ENVIRONMENTAL TESTING OF REI-MULLITE THERMAL PROTECTION SYSTEM FOR THE SPACE SHUTTLE ORBITER

BY

R. GLUCK, R. ROMANO, H. THIBAULT

GENERAL ELECTRIC COMPANY
RE-ENTRY & ENVIRONMENTAL SYSTEMS DIVISION
PHILADELPHIA, PENNSYLVANIA

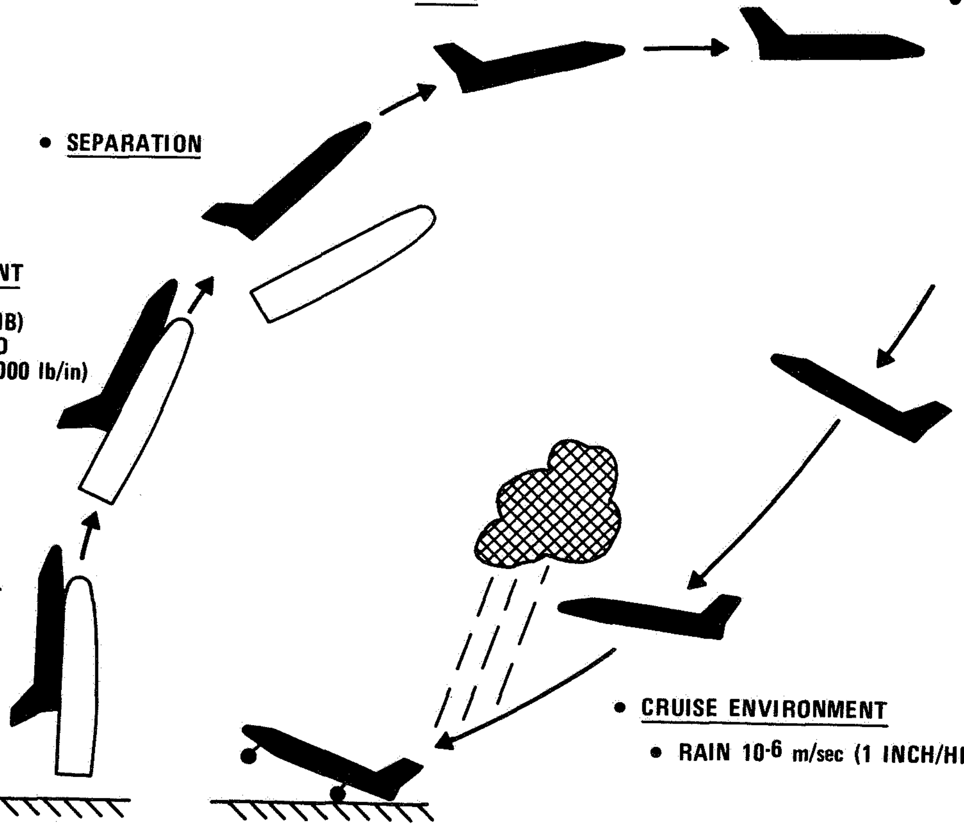
INTRODUCTION
TPS DESIGN ENVIRONMENTS
(Figure 1)

The Space Shuttle Orbiter has as its requirements a 10-year lifetime with 100 or more mission reuse capability to re-entry surface temperatures of 1644° K (2500° F). To meet these requirements, the thermal protection system (TPS) for the Orbiter must, in addition to surviving the thermostructural environments of entry into the earth's atmosphere, have all-weather capability similar to current aircraft operations, resistance to vacuum/temperature exposure in space, and resistance to the structural fatique environments of aircraft mode operations.

The objectives of this paper are to discuss and present results of special environmental tests performed on the General Electric Company's Re-entry and Environmental Systems Division (GE-RESD) Reusable Surface Insulation System, REI-Mullite. These environmental tests make up the mission environments that affect the design and reliability of the Orbiter TPS, and include salt spray, humidity, rain erosion, acoustics, orbital vacuum, hot and cold orbital soak conditions, re-entry heat, and structural loads.

Discussions are first presented on individual test series to evaluate the natural environments of salt spray, humidity, rain and vacuum followed by a discussion of the results of the Structures Test Program (STP) performed for North American Rockwell/Space Division (NR/SD) to evaluate the performance of the REI-Mullite TPS for induced multiple cycle environments of acoustics, orbital temperature, re-entry heat, and structural loadings.

TPS DESIGN ENVIRONMENTS



- **BOOST**
- **ON-ORBIT ENVIRONMENT**
  - VACUUM 0.13 X 10^{-3} N/m^2 (10^{-6} TORR)
  - TEMPERATURE
    116°K → 328°K
    (-250°F → + 130°F)
- **SEPARATION**
- **BOOST ENVIRONMENT**
  - ACOUSTICS (163 dB)
  - STRUCTURE LOAD
    705 X 10^3 N/m (4000 lb/in)
- **RE-ENTRY ENVIRONMENT**
  - TEMPERATURE
    SURFACE 1644°K (2500°F)
    STRUCTURE 450°K (350°F)
  - ACOUSTICS 145 dB
  - STRUCTURE LOAD
    705 X 10^3 N/m (4000 lb/in)
- **PAD ENVIRONMENT**
  - SALT SPRAY
  - HUMIDITY
- **CRUISE ENVIRONMENT**
  - RAIN 10^{-6} m/sec (1 INCH/HR)
- LANDING

Figure 1

REI-MULLITE TPS INSTALLATION

(Figure 2)

The General Electric Company's RSI Thermal Protection System consists of REI-Mullite coated on five sides with a thin ceramic base material, SR-2, bonded with PD200 foamed elastomeric pads to an aluminum primary skin structure. The REI-Mullite is a low density, 192 kg/m^3 (12 lb/ft^3) rigidized fibrous material that provides the insulative characteristics necessary to protect the aluminum structure to its maximum operating temperature of 450° K (350° F). The ceramic coating provides a hard waterproof surface for resistance to rain erosion and handling damage. This coating, being the outer surface of the vehicle, must also have proper high temperature emissivity characteristics, $\epsilon > 0.8$, to maximize re-entry heat rejection by reradiation and proper optical property characteristics, $\alpha/\epsilon \approx 0.4$ to 0.5, to limit on-orbit temperature extremes.

Differences in thermal expansion coefficient between the insulation and structure and deformations of approximately 0.5 percent strain require, for structural margin considerations, that interaction between the structure and the TPS be minimized. This strain isolation is accomplished by means of a foamed silicone elastomeric pad, PD-200, bonded in place between the insulation and the structure.

The insulation tiles are provided with a vent to allow depressurization of the material during ascent.

REI-MULLITE TPS INSTALLATION

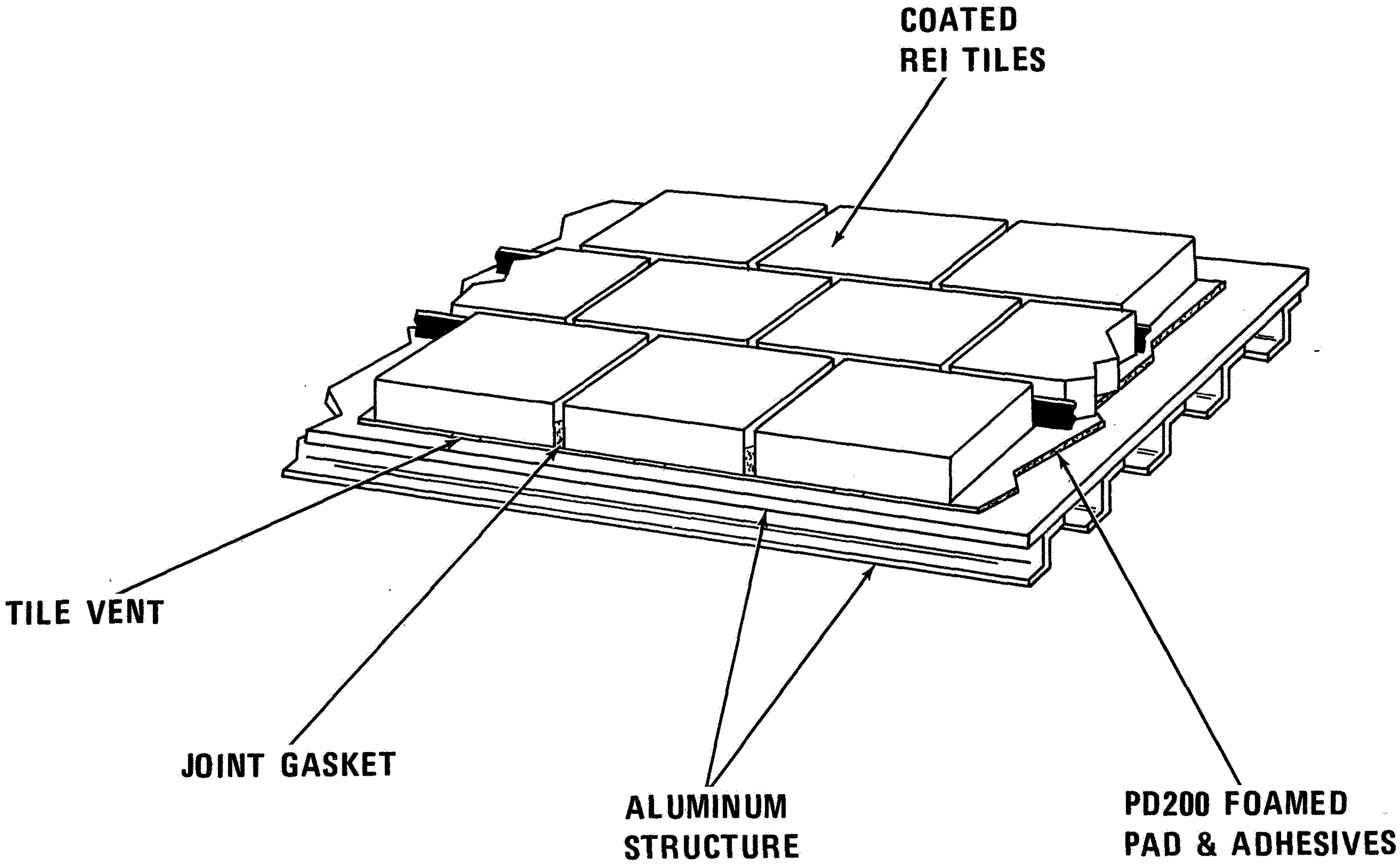


Figure 2

VACUUM VENT TESTING

(Figure 3)

The REI-Mullite TPS panel must be vented to allow decompression during boost and repressurization during re-entry while preventing boundary layer flow through from surface pressure gradients and water and moisture injestion. A test series(1) was performed in which coated REI-Mullite tiles bonded to aluminum plates were subjected to boost depressurization and boost heating, orbital vacuum, and re-entry heating. The specimens were 0.1 × 0.2 × 0.038 m (4 × 8 × 1.5 in.) with a pressure tap located in the center of the REI-Mullite tile. The vent for the tile is located on the aft facing tile side and consists of a 0.8×10^{-4} square meter (0.125 square inch) vent hole in the PD-200. The vented REI-Mullite surface is coated with PD-200 primer to provide waterproofness to the tile.

Tests were run on both dry and wet specimens because it was determined that the case of absorbed moisture in a damaged tile that had escaped detection during nondestructive evaluation (NDE) would be the critical design condition. One test was performed with 30 percent H_2O by weight in the tile with the vent sealed to determine the failure mode.

VACUUM VENT TESTING MATRIX

MODEL NO.	TEST NO.	CONDITIONS	FACILITY	OBJECTIVE
1	1	COATED REI-MULLITE SPECIMEN WITH VENT HOLE	VACUUM SYSTEM TO SIMULATE VENT PRESSURE HISTORY	DEMONSTRATE ADEQUACY FOR DEPRESSURIZATION OF DRY REI-MULLITE
	2	COATED REI-MULLITE SPECIMEN WITH VENT HOLE	VACUUM SYSTEM COUPLED WITH RE-ENTRY SIMULATOR	DETERMINE EFFECT OF BOOST THERMAL ENVIRONMENT ON VENTING REQUIREMENTS
	3	COATED REI-MULLITE SAMPLE WITH VENT HOLE (10% H_2O BY WEIGHT)	VACUUM SYSTEM TO SIMULATE VENT PRESSURE HISTORY	DEMONSTRATE ADEQUACY OF VENTING AREA FOR WATER/AIR MIXTURE IN REI-MULLITE
	4	COATED REI-MULLITE SAMPLE WITH VENT HOLE (10% H_2O BY WEIGHT)	VACUUM SYSTEM COUPLED WITH RE-ENTRY SIMULATOR	SHOW THAT VENTING AREA IS SUFFICIENT TO PREVENT PRESSURE BUILD UP IN REI-MULLITE FOR WATER/AIR MIXTURE
	5	COATED REI-MULLITE SAMPLE WITH VENT SEALED (30% H_2O BY WEIGHT)	RE-ENTRY SIMULATOR	DEMONSTRATE ACCEPTABLE SINGLE MISSION CAPABILITY FOR WATER IMPREGNATED REI-MULLITE
2	1	COATED REI-MULLITE SAMPLE WITH VENT HOLE (5% H_2O BY WEIGHT ON 3rd CYCLE)	VACUUM SYSTEM COUPLED WITH RE-ENTRY SIMULATOR	DEMONSTRATE ADEQUACY OF VENTED REI-MULLITE DESIGN FOR MULTIPLE (3) MISSION CYCLES OF BOOST DEPRESSURATION AND HEAT, ORBITAL VACUUM AND COLD SOAK, AND RE-ENTRY HEATING

Figure 3

VACUUM VENTING TEST RESULTS

(Figure 4)

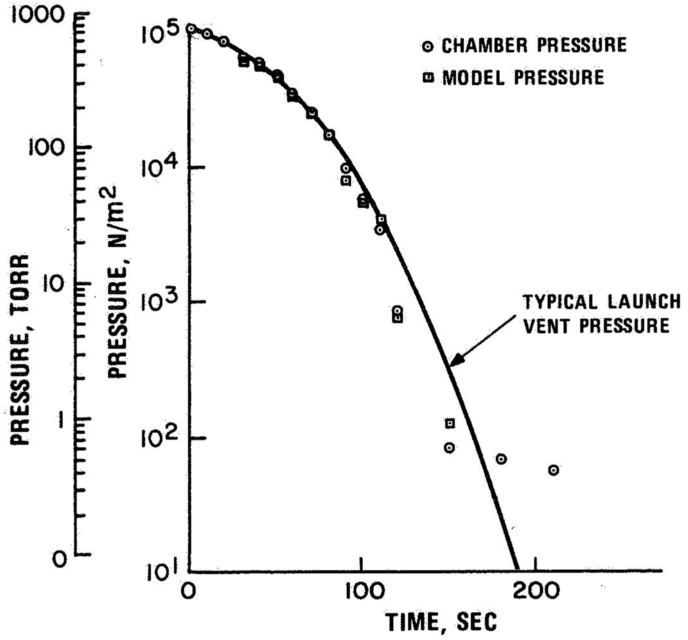
Results of this test series showed the proposed vent design would provide adequate venting of a coated REI-Mullite panel without impairing the waterproof characteristics of the design. Model pressures tracked the vacuum chamber pressures to within 667 N/m^2 (5 mm Hg) for up to 10 percent of H_2O by weight in the specimen even with boost heating applied.

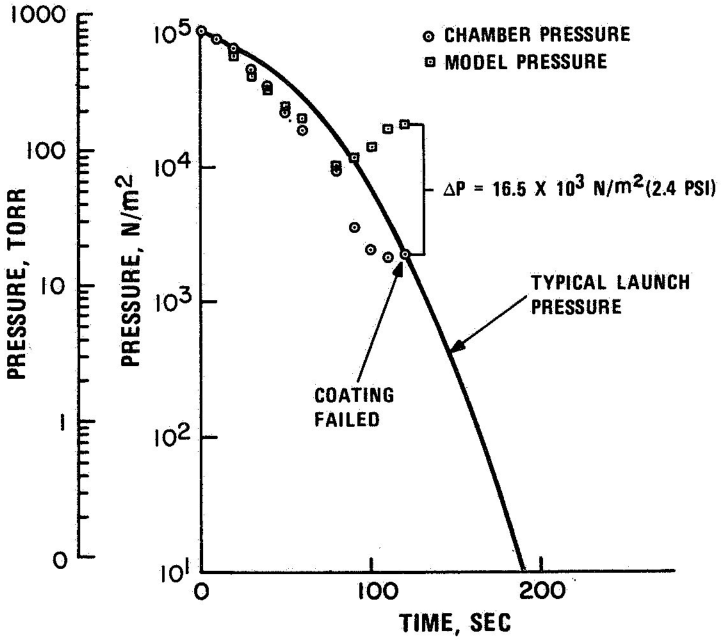
Eighty-five to ninety-nine percent of the initial H_2O in the specimens was lost during the boost depressurization and heating cycles.

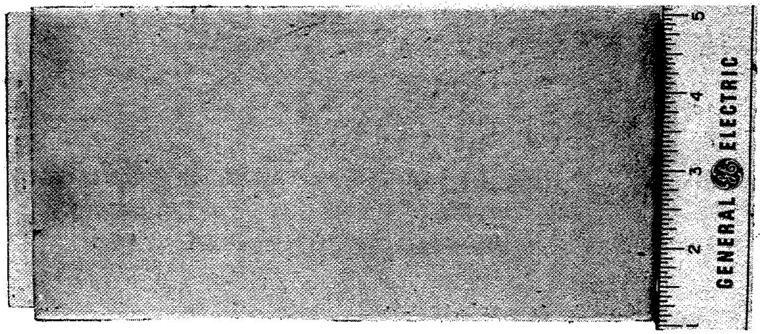
Pressure levels in the specimen of less than 10^3 N/m^2 (10^{-2} atm) were measured after a period of 94 minutes. This represents a launch orbit cycle, confirming the use of 10^3 N/m^2 (10^{-2} atm) conductivity data for TPS design.

The failure mode for a tile that had 30 percent H_2O and a sealed vent was found to be that of surface coating failure. The tile remained intact, still capable of providing thermal protection for one re-entry condition, demonstrating the fail safe characteristics of the system for water injestion. A ΔP of 16.5×10^3 N/m^2 (2.4 psi) was developed across the coating prior to failure.

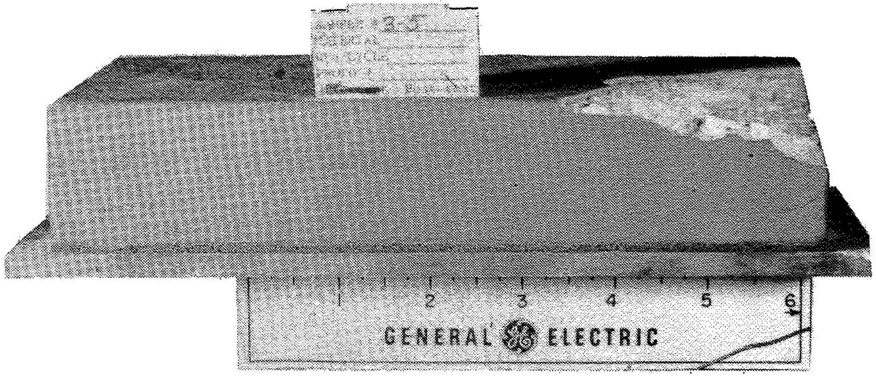
VACUUM VENTING TEST RESULTS







VENTING TEST – MODEL 1, TEST NO. 4, AIR/WATER
(10 PERCENT H_2O)



VENTING TEST – MODEL 1, TEST NO. 5, SEALED MODEL
(30 PERCENT WATER)

Figure 4

SALT SPRAY AND HUMIDITY TESTING

(Figure 5)

Salt spray and humidity tests were performed to evaluate the performance of the REI-Mullite TPS. Specimen geometry consisted of 0.1 × 0.2 × 0.038 m (4 × 8 × 1.5 inch) coated tiles bonded to aluminum plates with 0.008 m (0.3 inch) thick PD-200. The REI-Mullite tiles were vented with the design previously discussed. Three specimens were subjected to the salt spray and humidity environment. The salt spray environment consisted of a forty-eight hour exposure to a 5 percent salt spray at 308° K (95° F). Following salt spray, the specimens were exposed to seven twenty-four hour humidity cycles. Each cycle consisted of an increase to 95 percent ± 5 percent relative humidity and 308° K ± 3° (95° F ± 5°) in two hours, a six hour hold at 95 percent R.H. and 308° K, and a reduction to 85 percent R.H. and 294° K (70° F) in sixteen hours. Following salt spray and humidity exposure two specimens, along with an identical specimen that had not been exposed, were subjected to a re-entry temperature simulation cycle where the surface temperature of the panels were maintained at 1478° K (2200° F) for a period of eighteen hours at 10^3 N/m^2 (10^{-2} atm). This represents the equivalent time at temperature of 100 missions. The specimens were actively cooled on the backface to maintain the REI/PD-200 interface to below 616° K (650° F).

Specimens were evaluated by means of coating bending test specimens and scanning electron micrographs (SEM's) to assess the material behavior as a function of exposure environment.

SALT SPRAY & HUMIDITY TEST PROGRAM

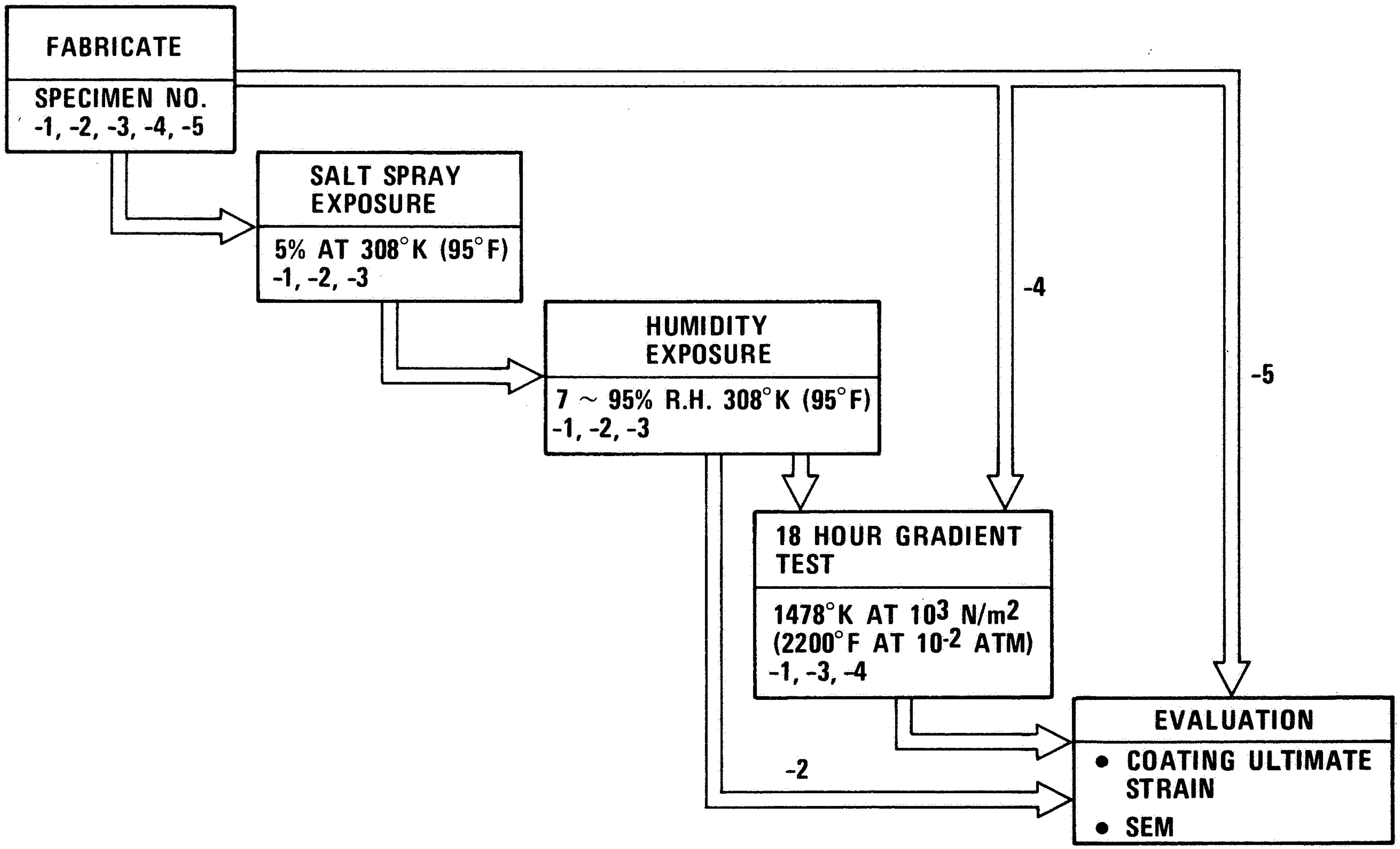


Figure 5

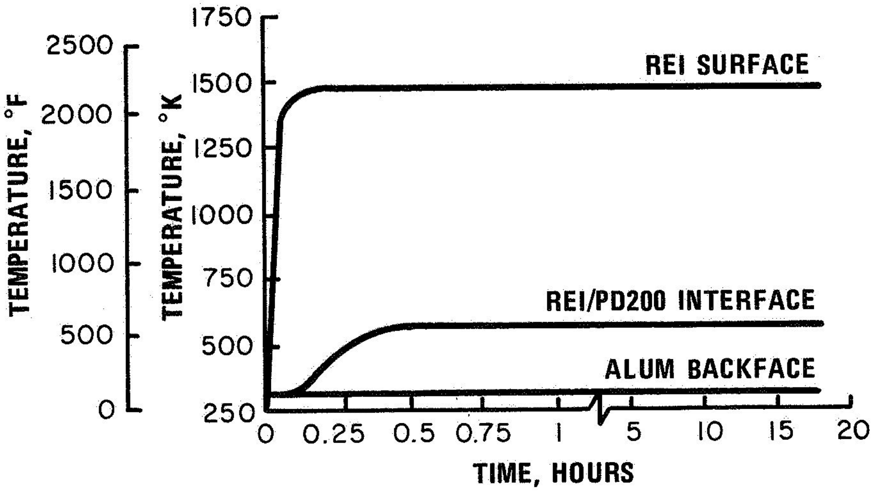
SALT SPRAY AND HUMIDITY TEST RESULTS
(Figure 6)

Specimens were weighed before and after exposure to salt spray and humidity. One specimen showed a slight increase in weight during salt spray and remained stable during the humidity testing. The other two specimens were unchanged throughout the test cycles. Initial plans were to run the 18 hour gradient test at 1644° K (2500° F) surface temperature; however, the maximum temperature limit of 616° K (650° F) was exceeded and caused bond decomposition on one specimen. Remaining specimens were tested at 1478° K (2200° F) surface temperature. Maximum surface temperature was achieved in approximately eight minutes and held constant for 18 hours. The REI-Mullite/PD-200 interface reached a maximum temperature of 566° K (560° F) after approximately 1/2 hour and remained constant for the remainder of the test indicating no change in thermal conductivity after long exposure at temperature. No degradation of performance was determined as a result of exposure to salt spray and humidity.

Tensile failure strain of the SR-2 coating of each specimen was obtained after testing. 0.0127 m (1/2 inch) square cross-section beams with the coating on the tensile face were machined from the specimens and loaded by four point bending. Failure strains were determined by strain gage measurements. Comparison with virgin coating data indicates that the exposure conditions did not have a detrimental effect on coating structural capability.

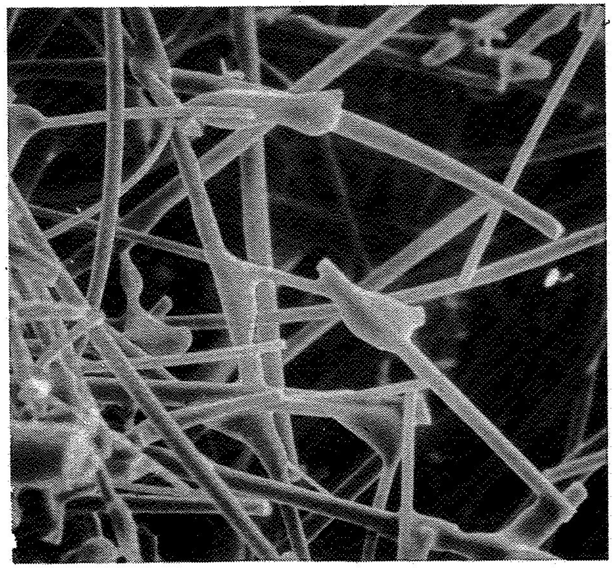
SEM's were obtained from coupons cut from the front and back face of the specimens. Visual scanning and photographs showed no damage to the fibers or deterioration of the binder fillets between fibers confirming that exposure to salt spray, humidity and thermal gradient, or salt spray and humidity only, has no harmful effects on the REI-Mullite. These conclusions were confirmed by NASA tests.(2)

SALT SPRAY & HUMIDITY TEST RESULTS



SPECIMEN NO.	WEIGHT (GRAMS)		
	AS FABRICATED	AFTER SALT SPRAY	AFTER HUMIDITY
-1	595	595.5	595.5
-2	577	590	589
-3	600	601	601

	COATING FAILURE STRAIN (%)				
	AFTER SALT AND HUMIDITY	AFTER SALT, HUMIDITY AND GRADIENT	AFTER 18 HOUR GRADIENT	AS FABRICATED	PRIOR DATA
ϵ	0.016	0.067	0.030	0.015	0.026
RANGE	0.012 0.022	0.058 0.082	0.012 0.052	0.014 0.015	0.013 0.034
N	3	3	3	2	25



SEM AFTER SALT SPRAY, HUMIDITY AND 18 HOUR GRADIENT TEST

Figure 6

FREEZE/THAW TESTING

(Figure 7)

The results of the vacuum vent test program showed that moisture can be retained in the REI-Mullite tile after the boost cycle. Hence, two specimens, a coated specimen and an uncoated REI-Mullite specimen were impregnated with 30 and 43 percent H_2O by weight and subjected to a freeze thaw cycle. The specimens were cooled with LN_2 to 166° K (-160° F) and held for a period of four hours. The specimens were then warmed to room temperature. No degradation of the coating or REI-Mullite was observed.

FREEZE/THAW TEST RESULTS

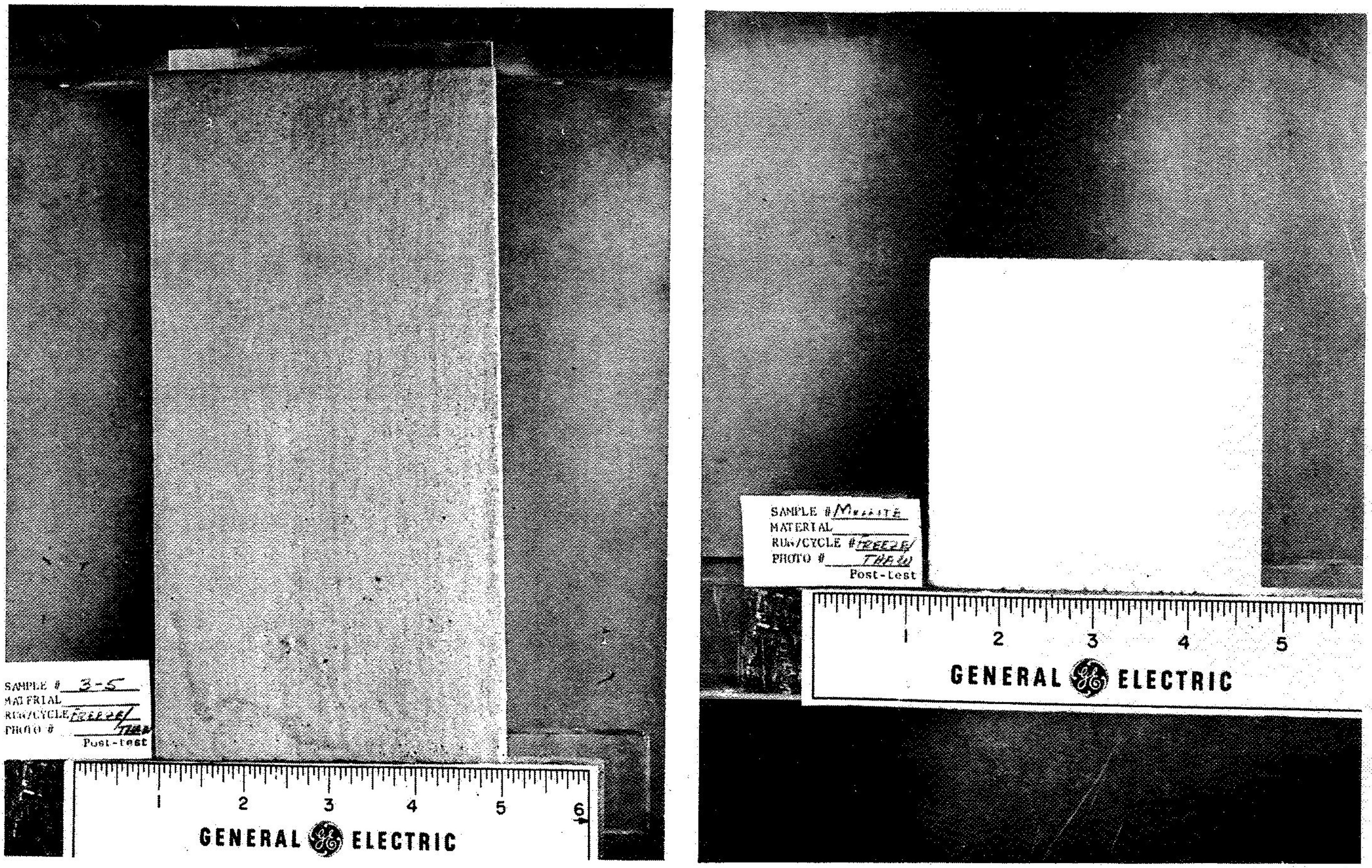


Figure 7

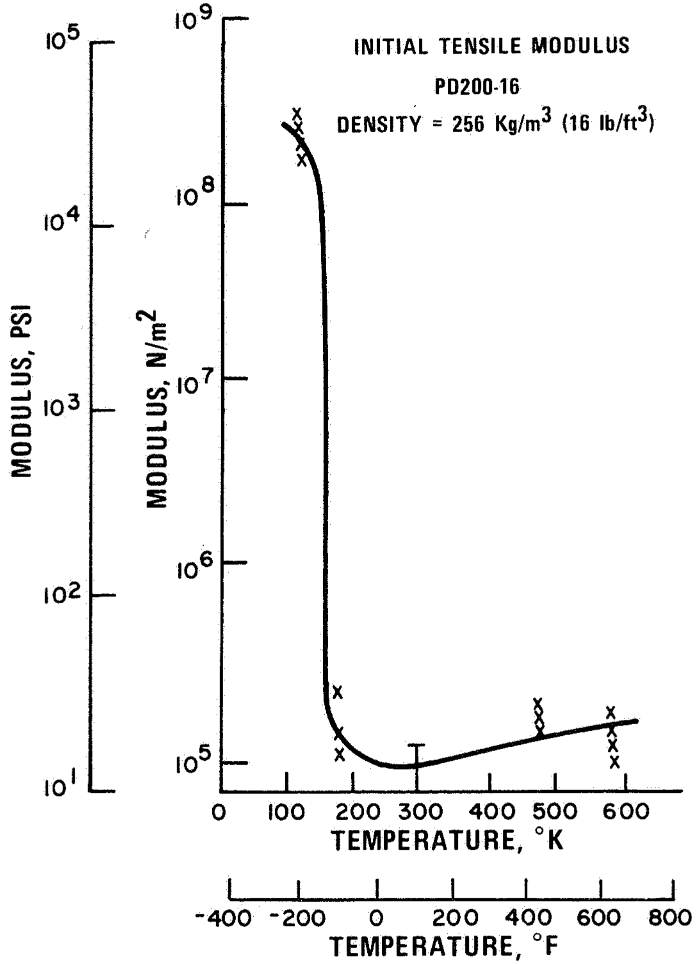
COLD SOAK TESTS

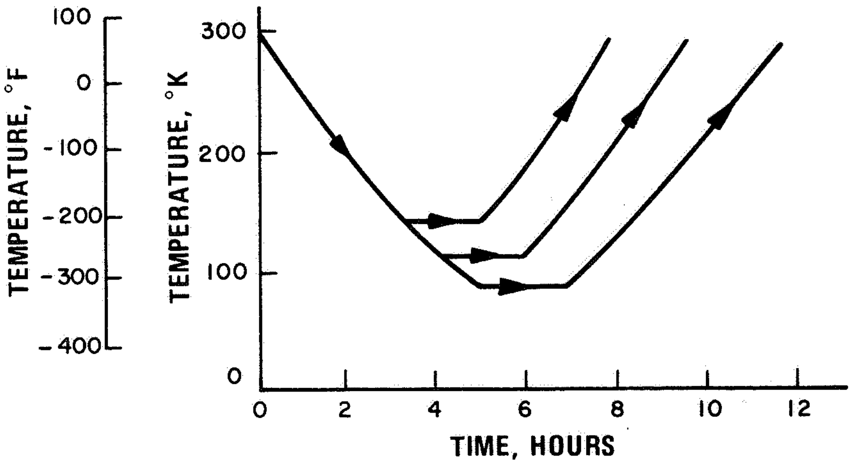
(Figure 8)

The orbital phase of the mission results in a cold environment of 116° K (-250° F). This temperature is significantly below the glass transition temperature of the PD200 strain isolator system. High tensile and shear stress are developed at the REI-Mullite/PD200 and PD200/Aluminum interface as the temperature is lowered below glass transition. Cold soak tests on representative REI-Mullite/PD200/structure composites were conducted. The tests consisted of a controlled cool-down to the desired temperature, a hold at temperature, and a controlled warm-up to room conditions. Tests were conducted to temperatures as low as 89° K (-300° F) to empirically demonstrate a 50% margin of safety on the ΔT below the glass transition temperature.

Results showed that PD 200-28, 448 kg/m^3 (28 lb/ft^3) density material, could not provide a satisfactory margin for the 116° K (-250° F) environment. Subsequent tests showed that PD200-16, 256 kg/m^3 (16 lb/ft^3) was completely compatible for the cold soak condition.

COLD SOAK TESTS





TEST TEMP °K (°F)	PD200-28		PD200-16	
	THICKNESS m (IN)	RESULTS	THICKNESS m (IN)	RESULTS
144 (-200)	7.6 x 10^{-3} (0.3)	NO FAILURES	6.3 x 10^{-3} (0.25)	NO FAILURES
116 (-250)	7.6 x 10^{-3} (0.3)	NO FAILURE	6.3 x 10^{-3} (0.25)	NO FAILURES
89 (-300)	7.6 x 10^{-3} (0.3)	REI-MULLITE COATING CRACKED	6.3 x 10^{-3} (0.25)	NO FAILURES

Figure 8

RAIN EROSION TESTING

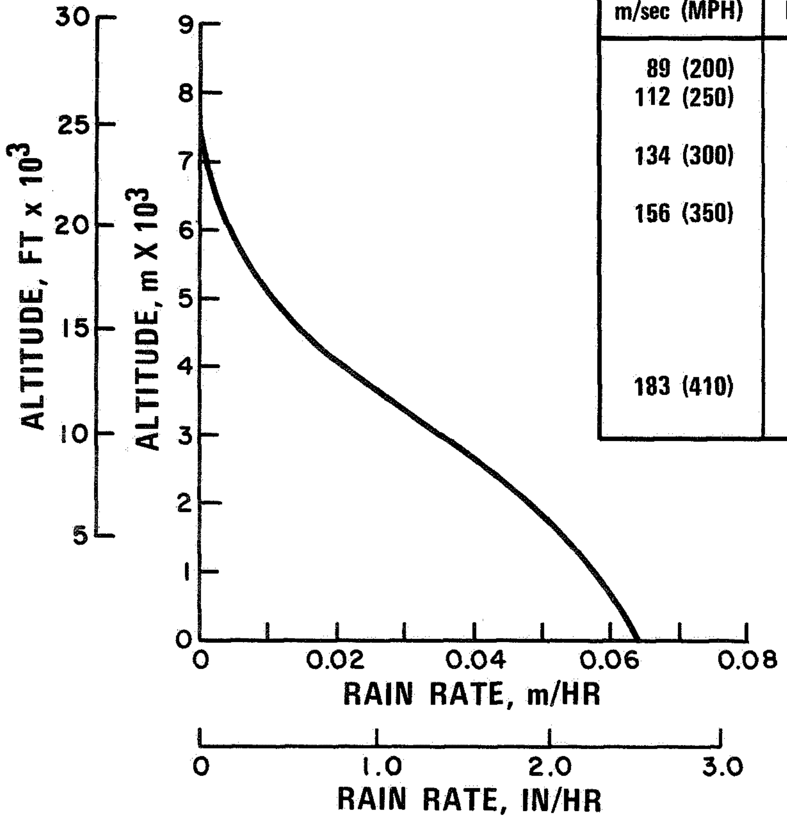
(Figure 9)

Rain erosion tests(3)(4) were performed in the AFML-Bell rotating arm rain and sand erosion test apparatus on REI-Mullite coated with SR-2. Tests were conducted at 0.175, 0.35, and 0.7 rad (10, 20, and 40 degree) incidence angles and velocities ranging from 89 m/sec (200 mph) to 183 m/sec (410 mph). Rain rates were limited to a maximum of 0.025 m/hr (1 in/hr), which is representative of subsonic cruise above 3,500 m (11,500 ft). Test data showed no erosion of the SR-2 coating. Impact damage to the coating was observed and found to be time dependent. After initial impact damage, coating removal was evident. In evaluating this failure mode it was determined that rain rates were constant at 0.025 m/hr (1 in/hr). Lower rain rates were achieved by intermittently subjecting the specimens to the 0.025 m/hr (1 in/hr) rate. These conditions result in constant droplet mass, frequency and distribution with exposure time the only variable.

Two possible reasons exist for the time dependent failure mode. The first is the statistical probability of a droplet impacting a weak spot in the coating. The second is the possibility of cumulative damage to the coating by multiple impacts. Improvements to the damage threshold of the SR-2 coating are readily achievable by increased coating thickness and more uniform application.

RAIN EROSION TESTING

SUMMARY OF RAIN DAMAGE THRESHOLD			
VELOCITY m/sec (MPH)	INCIDENCE ANGLE RAD (DEG)	RAIN RATE m/hr (in/hr)	DAMAGE THRESHOLD
89 (200)	0.35 (20)	0.025 (1)	NO DAMAGE AFTER 60 MINUTES
112 (250)	0.175 (10)	0.025 (1)	NO DAMAGE AFTER 30 MINUTES
	0.35 (20)	0.025 (1)	DAMAGE STARTS AFTER 20 MINUTES
134 (300)	0.175 (10)	0.025 (1)	NO DAMAGE AFTER 20 MINUTES
	0.35 (20)	0.025 (1)	NO DAMAGE AFTER 10 MINUTES
156 (350)	0.175 (10)	0.012 (.5)	DAMAGE STARTS AFTER 18.5 MINUTES
		0.025 (1)	DAMAGE STARTS AFTER 5 MINUTES
	0.35 (20)	0.006 (.25)	DAMAGE STARTS AFTER 3 MINUTES
		0.012 (.5)	DAMAGE STARTS AFTER 1.7 MINUTES
		0.025 (1)	DAMAGE STARTS AFTER 1.3 MINUTES
	0.70 (40)	0.006 (.25)	DAMAGE STARTS AFTER .25 MINUTES
183 (410)	0.175 (10)	0.025 (1)	NO DAMAGE AFTER 5 MINUTES
	0.35 (20)	0.006 (.25)	DAMAGE STARTS AFTER 2 MINUTES



RAINFALL RATE FOR
0.0635 m/hr (2.5 in/hr) THUNDERSTORM
REF.: TMX53872 & 64589

Figure 9

STRUCTURES TEST PROGRAM

(Figure 10)

A Structural Test Program (STP) was performed by GE-RESD for NR/SD. Under this program, a series of mission environmental simulation tests was performed to establish multimission capability of REI-Mullite. Testing was performed on specimens that realistically simulated panels of the TPS for both hot windward, maximum surface temperature of 1644° K (2500° F), and cool windward, maximum surface temperature of 978° K (1300° F). Mission simulations included twenty-five cycles of boost acoustics and one-hundred cycles of re-entry heat simulation with interspersed orbital-cold and orbital-hot vacuum soaks and structural loadings. In order to demonstrate the multimission capability, the following test objectives were established:

- Determination of ultimate load capability on representative primary airframe structure
- Determination of effects of acoustics, orbital soak, and re-entry cycling on failure mode and load
- Evaluation of coating, attachment, and REI overall performance after simulated environmental cycling

Four phases of tests on the hot windward specimens to determine one, 10, 25, and 100 mission cycle performance and two phases of tests on the cool windward specimens to determine one and 25 mission cycle performance were conducted.

STRUCTURAL TEST PROGRAM (STP) TEST FLOW

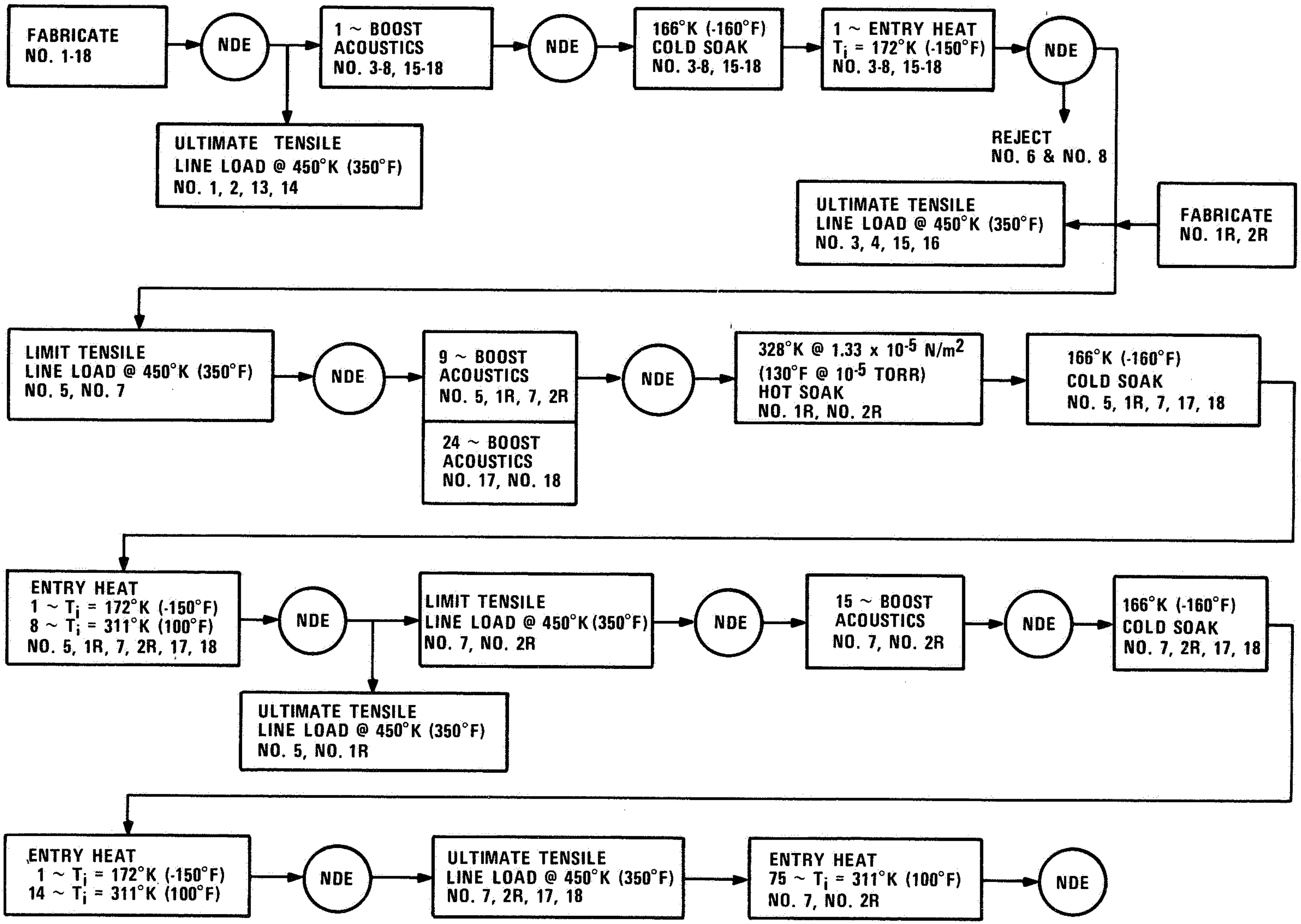


Figure 10

STP TEST MATRIX AND SPECIMEN CONFIGURATION
(Figure 11)

The specimens tested represented the baseline REI-Mullite system proposed for the Phase C/D Space Shuttle Orbiter and considered two vehicle configurations:

- Hot windward conditions for an all-bonded system
- Cold windward conditions for an all-bonded system

The materials utilized were the REI-Mullite coated on five sides with PD-200-28 foam pads for attachment to the aluminum substrates. Mission simulation tests were performed in a sequential fashion to evaluate the thermal-structural capability of the REI-Mullite TPS to the critical design environments.

The aluminum structures were designed and provided by NR/SD. The REI-Mullite and foam pad thicknesses were sized for heating environments and test conditions established to subject the hot windward specimen to 1644° K (2500° F) surface temperature and the cold windward specimen to 978° K (1300° F) surface temperature without exceeding an aluminum substrate temperature of 450° K (350° F).

The designs were configured to simulate the thermal, structural, and dynamic response characteristics of an aluminum primary airframe structure protected by REI-Mullite. The configurations were:

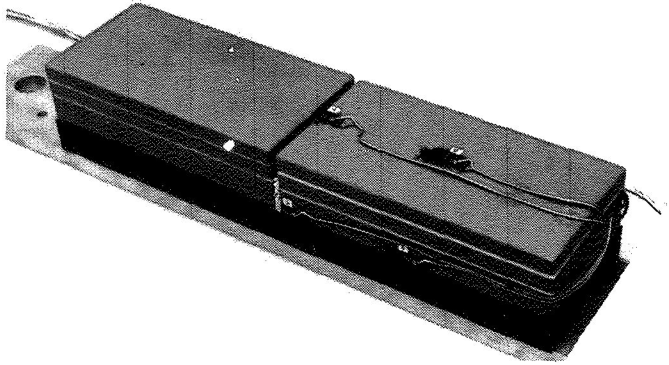
- Hot windward area simulation consisting of 0.048 m (1.9 inch) thick REI-Mullite bonded with 0.028 m (1.1 inch) thick PD-200 foam pads.
- Cold windward area simulation consisting of 0.043 m (1.7 inch) thick REI-Mullite bonded with 0.008 m (0.3 inch) thick PD-200 foam pads.

The specimens incorporated all the features of the proposed flight design except the final design solution for the tile sidewall coating. Analyses predicted that fully coated tile sidewalls would develop cracks normal to the vehicle outer moldline from the re-entry heating gradient. At the time of this test program, a design configuration was not sufficiently developed to prevent this problem and specimens were tested with uncoated grooves in the sidewall that provided some degree of stress relief. This problem is under intensive investigation. Sidewall designs utilizing coated grooves configured to provide increased flexibility have been successfully tested.

STP TEST MATRIX AND SPECIMEN CONFIGURATION

DESIGN CONFIGURATION	SPECIMEN NUMBER	ACOUSTIC CYCLES	ENTRY HEAT CYCLES	COLD SOAK CYCLES	HOT SOAK CYCLES	LIMIT LOAD CYCLES	ULTIMATE LOAD CYCLE
HOT WINDWARD	1	–	–	–	–	–	1
ALL BONDED	2	–	–	–	–	–	1
0.048 m REI/0.028 m PD200	3	1	1	1	–	–	1
(1.9 IN. REI/1.1 IN. PD200)	4	1	1	1	–	–	1
	5	10	10	2	–	1	1
	6 (1R)*	1 (9)	1 (9)	1 (1)	1	–	(1)
	7	25	100	3	–	2	1
	8 (2R)*	1 (24)	1 (98)	1 (2)	1	(1)	(1)
COLD WINDWARD	13	–	–	–	–	–	1
ALL BONDED	14	–	–	–	–	–	1
0.043 m REI/0.008 m PD200	15	1	1	1	–	–	1
(1.7 IN. REI/0.3 IN. PD200)	16	1	1	1	–	–	1
	17	25	25	3	–	–	1
	18	25	25	3	–	–	1

*SPECIMENS NO. 6 & NO. 8 REPLACED AFTER 1st ENTRY HEAT CYCLE



STP TEST SPECIMEN

Figure 11

ACOUSTIC TESTING

(Figure 12)

Acoustic tests were performed on the STP program to assess the TPS design when subjected to the dynamic environment associated with the lift-off and boost acoustics. The tests were performed in the progressive wave acoustic facility of Wyle Laboratories, Huntsville, Alabama. The tests were performed in three phases to comply with the STP Test Flow. Each test cycle was 2 minutes in duration, the equivalent of one boost cycle, at a sound pressure level (SPL) of 163 dB. The test specimens were mounted so that the flow was parallel with the panel length. Radius blocks were used at the mounting points to give simple support conditions. Test instrumentation included four microphones to monitor the acoustic environment as well as accelerometers mounted to the backface of the substrate at the midspan to record structural response. Prior to mounting the specimens in the test chamber, the acoustic spectrum was shaped, resulting in an overall SPL of 161.5 dB. During actual test runs, processed microphone data revealed overall SPL's of as high as 164 dB.

The hot windward specimens were tested in three phases to accumulate 25 simulated mission cycles. The first phase subjected specimens not having been exposed to prior cyclic environments to the equivalent of one boost acoustic cycle. The second phase subjected specimens that had been exposed before testing to one-entry heat and one-limit tensile load cycle to an accumulation of 10 boost acoustic cycles. The third phase subjected specimens that had prior exposure to 10-entry heat and two limit load cycles to an accumulation of 25 boost acoustic cycles. Similarly, cold windward specimens were subjected to one boost acoustic cycle without prior environmental cycles and to an accumulation of 25 boost acoustic cycles after prior exposure to 10 entry heat and two limit load cycles.

ACOUSTIC TESTING

MODEL CONFIGURATION	MODEL NO.	NO. OF 2-MINUTE CYCLES		
		1st PHASE	2nd PHASE	3rd PHASE
HOT WINDWARD	3	1		
	4	1		
	5	1	9	
	6 (1R)	1	(10)	
	7	1	9	15
	8 (2R)	1	(10)	(15)
COLD WINDWARD	15	1		
	16	1		
	17	1		24
	18	1		24

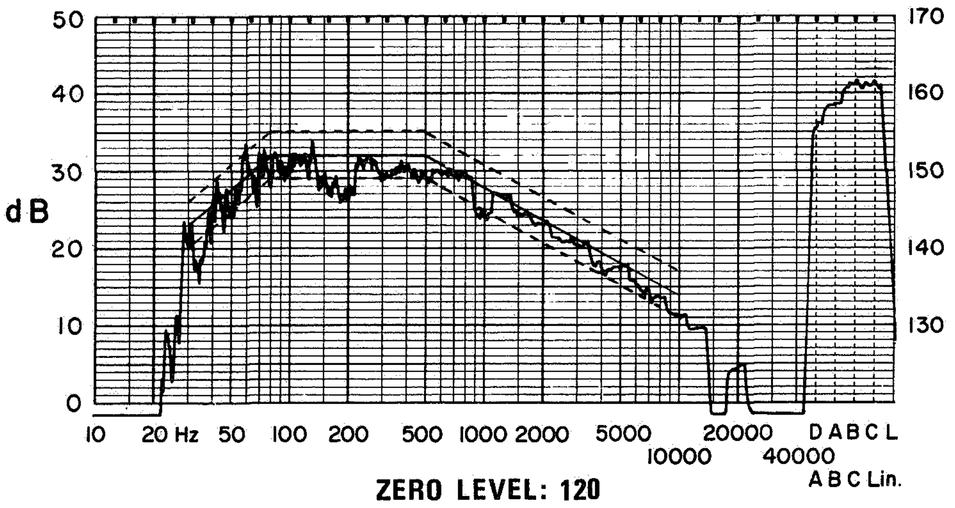


Figure 12

ACOUSTIC TEST PSD ACCELERATION
(Figure 13)

Substructure accelerometer data for the hot windward specimens showed the performance of the REI-Mullite system to be predictable. The initial response peak between 150 and 200 Hz is associated with a series of modes where the REI-Mullite is "bouncing" on the PD-200 with some substrate bending motion. The second response peak between 300 and 400 Hz is associated with a mode where the REI-Mullite and substrate are moving in opposite directions. The power spectral density (PSD) plots for the acoustic test sequence are all very similar and show that:

- There is no structural deterioration of the REI-Mullite system from long term exposure to the boost acoustic environment.

- There is no structural deterioration of the REI-Mullite system from prior entry heat and limit load applications.

The PSD plots were evaluated to determine 'g' rms levels. These ranged from a low of 10 to a high of 28, the range being attributable to differences in input acoustic spectrum for each acoustic cycle and location of specimen within the facility. This corresponds to a peak acceleration response of 84 g's.

The data from the cold windward specimens showed a slightly different spectrum shape, resulting primarily from the decreased thickness of PD-200. The 'g' rms values ranged from 8 to 26. On one specimen during test the 'g' rms value increased from 26 during the initial cycles to 42 on the twenty-fifth cycle.

Non-destructive evaluation (NDE) was performed after each test phase. The acoustic testing caused minor side coating cracks on two specimens, which are attributable to the uncoated grooves. The specimen whose response increased to 42 g rms showed partial delamination of the PD-200 foam pad from the aluminum structure after 25 accumulated cycles. This failure was diagnosed as an adhesive failure resulting from inadequate loading during bonding.

ACOUSTIC TEST PSD ACCELERATION

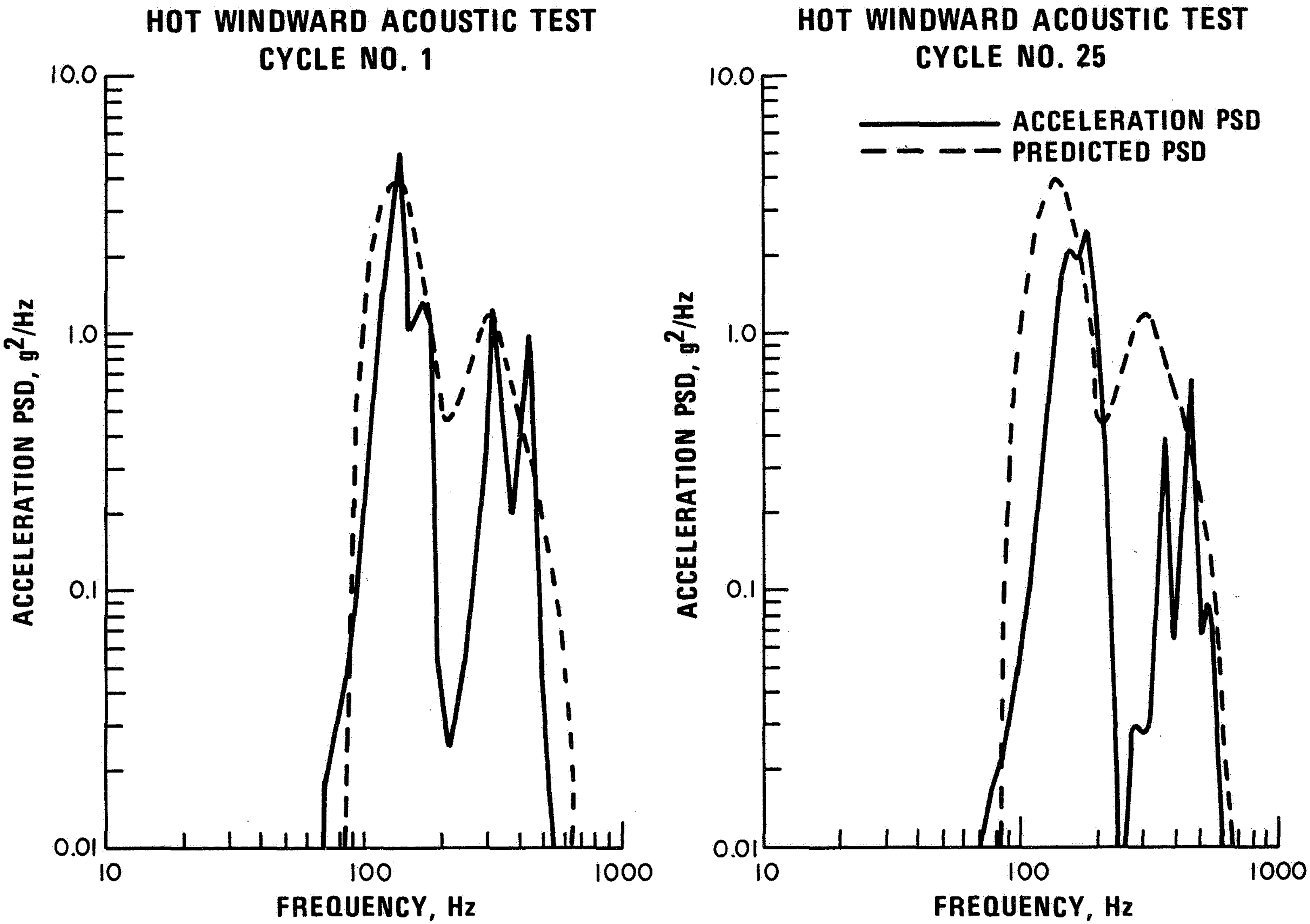


Figure 13

RE-ENTRY HEAT SIMULATION

(Figure 14)

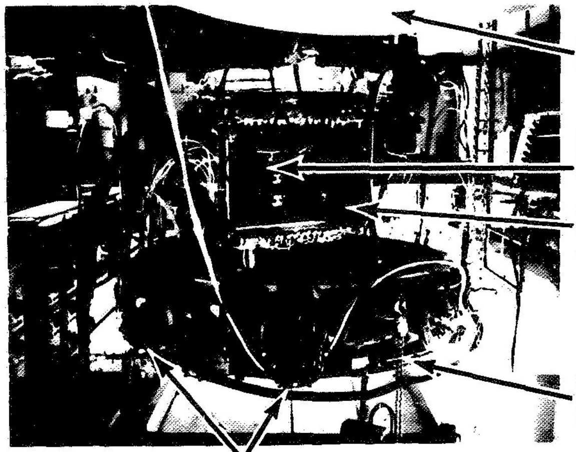
Re-entry heating simulation was performed in the 3 meter (10 foot) diameter vacuum chamber at the GE-RESD facility. The chamber is capable of being evacuated to pressures as low as 0.13×10^{-3} N/m^2 (10^{-6} torr). The radiant heater array is comprised of heater elements of silicon carbide resistance rods enshrouded by quartz tubes to eliminate the possibility of contamination. The heating elements are energized through a power controller. Feedback signals from the thermocouples on the test specimens or on control strips in the heater cavity control the power program. The heater elements are powered in banks of six so that each bank can be separately powered and controlled. This feature allowed the hot windward and the cold windward simulations to be conducted simultaneously.

A number of test specimens were instrumented with platinum-platinum rhodium surface thermocouples located at the center of each 0.1 × 0.2 m (4 × 8 inch) REI-Mullite tile. These specimens were used for controlling the heat input by using the surface thermocouple output in the controller feedback loop. These specimens were further instrumented with chromel-alumel thermocouples at the REI-Mullite mid-depth, REI-Mullite/PD-200 interface, PD200 mid-depth, and PD-200/aluminum interface to monitor in-depth temperature responses.

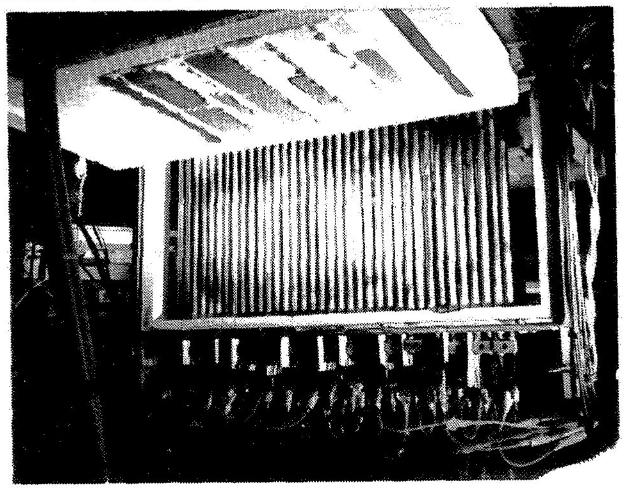
At discrete intervals in the test flow, specimens were subjected to the hot and cold conditions to be encountered during an orbital stay period. Test panels were subjected to 166° K (-160° F) prior to the start of the first, second, and eleventh re-entry heat cycles. The entry heating test was started with the panels at 194° K (-110° F).

For hot soak testing, two specimens were heated to 328° K (+130° F) at 1.3×10^{-3} N/m^2 (10^{-5} torr) for eight hours prior to the second entry heat cycle. The test panels were mounted back to back and wrapped in a rubber resistance heating blanket. This unit was then mounted in the vacuum chamber.

RE-ENTRY HEAT SIMULATION



RE-ENTRY SIMULATOR VACUUM TANK



TEST SETUP SHOWING GLO-BARS AND TEST SPECIMENS

ENTRY HEAT CYCLE MATRIX

SPECIMEN NUMBER		ENTRY CYCLE									
		1*	2*	3 – 10			11 – 25*			26 – 100	
HOT WINDWARD	3	X										
	4	X										
	5	X	X	X	X	X						
	6	X										
	1R			X	X	X						
	7	X	X	X	X	X	X	X	X	X	X	X
	8	X										
	2R			X	X	X	X	X	X	X	X	X
COLD WINDWARD	15	X										
	16	X										
	17	X	X	X	X	X	X	X	X			
	18	X	X	X	X	X	X	X	X			

*172°K(-150°F) INITIAL CONDITION

Figure 14

HOT WINDWARD ENTRY HEATING RESULTS

(Figure 15)

Hot windward specimens were tested through 100 entry simulation cycles at surface temperatures between 1590° K (2400° F) and 1644° K (2500° F). Temperature control problems were encountered on the first cycle resulting in a severe overtest requiring the replacement of two of the specimens. Modifications to the control system were made through cycle nine, after which power conditions were held constant. Upper and lower bounds of the thermocouple data show the stability and repeatibility of REI-Mullite as a TPS for multicycle usage. The data spread from cycle to cycle; 60° K (110° F) for the REI-Mullite/PD-200 interface and 33° K (60° F) for the PD-200/aluminum interface is attributable to the variations in actual surface temperature achieved and the initial temperature of the specimens at the beginning of each cycle. In no case were the design limits of 616° K (650° F) for the PD-200 and 450° K (350° F) for the aluminum substrate exceeded.

NDE during the test program showed minor cracking of the sidewall coating occurred. After cycle 57, both tiles of one specimen developed surface cracks and then buckled, resulting in subsequent failure of the coating. On cycle 91, one of the two tiles on the second specimen developed surface cracks and buckled. The remaining tile was structurally sound throughout the 100 cycles.

HOT WINDWARD ENTRY HEATING RESULTS

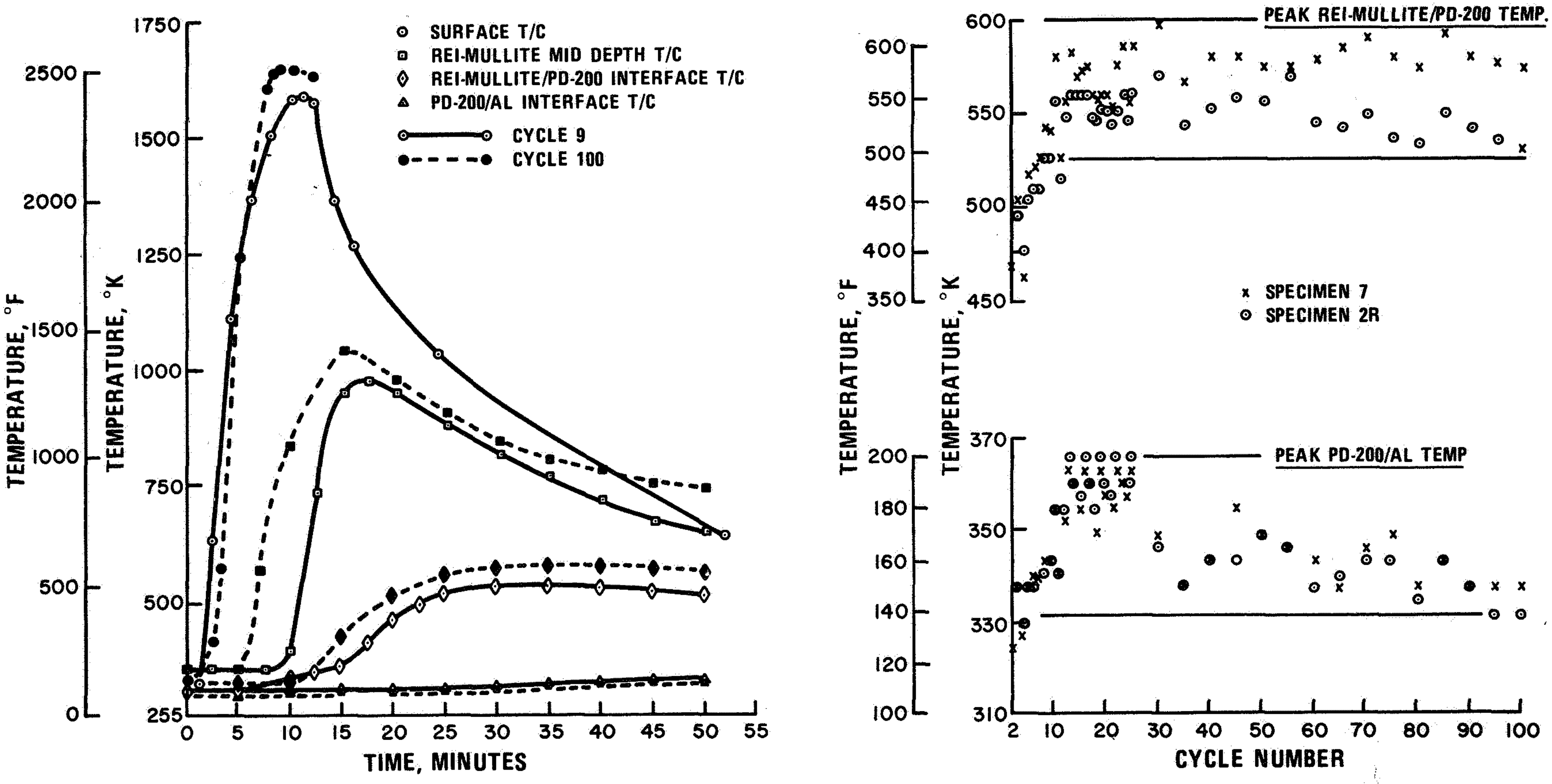


Figure 15

COLD WINDWARD ENTRY HEATING RESULTS

(Figure 16)

Cold windward specimens were tested through twenty-five entry simulation cycles at surface temperatures of 922° K (1200° F) and 978° K (1300° F). Modifications were made in the control cycle to raise the surface temperature to 978° K (1300° F) after cycle 7. Upper and lower bounds of the thermocouple data again show no change in performance of the REI-Mullite with re-entry heat cycling and that the design limits were not exceeded.

NDE during the test cycles again showed minor cracking of the sidewall coating.

Hot vacuum soaking to 328° K (130° F) at 1.3×10^{-3} N/m^2 (10^{-5} torr) and cold soaking to 166° K (-160° F) followed by entry heat from cold initial conditions of 194° K (-110° F) showed no structural changes in performance.

Coatings, except immediately adjacent to cracks, retained their waterproof characteristics throughout the one-hundred mission simulation.

COLD WINDWARD ENTRY HEATING RESULTS

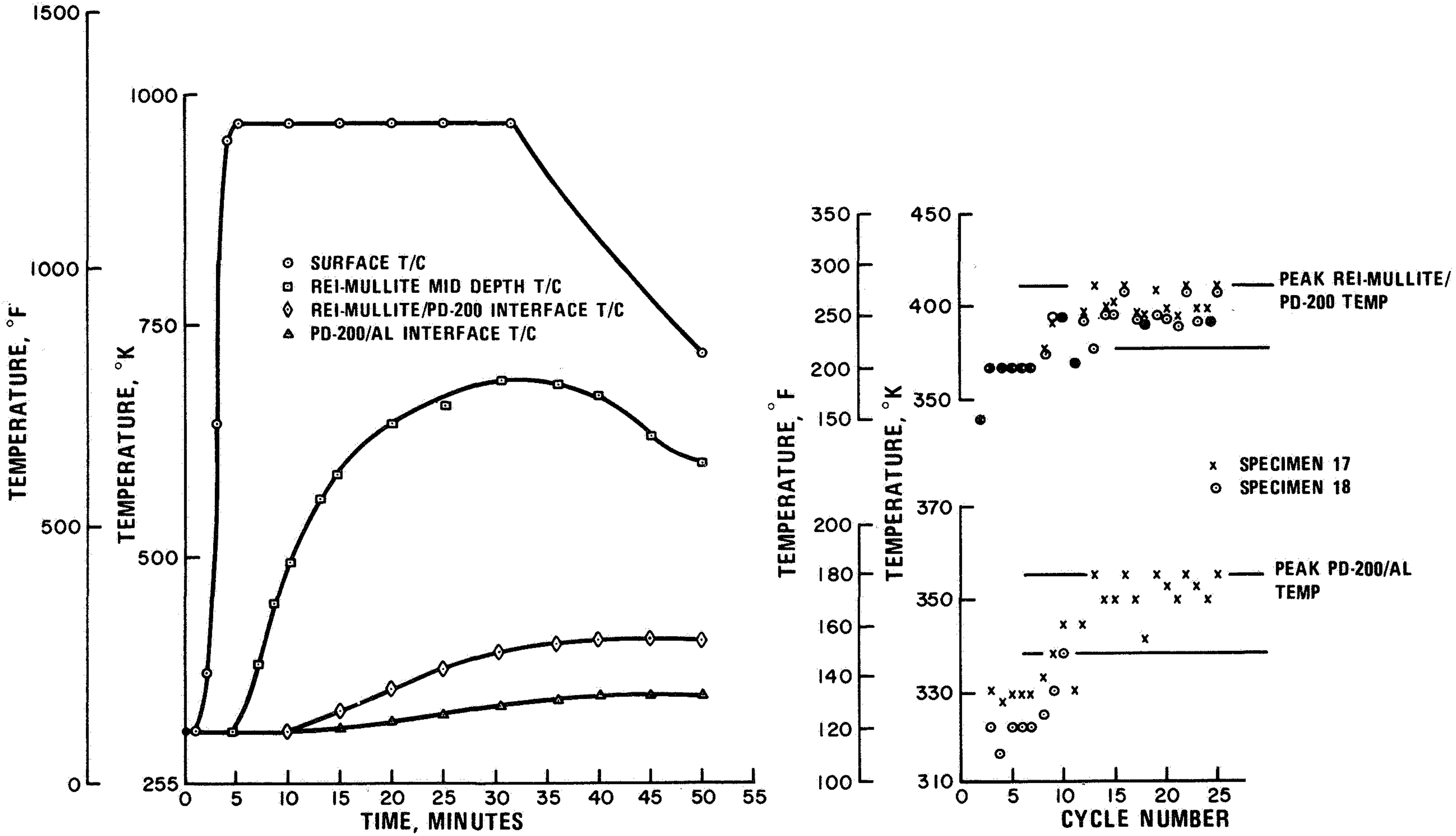


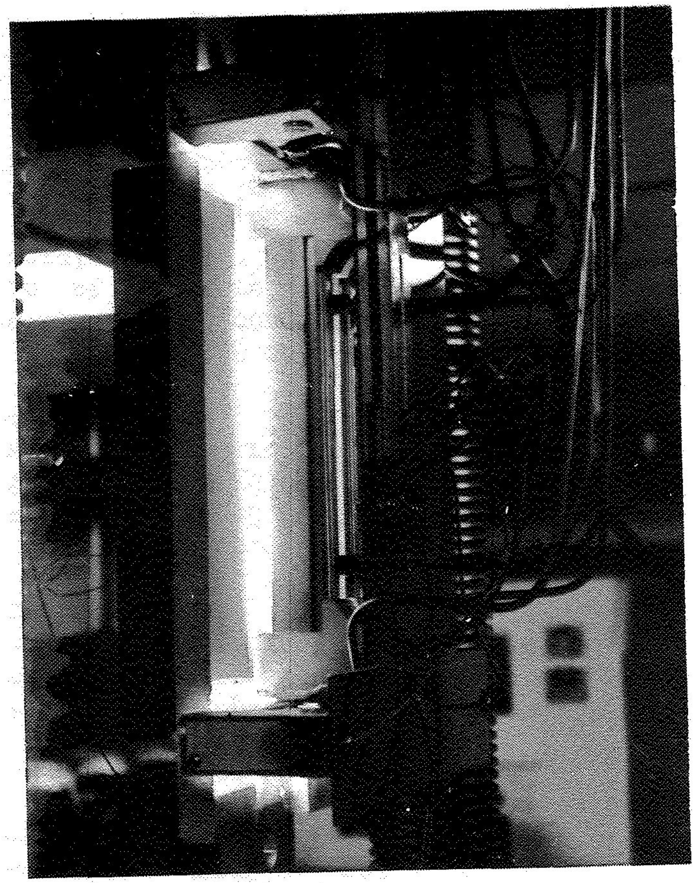
Figure 16

TENSILE LOAD TESTING

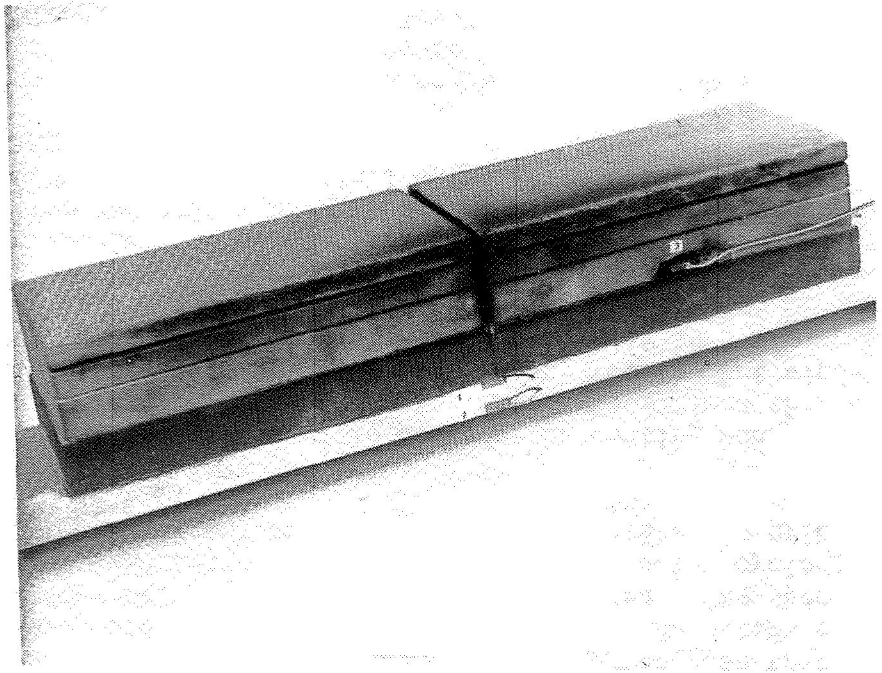
(Figure 17)

Tensile load tests were conducted to determine the ultimate load capability of the TPS for line loads at 450° K (350° F) after prior flight exposures to acoustics, entry heat, orbital conditions, and limit load conditions. This was found to be the worst case condition by prior analyses. The ultimate load was defined as the lowest of: (1) the load to delaminate coating or insulation; (2) load to produce normal cracks in coating or insulation; or (3) load that produces ultimate stress levels in the structure. The aluminum substrates were fabricated from 2024 T351 plate and had a calculated load capability of 199, 270 N (44,800 lb) at 450° K (350° F). Limit loads applied as part of the flight simulation cycles were two-thirds the ultimate load or 132,995 N (29,900 lb). Instrumentation consisted of chromel-alumel thermocouples to monitor the structure bondline temperature during test and strain gages on the coated tile and structure to determine the effectiveness of the PD-200 pad as a strain isolator.

TENSILE LOAD TESTING



VIEW OF SPECIMEN BACKFACE WITH QUARTZ HEATING LAMPS IN OPERATION



TYPICAL STRAIN GAGE INSTALLATION

Figure 17

TENSILE LOAD TEST RESULTS
(Figure 18)

A summary of the loading data is shown on the figure. For the hot windward specimens, it was found that the ratio of strain developed in the coating to the strain applied to the structure ranged between 0.00311 and 0.00783 with an average value of 0.0053. Maximum coating strain measured at ultimate load conditions was 43×10^{-6} m/m (in./in.) clearly demonstrating the effectiveness of the PD-200 as a strain isolator.

NDE showed no damage initiated in any specimens due to the limit load cycles. In one case there was propagation of a side coating crack that had developed in prior thermal cycles. During ultimate load tests propagation of a sidewall coating crack from previous thermal cycles was noted. One specimen did develop sidewall coating cracks when ultimate load tested after 25 mission simulation cycles; however, these cracks were located away from peak stress regions and were probably initiated in prior cycles.

For the cold windward specimens, it was found that the strain ratio between the coating and structure ranged between 0.0105 and 0.0270 with an average of 0.019 or approximately four times that of the hot windward specimens. This is consistent with the reduction in pad thickness from the hot windward specimens to the cold windward specimens. Maximum measured coating strain was 164×10^{-6} m/m (in./in.).

NDE of the cold windward specimens showed one specimen to develop cracks in the side coating under ultimate load conditions. The strain gage output for the cold windward specimens showed erratic behavior at structure strain levels of approximately 4000×10^{-6} m/m (in./in.) which corresponds to approximately 80×10^{-6} m/m (in./in.) strain in the coating.

The tensile load test results showed (1) the limit and ultimate load capability of REI-Mullite bonded with PD-200 foam pads for tensile line loading is limited by substrate stress levels; (2) PD-200 foam pads effectively isolate REI from structural loads, reducing strain levels in the coating to less than two percent of the applied strain to the structure; and (3) prior exposure to up to 25 mission cycles of acoustics and re-entry gradients does not result in degradation of load capability of the TPS.

TENSILE LOAD TEST RESULTS

	SPECIMEN NO.	PRIOR CYCLES	TENSILE LOAD NEWTONS (POUNDS)	AVERAGE MEASURED STRUCTURE STRAIN (10^{-6} m/m (IN/IN))	MEASURED COATING STRAIN (10^{-6}m/m (IN/IN))	$\frac{\epsilon \text{ COATING}}{\epsilon \text{ ALUMINUM}}$
HOT WINDWARD	1	AS FABRICATED	197,936 (44,500)	7,000	30	0.00569
	2	AS FABRICATED	186,816 (42,000)	7,700	29	0.00603
	3	1 ACOUSTIC 1 ENTRY	195,712 (44,000)	7,000	OUT	0.0045
	4	1 ACOUSTIC 1 ENTRY	200,160 (45,000)	7,200	--	--
	5	10 ACOUSTIC 10 ENTRY 1 LIMIT	195,712 (44,000)	7,500	23	0.00465
	1R	9 ACOUSTIC 8 ENTRY	191,264 (43,000)	7,000	43	0.00783
	7	25 ACOUSTIC 25 ENTRY 2 LIMIT	200,160 (45,000)	7,000	18	0.00311
	2R	24 ACOUSTIC 23 ENTRY 1 LIMIT	191,264 (43,000)	6,900	--	--
COLD WINDWARD	13	AS FABRICATED	197,936 (44,500)	7,300	105	0.0198
	14	AS FABRICATED	191,264 (43,000)	5,400	66	0.0105
	15	1 ACOUSTIC 1 ENTRY	182,368 (41,000)	4,800	89	0.0202
	16	1 ACOUSTIC 1 ENTRY	195,712 (44,000)	7,600	46	0.0115
	17	25 ACOUSTIC 25 ENTRY	193,488 (43,500)	7,400	129	0.0248
	18	25 ACOUSTIC 25 ENTRY	186,816 (42,000)	6,300	164	0.0270

$\frac{\epsilon \text{ COATING}}{\epsilon \text{ ALUMINUM}}$ = 0.0053 AVG.

$\frac{\epsilon \text{ COATING}}{\epsilon \text{ ALUMINUM}}$ = 0.019 AVG.

Figure 18

NDE SUMMARY — STRUCTURES TEST PROGRAM

(Figure 19)

Non-destructive evaluation (NDE) was used to obtain characterization information on the quality of the REI-Mullite, coating, and foam pads, and to assess any damage or degradation that may have occurred after environmental exposure. The following techniques were employed during the program: X-Ray for cracking and attachment; microwave for moisture content; infrared for waterproofness; and visual examination. The following summary points are made with respect to the NDE performed:

- Coating Evaluation
  1. Specimens tested to 1644° K (2500° F) show surface color changes from tan to light blue.
  2. Surface coating cracks were found to occur after 57 entry heat cycles on two tiles and 91 cycles on one tile. One tile had no surface cracks after 100 cycles.
  3. Coating is waterproof except at pinhole and crack locations.
  4. Side coating cracks were observed after exposure to acoustic, entry heat, and tensile loading. Majority of side coating cracks resulted from entry heat tests.

- REI-Mullite Evaluation
  1. No degradation of the REI-Mullite was observed.

- PD-200 Evaluation
  1. No degradation of PD-200 was observed except as a result of the overtest condition experienced on entry heating cycle No. 1.
  2. Only one specimen showed delamination of PD-200/aluminum bond.

NDE SUMMARY – STRUCTURES TEST PROGRAM

DESIGN CONFIGURATION	SPECIMEN NO.	AS FABRICATED CONDITION	AFTER 1 ACOUSTIC CYCLE	AFTER 1st ENTRY HEAT CYCLE	AFTER LIMIT LOAD	AFTER ACOUSTIC CYCLE NO. 10	AFTER ENTRY HEAT CYCLE NO. 10	AFTER LIMIT LOAD	AFTER ACOUSTIC CYCLE NO. 25	AFTER ENTRY HEAT CYCLE NO. 25	AFTER ULTIMATE LOAD	AFTER ENTRY HEAT CYCLE NO. 100
HOT WINDWARD	1	COATING CHIP				(N/A)					N/C	
	2	N/D						(N/A)			N/C	
	3	PINHOLES	N/C	COATING CHIP SIDE COATING CRACKS				(N/A)			N/C	
	4	COATING CHIP	COATING CHIP	SIDE COATING CRACKS				(N/A)			N/C	
	5	PINHOLES	SIDE COATING CRACK	SIDE COATING CRACKS	N/C	SIDE COATING CRACK PROPAGATED	N/C		(N/A)		SIDE COATING CRACK PROPAGATED	
	6	N/D	COATING CHIP	CHARRED PD200 (REJECTED)								
	1R	COATING CHIP				N/C	SIDE COATING CRACK		(N/A)		N/C	
	7	N/D	N/C	N/C	N/C	SIDE COATING CRACK COATING CHIP	N/C	N/C	N/C	PINHOLES	SIDE COATING CRACK	SURFACE CRACK (CYCLE 91)
	8	SIDE COATING CRACK	N/C	CHARRED PD200 (REJECTED)								
	2R	N/D				N/C	SIDE COATING CRACK	SIDE COATING CRACK PROPAGATED	N/C	SIDE COATING CRACKS COATING CHIP	N/C	SURFACE CRACK (CYCLE 57)
COLD WINDWARD	13	PINHOLES					(N/A)				N/C	
	14	PINHOLES					(N/A)				SIDE COATING CRACKS	
	15	PINHOLES	N/C	SIDE COATING CRACK			(N/A)				N/C	
	16	N/D	N/C	SIDE COATING CRACK			(N/A)				N/C	
	17	PINHOLES	N/C	N/C			(N/A)		SIDE COATING CRACK	SIDE COATING CRACK	N/C	
	18	PINHOLES	SIDE COATING CRACK	SIDE COATING CRACK			(N/A)		BOND DELAMINATION	SIDE COATING CRACK	N/C	

N/D – NO DEFECTS NOTED
N/C – NO CHANGE NOTED
N/A – NOT APPLICABLE

Figure 19

SUMMARY

(Figure 20)

A major element of GE's development of the Reusable External Insulation, REI-Mullite, for the Space Shuttle Orbiter is testing in simulated natural and induced environments. The test programs reported here, although a small part of the total number of tests performed, clearly demonstrate that REI-Mullite is capable of meeting all requirements for the orbiter TPS.

Tests conducted to evaluate the system's performance in the natural environments of salt spray, humidity, rain, vacuum, and cryogenic temperatures have shown the REI-Mullite to be completely compatible and that these environments have no adverse effects on subsequent mission performance. Rain erosion testing has indicated a damage threshold that must be accounted for in the final design.

Tests conducted to evaluate the performance of the REI-Mullite to the induced acoustic, re-entry, and structural load environments again have shown complete capability to fulfill mission environments. Although minor cracking of the sidewall coating was seen to occur throughout the induced environment test program, sidewall designs configured to provide increased flexibility have been successfully tested.

Additional materials development for both the REI-Mullite insulation and the SR-2 coating is continuing with testing similar to that discussed being used to evaluate the improvements.

SUMMARY

REI MULLITE CAPABILITY DEMONSTRATED FOR ALL TPS REQUIREMENTS

- NATURAL ENVIRONMENTS
  - SALT SPRAY/HUMIDITY – NO DEGRADATION
  - VACUUM – NO DEGRADATION
  - CRYOGENIC TEMPERATURES – DEMONSTRATED 50 PERCENT SAFETY MARGIN
  - RAIN – NO EROSION
    – IMPACT DAMAGE THRESHOLD REQUIRES PROPER DESIGN
- INDUCED ENVIRONMENTS
  - ACOUSTICS – NO DEGRADATION
    – DEMONSTRATED 25 MISSION CAPABILITY FOR 163 dB
  - RE-ENTRY – DEMONSTRATED THERMAL STABILITY TO 1644°K (2500°F) FOR 100 MISSIONS
    – DEMONSTRATED STRUCTURAL CAPABILITY TO 1644°K (2500°F) FOR 57 MISSIONS ON TWO TILES, 91 MISSIONS ON ONE TILE AND 100 MISSIONS ON ONE TILE.
    – SIDEWALL COATING CRACKING SOLUTION REQUIRES PROPER DESIGN
  - STRUCTURE LOADS – PD-200 DECOUPLES AIRFRAME STRUCTURAL LOADS FROM REI-MULLITE TPS

Figure 20

REFERENCES

1. Final Report for Reusable Surface Insulation Thermal Protection System Development Program, GE-EYP-012, May 1972. NASA, MSC Contract No. NAS 9-12084. General Electric Co., Philadelphia, Pa.
2. Final Report on Evaluation of Nonmetallic Thermal Protection Materials for the Manned Space Shuttle, Volume V, June 1, 1972, NASA Contract NAS 9-10853, Battelle Memorial Institute, Columbus, Ohio.
3. Development of an External Insulation for the Space Shuttle Orbiter, NASA CR-112038, April 1972, General Electric Company, Philadelphia, Pa.
4. Rain Erosion Characteristics of Thermal Protection System Materials at Subsonic Velocities, AFML TR-72-145, August 1972, Textron Bell Aerospace Company.