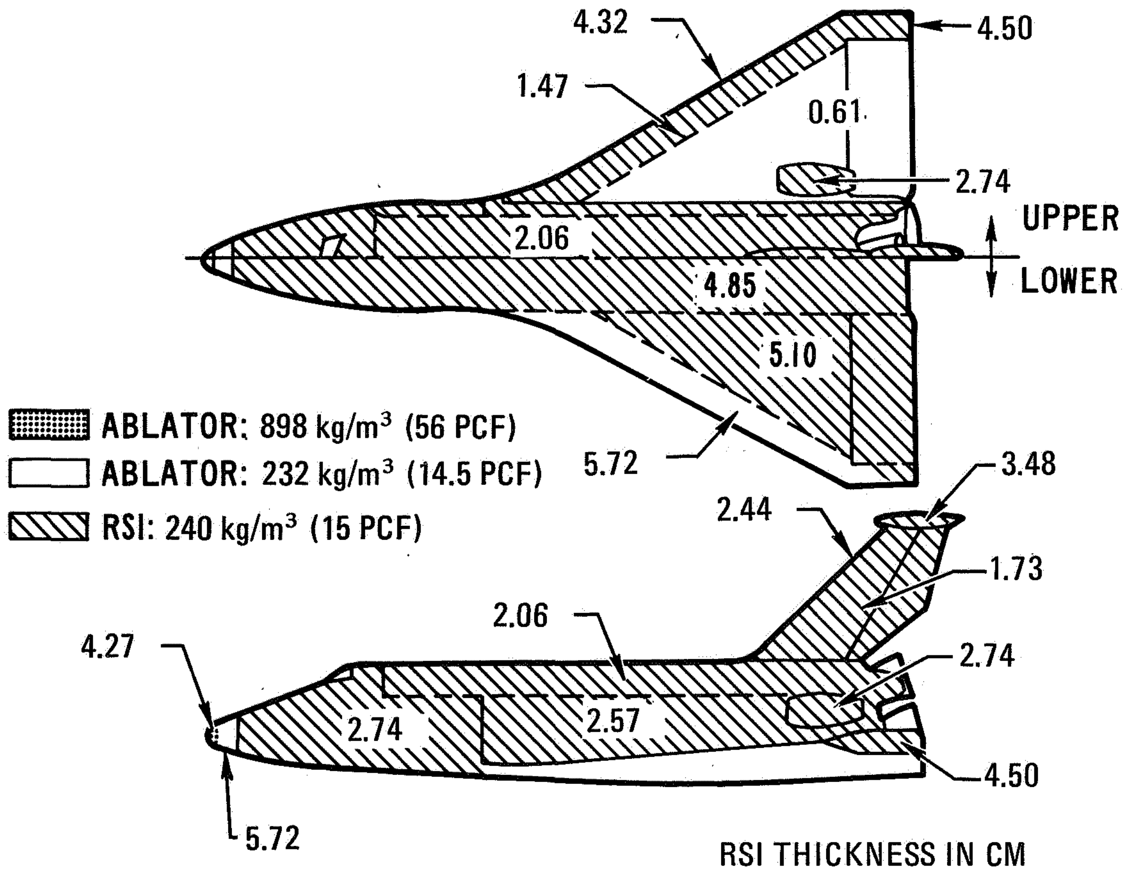
RSI SURFACE AREA COVERAGE

(Figure 9)

The penetration equations developed from tests were used to predict surface damage and to estimate probability of no penetration of the Shuttle Orbiter primary structure. Typical results are shown in figures 9 through 11.

For the Shuttle Orbiter configuration studied, RSI covers 77 percent of the surface area or about 890 m^2 (9600 ft^2). For meteoroid analysis, the surface area was divided into three parts with different RSI thicknesses: 1.60 cm (0.63"), 2.41 cm (0.95"), and 4.90 cm (1.93").

RSI SURFACE AREA COVERAGE



AREA FT^2 (a)	AVERAGE RSI THICKNESS IN. (b)
1400 (130)	0.63 (1.60)
4350 (404)	0.95 (2.41)
3880 (360)	1.93 (4.90)

(a) UNITS IN PARENTHESIS ARE M^2.
(b) UNITS IN PARENTHESIS ARE CM.

Figure 9

METEOROID ENVIRONMENT, MASS--FLUX MODEL

(Figure 10)

Environments for sporadic and stream meteoroids are summarized on this chart. Environments were taken from NASA TM X-53957. The seasonal factors are based on a seven day mission occurring during periods of peak sporadic and stream meteoroid activity. An orbital altitude of 370 Km (200 nm) was used to determine values for the defocusing factor and earth gravitational effects.

METEOROID ENVIRONMENT, MASS—FLUX MODEL

- SPORADIC METEOROIDS

FOR $10^{-6} \leq m \leq 10^{0}$

$$\log N_{sp} = -14.41 - 1.22 \log m + \log G_e + \log \left(\frac{1 + \sqrt{1 - 1/r^2}}{2} \right) + \log F_{seasonal}$$

N_{sp} = NO. OF PARTICLES/m^2/SEC OF MASS m OR GREATER

m = MASS IN GRAMS

G_e = DEFOCUSING FACTOR = 0.976 (370 km ORBIT)

r = 1.06 (3.70 km ORBIT)

$F_{seasonal}$ = 1.77 (7 DAY MISSION)

- STREAM METEOROIDS

FOR $10^{-6} \leq m \leq 10^{0}$

$$\log N_{st} = -14.41 - \log m - 4.0 \log (V_{st}/20) + \log F$$

N_{st} = NO. OF PARTICLES/m^2/SEC OF MASS m OR GREATER

V_{st} = 40 Km/SEC

F = 6.0 (7 DAY MISSION)

REFERENCE: NASA TMX 53957

Figure 10

EFFECTS OF STRUCTURAL SKIN THICKNESS ON PENETRATION PROBABILITY

(Figure 11)

Probability of no structural penetration was determined for a seven day mission, assuming 77 percent of the shuttle covered with RSI and considering sporadic and stream meteoroids. For a 0.081 cm (0.032 inch) aluminum skin thickness the probability of no structural penetration is 0.99988. The probability of no penetration exceeding the thickness of RSI only was also calculated using the RSI penetration equation. A curve was drawn connecting the two points based on penetration probability analyses of other materials. Tests of other skin thicknesses are required to establish the correct relationship for RSI bonded to aluminum.

EFFECTS OF STRUCTURAL SKIN THICKNESS ON PENETRATION PROBABILITY

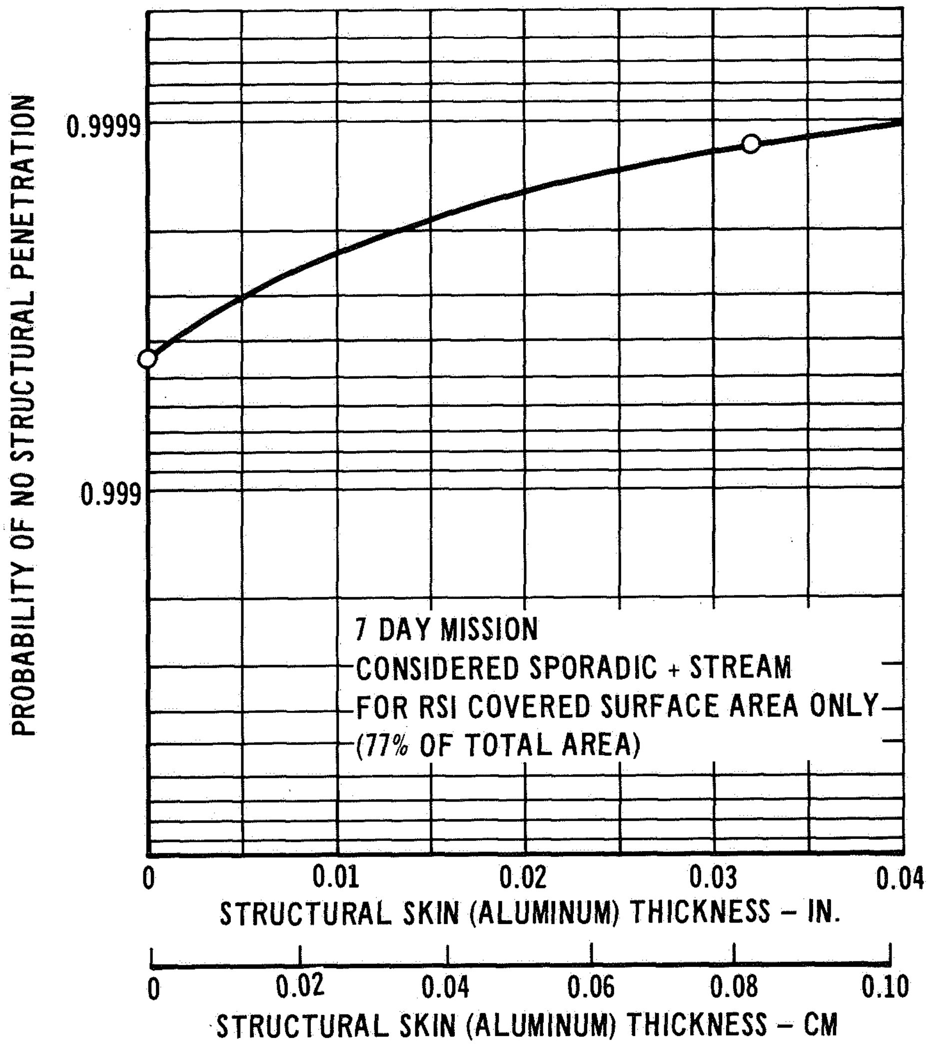


Figure 11

RSI SPECIMENS FOR THERMAL DEGRADATION TESTS
(PLASMA JET TESTS)

(Figure 12)

A RSI tile with simulated meteoroid cavities was tested in a plasma jet tunnel to determine the effects of cavity size on bondline heating. The heat pulse produced total heat and peak temperatures equivalent to a shuttle entry heating cycle. The same tile was tested four times with a successively larger cavity each test to obtain comparative data. The same heat pulse was used for each test except heating was terminated early if the bondline reached 423°K (300°F). Thermocouples were embedded in the tile to monitor temperatures during tests.

The test specimen was a 17.8 cm (7.0 inch) diameter by 5.08 cm (2.0 inch) thick RSI tile bonded with RTV 560 to a 0.64 cm (0.25 inch) thick sponge pad which was in turn bonded to a 0.25 cm (0.10 inch) thick titanium plate. The specimen was split along a diagonal to allow access for carving egg shaped cavities in the center of the tile. The specimen was bolted to support structure and was inclined at a 60° angle of attach to the air flow. The top surface of the specimen was coated with a high emittance coating. Thermocouples were located at several points through the thickness of the tile and at the RSI sponge bondline. Because of excessive electrical interference during tests with cavities in the RSI, only the thermocouples at the bondline functioned properly.

RSI SPECIMENS FOR THERMAL DEGRADATION TESTS

(PLASMA JET TESTS)

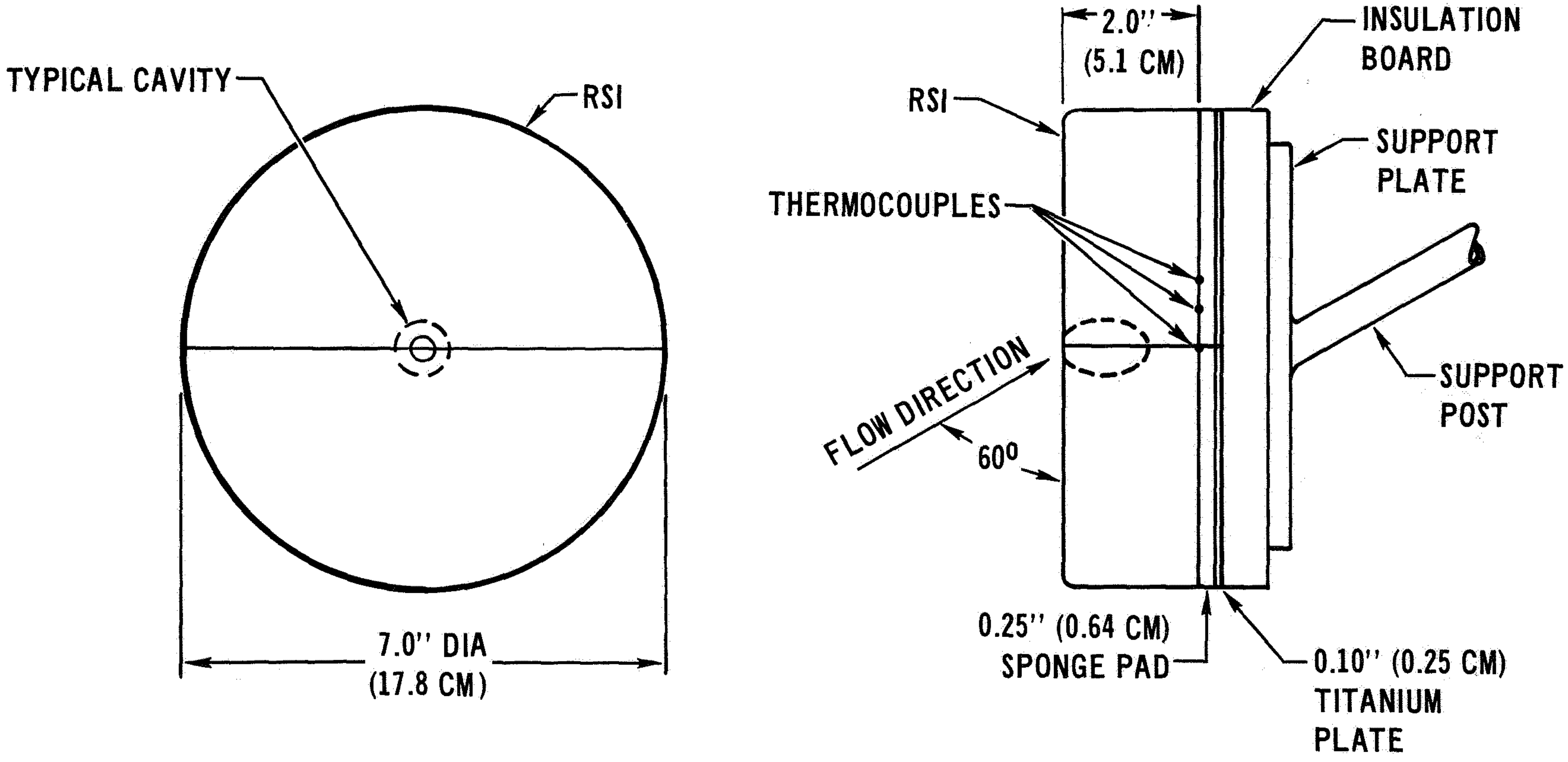


Figure 12

METEOROID CAVITY DIMENSIONS

(Figure 13)

Four tests were conducted; one with no cavity and three with successively larger egg-shaped cavities. For the four tests, cavity depths were respectively 0.0 cm, 1.93 cm (0.76 inch), 3.42 cm (1.35 inch), and 5.08 cm (2.0 inch). The 5.08 cm (2.0 inch) cavity completely penetrated the tile to the sponge. For tests 2, 3, and 4 the cavity proportions were approximately the same and the size of the entry hole was unchanged. Probable number of penetrations are indicated for each cavity size assuming seven day missions.

METEOROID CAVITY DIMENSIONS

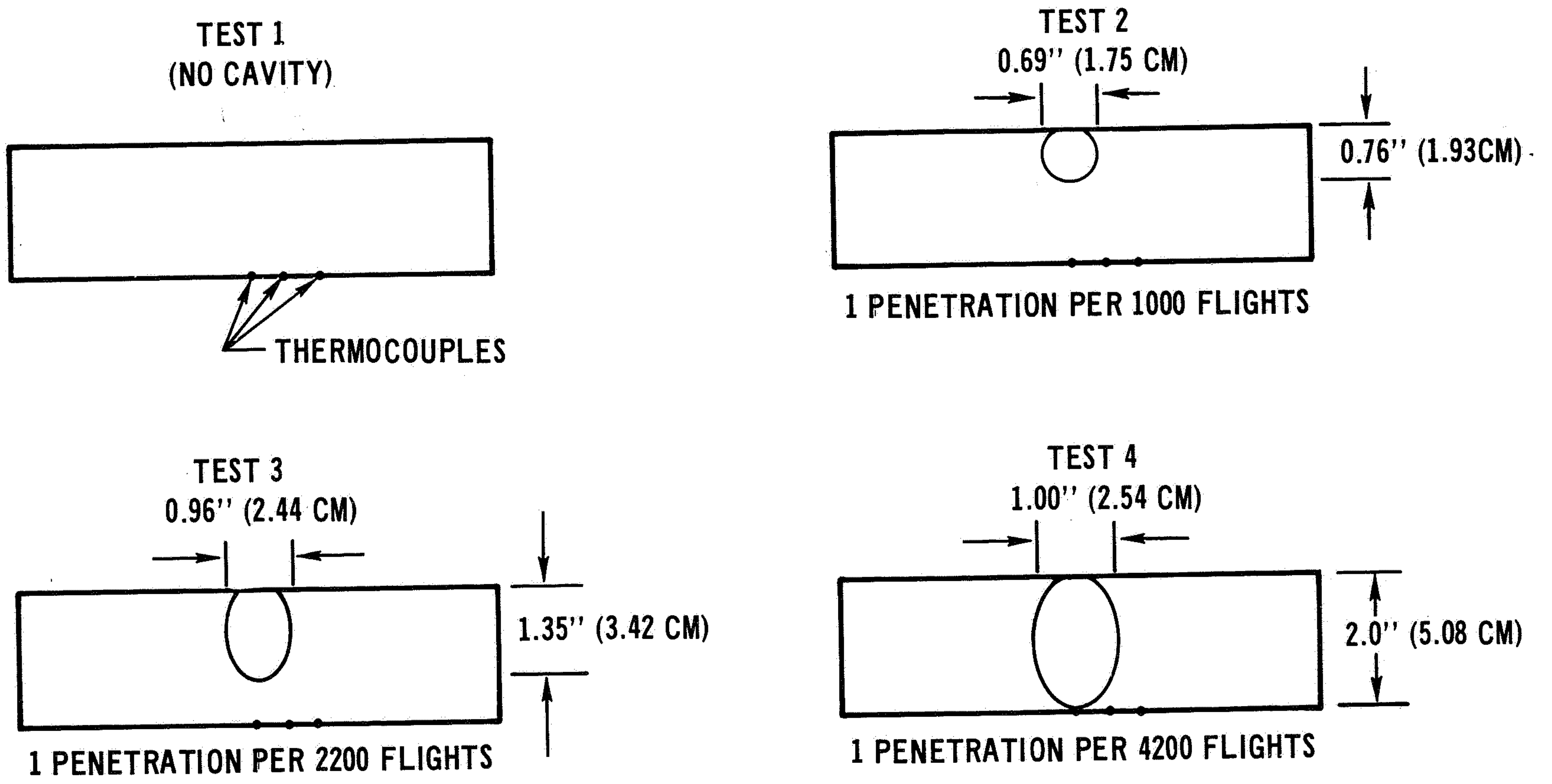


Figure 13

HEATING PULSE EQUIVALENT TO HEAT FROM 2000 KM (1100 MILE) CROSS-RANGE ENTRY

(Figure 14)

The tile was subjected to a heat pulse equivalent to the total heat and peak temperature of a shuttle entry cycle, except heating was terminated early if the bondline temperature reached 420°K (300°F). The linear heating plan consisted of: (1) a tile surface temperature rise from ambient to 870°K (1100°F) in a few seconds as the tile was inserted into the 870°K (1100°F) heating stream; (2) a 150 second linear surface heat up to 1530°K (2300°F); (3) a 490 second constant surface heating at 1530°K (2300°F); (4) a 150 second linear surface cool down to 870°K (1100°F); and (5) removal of specimen and cool to ambient conditions. The entire heating pulse was 790 seconds duration. The actual heating pulse for the first test differed slightly from the plan as shown. For tests 3 and 4, the heating pulse was of shorter duration because the bondline temperature reached 420°K (300°F).

HEATING PULSE EQUIVALENT TO HEAT FROM 2000km (1100 MILE) CROSS-RANGE ENTRY

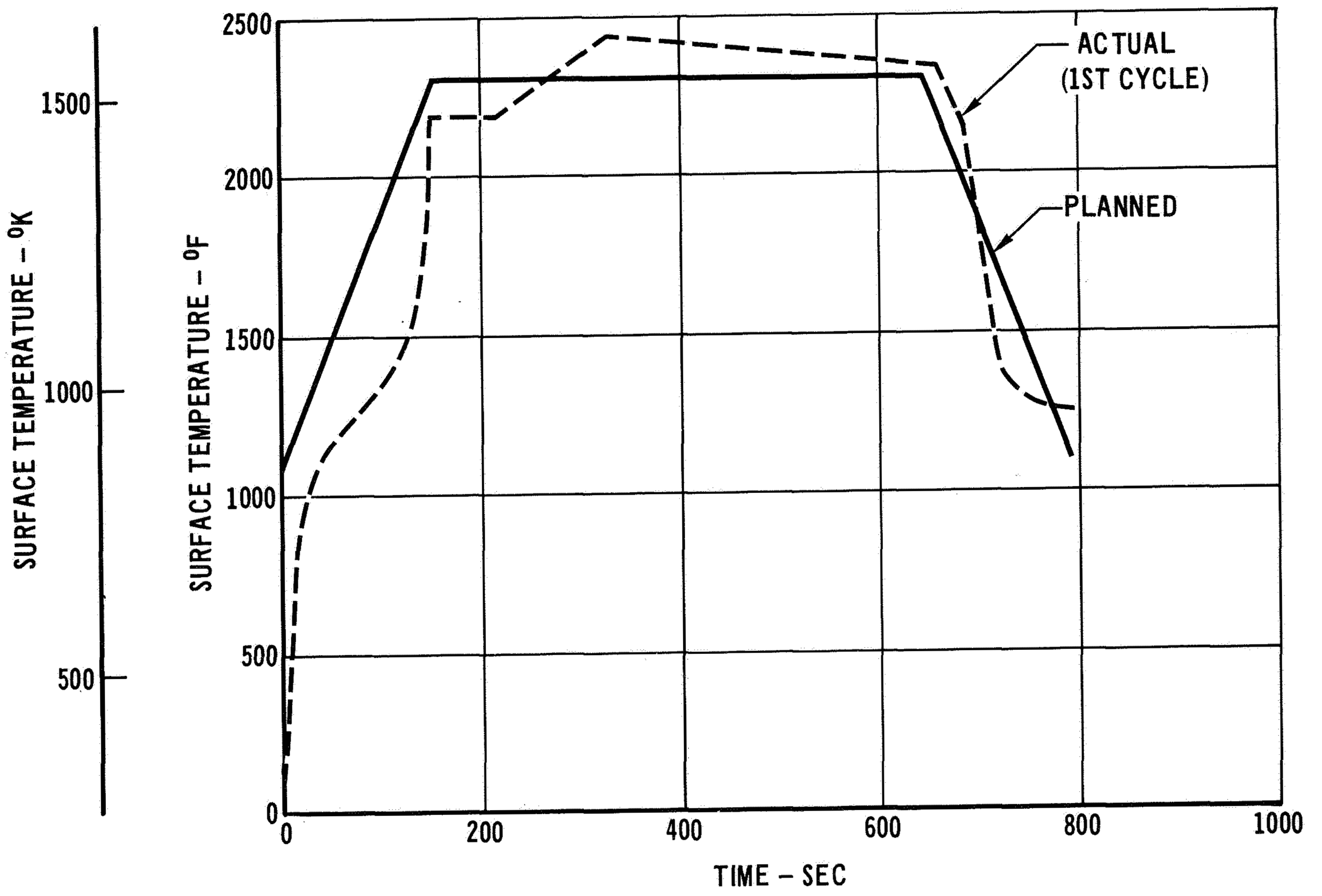


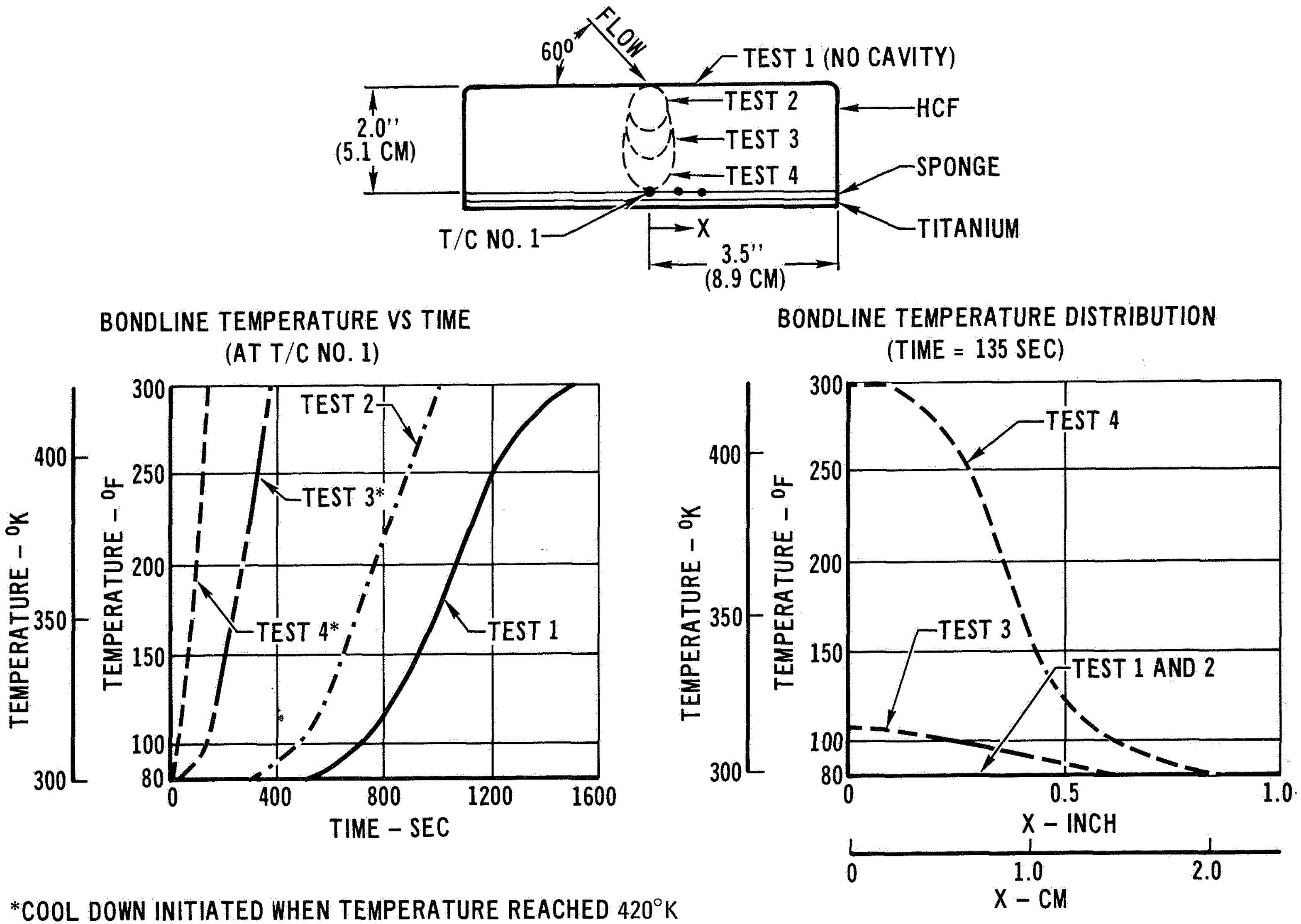
Figure 14

INFLUENCE OF CAVITY SIZE ON BONDLINE HEATING

(Figure 15)

The presence of cavities in the tile did influence the bondline heating. Both the bondline temperature-time history and temperature distribution changed with changes in cavity size. With no cavity, the full 790 second heat pulse was input before a bondline temperature of 420°K (300°F) was reached and the bondline temperature distribution was approximately uniform. The 1.93 cm (0.76 inch) cavity was also exposed to the full heat pulse and the bondline reached a peak temperature of 460°K (370°F). Heating was stopped early for the 3.42 cm (1.35 inch) and 5.08 cm (2.0 inch) cavities to prevent overheating. For the 5.08 cm (2.0 inch) deep cavity a 420°K (300°F) bondline temperature was reached when only 135 seconds of the 790 second thermal pulse had been input. Also the tile bondline temperature dropped from 420°K (300°F) at the cavity centerline to ambient only 2.54 cm (1 inch) away after 135 seconds of heating. The two smaller cavities produced approximately proportional changes. A meteoroid penetration sufficient to reach the bondline on the shuttle orbiter would be expected once every 2500 seven day missions.

INFLUENCE OF CAVITY SIZE ON BONDLINE HEATING



*COOL DOWN INITIATED WHEN TEMPERATURE REACHED 420°K

Figure 15

FURTHER STUDIES REQUIRED

(Figure 16)

Recommended future studies are identified on this chart. They include determination of dependency of damage on projective velocity, investigations of penetration mechanics and effects of oblique impacts. Also, additional thermal performance tests are recommended for different cavity shapes which may be associated with coated RSI and to determine heat pulse duration which would cause structural damage.

FURTHER STUDIES REQUIRED

- PROJECTILE VELOCITY DEPENDENCY
- PENETRATION MECHANICS
  - RSI (COATED AND UNCOATED)
  - RSI/STRUCTURE
- OBLIQUE IMPACT EFFECTS
- THERMAL DEGRADATION OF IMPACTED RSI

Figure 16