REUSABLE SURFACE INSULATION THERMAL PROTECTION SYSTEMS
TEST EVALUATION STATUS

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INTRODUCTION

The economical development of a space shuttle depends on the development of low cost, light weight, reliable systems for the orbiter vehicle. One of the systems in the success of the space shuttle is the thermal protection system (TPS). The TPS must be designed to perform multiple missions and be capable of withstanding static and dynamic loads as well as the other environments induced by launch, orbit, entry, and ground handling. Several TPS materials and concepts have been proposed; the most promising from weight, cost, and design simplicity viewpoints utilizes reusable surface insulation (RSI) materials.

This paper discusses the design requirements used in the RSI technology development programs, and the results of recent test programs conducted at NASA-MSC in support of the RSI design developments. These test programs have provided information concerning the thermal/structural performance of candidate RSI materials and designs. The tests have also provided design development guidance and an insight into the necessary test programs and logic for TPS verification.

SUMMARY SCHEDULE OF RSI TECHNOLOGY DEVELOPMENTS

(Figure 1)

This figure illustrates the various phases of the RSI technology programs and the test programs conducted in support of the evolving RSI materials and design concepts. In early 1970, MSC initiated a screening program to evaluate these classes of materials for possible use on the space shuttle vehicle. Test evaluations on six candidate materials consisted primarily of arc jet screening and limited thermal and mechanical property tests. Based on the early arc jet evaluations, a decision was made to initiate a material development program (Phase I) on the silica LI-1500 and mullite MOD I materials with Lockheed and McDonnell-Douglas, respectively. This activity was expanded in the Phase II technology development program with three sources; Lockheed for a silica system (LI-1500), McDonnell-Douglas, and General Electric for mullite systems MOD III and MOD IA, respectively. The Phase II program emphasized design, development, and basic improvement of the RSI materials. During the Phase I and Phase II periods, extensive thermal/structural tests were conducted on prototype TPS panels with full-scale components. Preliminary property data were also generated to support design activities. The current technology program (Phase III) is a continuation of design development with the selected three RSI contractors and is concerned primarily with improving TPS attachment techniques, RSI material and coating improvement, and the gathering of design property data. McDonnell Douglas has concentrated on simplifying their coating process for HCF MOD III, while General Electric has been involved in a basic material process modification that has resulted in a mullite RSI MOD IB material with improved mechanical properties. Lockheed has continued with their basic silica material process and has concentrated on reducing bulk density, which has resulted in a LI-900 material with a bulk density of 144.18 kg/m^3 (9 lb/ft^3). During January 1973, one material system will be selected for the shuttle TPS from the three candidate RSI materials.

SUMMARY SCHEDULE OF RSI TECHNOLOGY DEVELOPMENTS

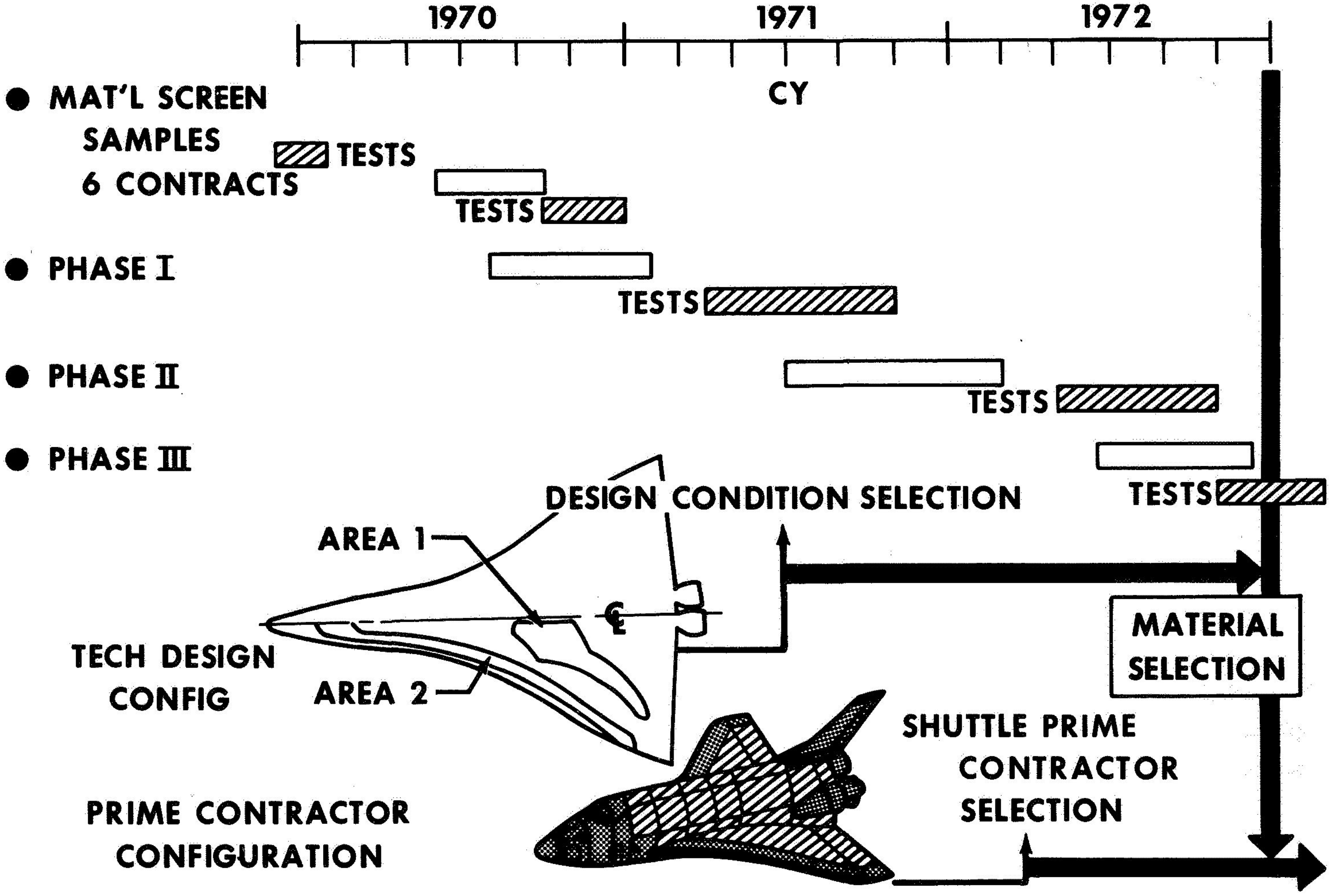


Figure 1

COMPARISON OF ENTRY HEATING HISTORIES

(Figure 2)

Reference heating rate histories to a 0.35 m (1 ft) radius sphere for the current North American baseline trajectory and the RSI technology baseline trajectory selected in the summer of 1971 are shown in this figure. It will be noted that the peak rates are similar for the two trajectories; the primary difference between the two is the shorter entry time of the current baseline trajectory.

COMPARISON OF ENTRY HEATING HISTORIES

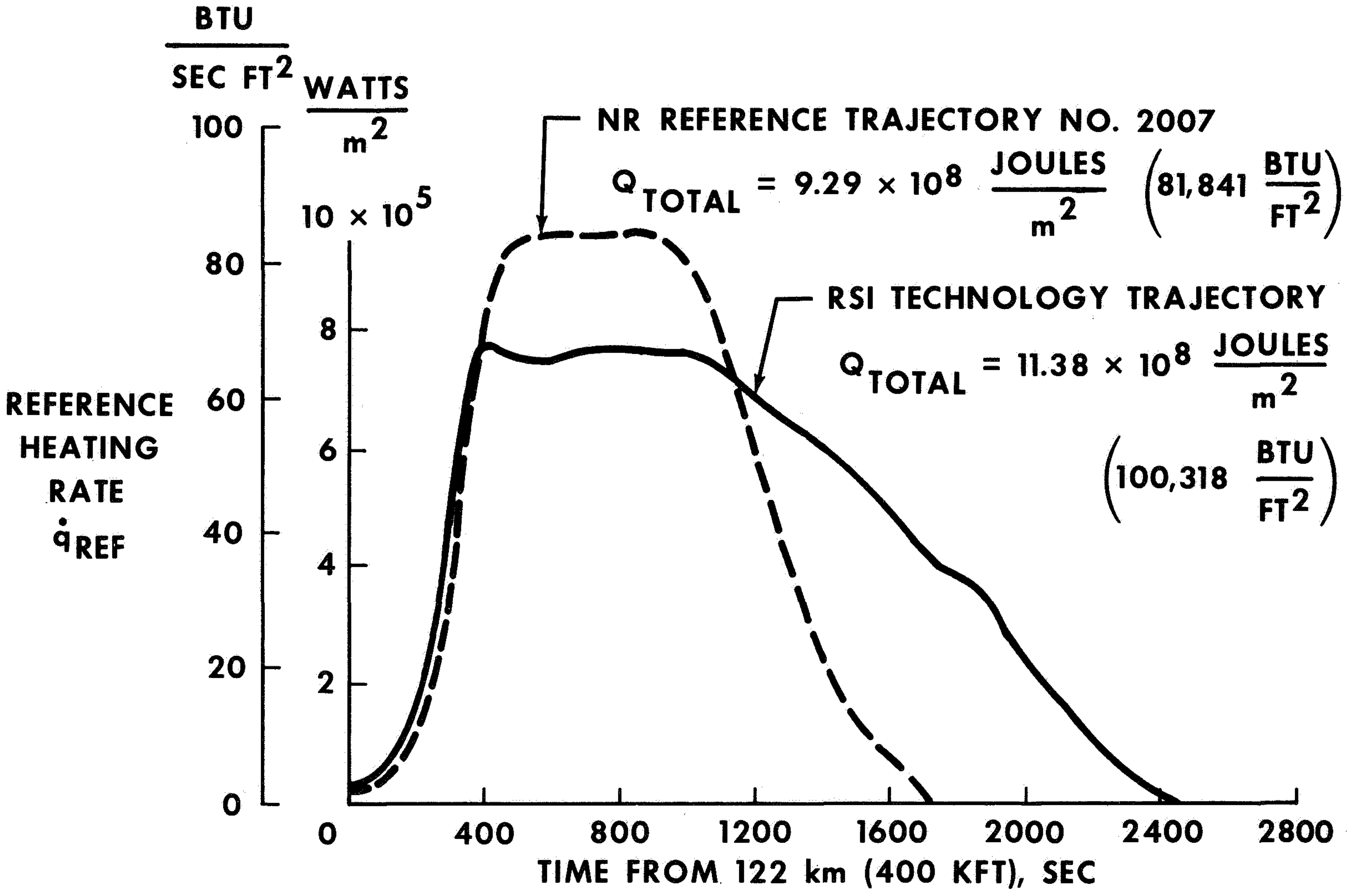


Figure 2

DISTRIBUTION OF PEAK SURFACE TEMPERATURE
RSI TECHNOLOGY BASELINE

(Figure 3)

Peak surface temperatures during entry were calculated for the reference heating rate trajectory shown in the previous figure and laminar heating rate distribution data obtained from wind tunnel tests. Isotherms for the vehicle lower surface are shown in this figure. Design requirements for prototype RSI panels were obtained by calculating heating environments and structural loads for two general locations on the vehicle lower surface. These locations are identified as Area 1 and 2 with boundaries as indicated. Area 1 experiences a peak temperature of 1035°K (1400°F) which is representative of the general acreage on the orbiter vehicle. The Area 2 panels were designed and thermally sized for a peak temperature of 1533°K (2300°F) with a capability for an overshoot test to 1643°K (2500°F).

Although 1476°K (2200°F) is more representative of Area 2 temperatures, 1533°K (2300°F) was selected for design. The combination of temperature with Area 2 loads is identified as an Area 2 perturbed (Area 2P) design.

DISTRIBUTION OF PEAK SURFACE TEMPERATURES

RSI TECHNOLOGY BASELINE

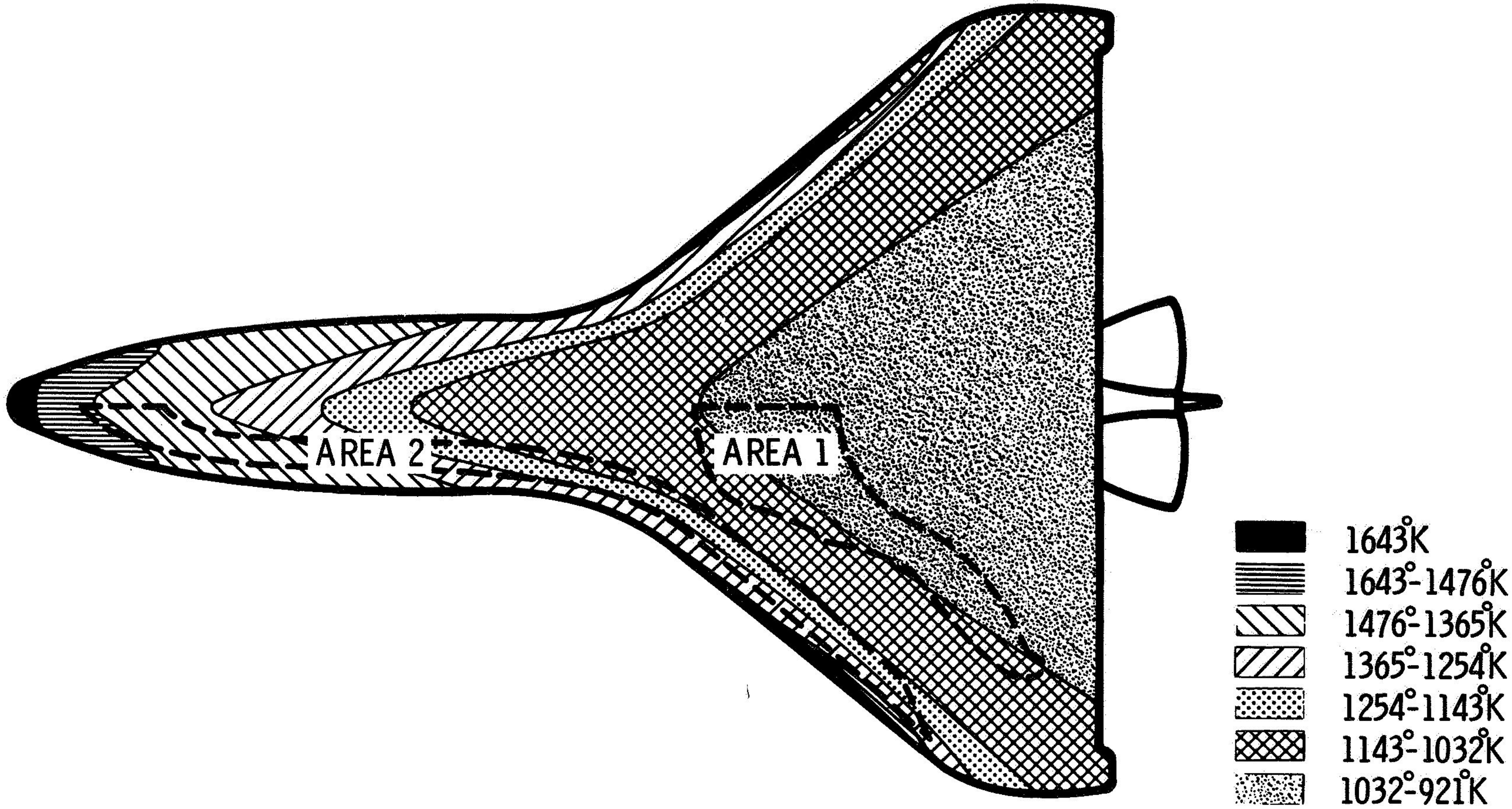


Figure 3

PEAK EQUILIBRIUM SURFACE TEMPERATURE/VEHICLE AREA DISTRIBUTION

(Figure 4)

Orbiter surface temperature distributions were calculated for each of the two reference entry trajectories shown previously and correlated as a function of area as shown in this figure. For any vehicle surface temperature selected on the abscissa, the ordinate value shows the percentage vehicle area at or above the selected temperature. Only a small percentage of the vehicle will be exposed to the peak temperature of 1533°K (2300°F) selected for Area 2P prototype TPS panel design. The temperature distribution for the NR reference trajectory is similar to that for the RSI technology trajectory shown.

PEAK EQUILIBRIUM SURFACE TEMPERATURE/ VEHICLE AREA DISTRIBUTION

- LAMINAR FLOW CONDITIONS
- TOTAL AREA 1163 m^2 (12,519 FT^2)

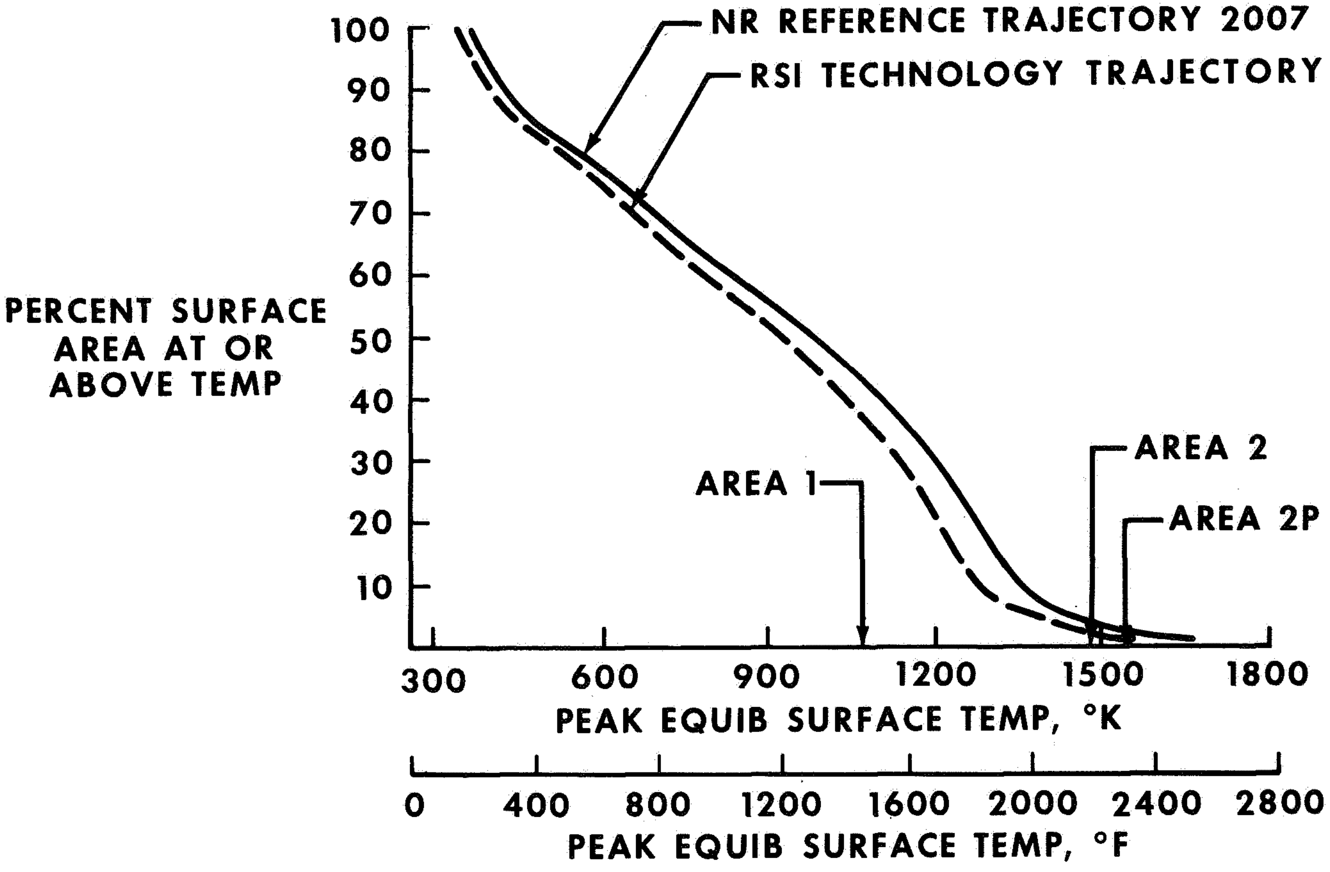


Figure 4

TEMPERATURE CHANGE RATE VERSUS EQUILIBRIUM SURFACE TEMPERATURE

(Figure 5)

In addition to peak temperature levels, one of the more critical environmental variables for the design of RSI thermal protection systems is the surface temperature change rate during entry. Surface temperature change rate is indicative of in-depth temperature gradients, which create thermal stress conditions within the thickness of RSI materials. Temperature change rate is plotted versus temperature for Area 2P for both the NR and RSI technology reference trajectories in this figure. For both trajectories, peak temperature change rates of +3.3°K/sec (6°F/sec) occur early in the entry phase (250 sec) at surface temperatures of 1050°K (1425°F). Thermal stress distribution surveys during entry tend to confirm that critical thermal stress occur at or around 250 seconds into the entry trajectory. After peak temperature levels of 1533°K (2300°F), temperature decrease rates are about one half of the temperature rise rates.

TEMPERATURE CHANGE RATE VERUS EQUILIBRIUM SURFACE TEMPERATURE

AREA 2P

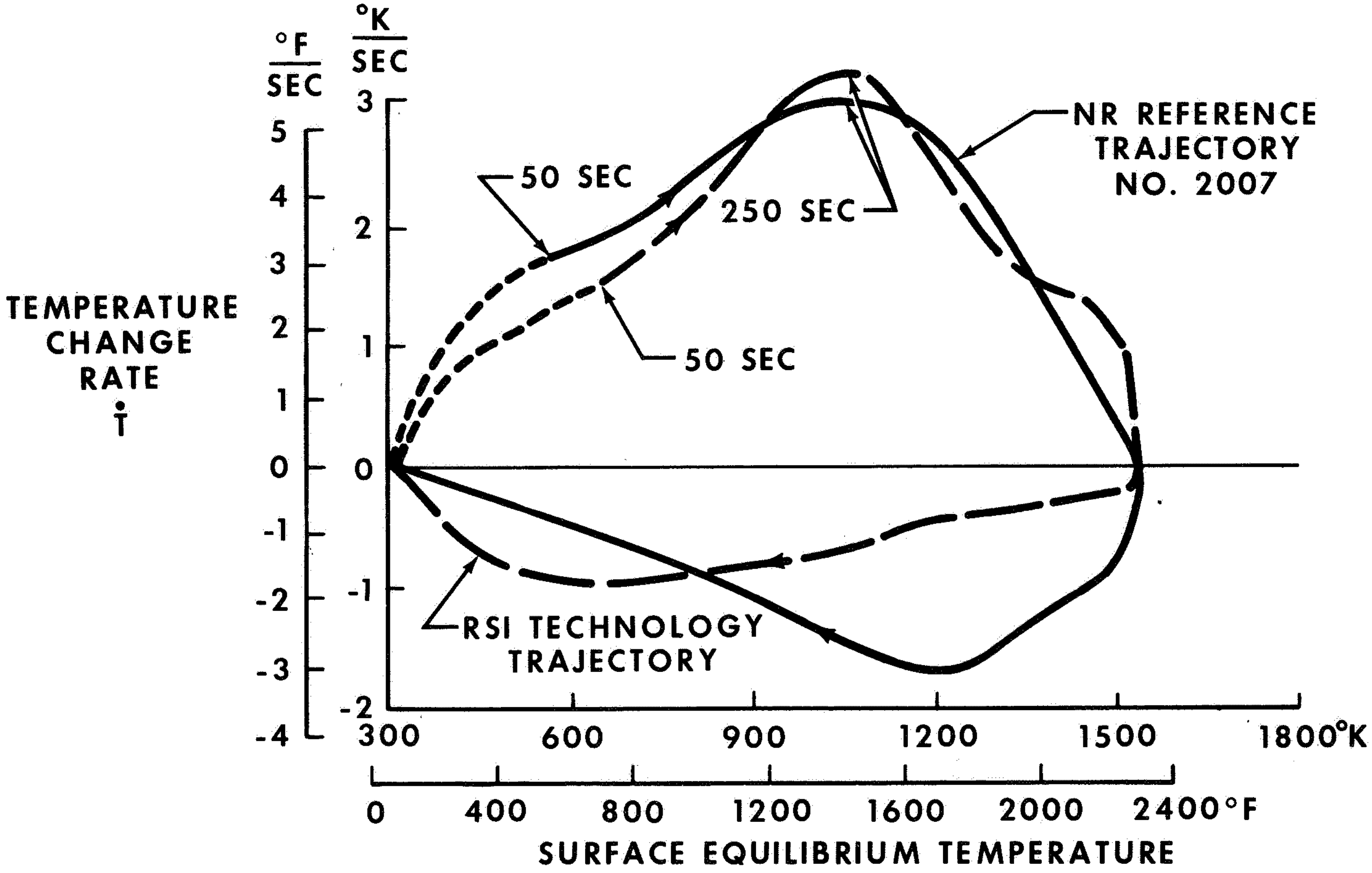


Figure 5

PRELIMINARY RSI MATERIAL PROPERTIES
USING SMALL SAMPLE STATISTICS

(Figure 6)

Available room temperature mechanical strength data have been analyzed statistically to obtain 90 percent exceedence values with 95 percent confidence levels using small sample statistics. Longitudinal and transverse direction tensile strengths and modulii for Phase II and III RSI materials are shown in this figure along with the number of sample data points used in the statistical analysis. Comparison indicates that the mullite materials have higher tensile strengths in the transverse direction than the silica materials. The scatter in properties appear to be higher for the silica materials than the mullite materials. It should be noted that the values shown represent as-received materials and do not contain data reflecting degradation effects of cyclic exposure to simulated entry environments.

PRELIMINARY RSI MATERIAL PROPERTIES USING SMALL SAMPLE STATISTICS

	GE MULLITE MOD 1A	GE MULLITE MOD 1B	LMSC SILICA LI-1500	LMSC SILICA LI-900	MDAC MULLITE MOD III
TENSILE STRENGTH $N/m^2 \times 10^{-5}$ LONGITUDINAL 90% EXCEEDENCE (PSI)	5.23 ± 2.09 3.14 (45.7) $\boxed{21}$	10.1 ± 2.03 8.07 (116.5) $\boxed{39}$	6.30 ± 3.50 2.80 (40.6) $\boxed{18}$	3.49 ± .77 2.72 (39.5) $\boxed{10}$	6.68 ± 2.61 4.07 (59.1) $\boxed{10}$
TENSILE STRENGTH $N/m^2 \times 10^{-5}$ TRANSVERSE 90% EXCEEDENCE (PSI)	1.79 ± .52 1.27 (18.4) $\boxed{38}$	2.27 ± .67 1.60 (23.2) $\boxed{35}$	1.05 ±.28 .77 (11.3) $\boxed{11}$	1.10 ± .68 .42 (6.1) $\boxed{10}$	2.41 ± .77 1.64 (23.9) $\boxed{6}$
TENSILE MODULUS $N/m^2 \times 10^{-5}$ LONGITUDINAL 90% NON-EXCEEDENCE (PSI $\times 10^{-3}$)	2900 ± 970 3870 (56) $\boxed{21}$	3650 ± 1240 4890 (71) $\boxed{39}$	5210 ± 3100 8310 (120.6) $\boxed{18}$	1620 ± 480 2100 (30.5) $\boxed{10}$	4340 ± 2060 6400 (92.9) $\boxed{10}$
TENSILE MODULUS $N/m^2/10^{-5}$ TRANSVERSE 90% NON-EXCEEDENCE (PSI $\times 10^{-3}$)	621 ± 145 766 (11.1) $\boxed{38}$	441 ± 172 613 (8.9) $\boxed{35}$	565 ± 248 813 (11.8) $\boxed{11}$	400 ± 220 620 (9.0) $\boxed{10}$	117 ± 65 182 (26.5) $\boxed{6}$

☐ NUMBER OF SAMPLES

Figure 6

THERMAL CONDUCTIVITY COMPARISONS

(Figure 7)

Thermal conductivities as a function of mean temperature at atmospheric pressure are shown in this figure for both silica and mullite RSI materials. Data measured by each of the RSI contractors are shown along with data measured by Battelle Memorial Institute (BMI) under contract to NASA-MSC. Some of the significant difference in conductivity values obtained by the different data sources can be attributed to measurement techniques. Despite these differences, the data shown as shaded areas for silica and mullite RSI still show that the conductivity of the silica is significantly lower than that of the mullite materials. Conductivity is dependent on pressure as well as temperature, and similar trends are exhibited at lower pressure on the order of 1.01×10^3 N/m^2 (10^{-2} atm).

THERMAL CONDUCTIVITY COMPARISONS
ATMOSPHERIC PRESSURE

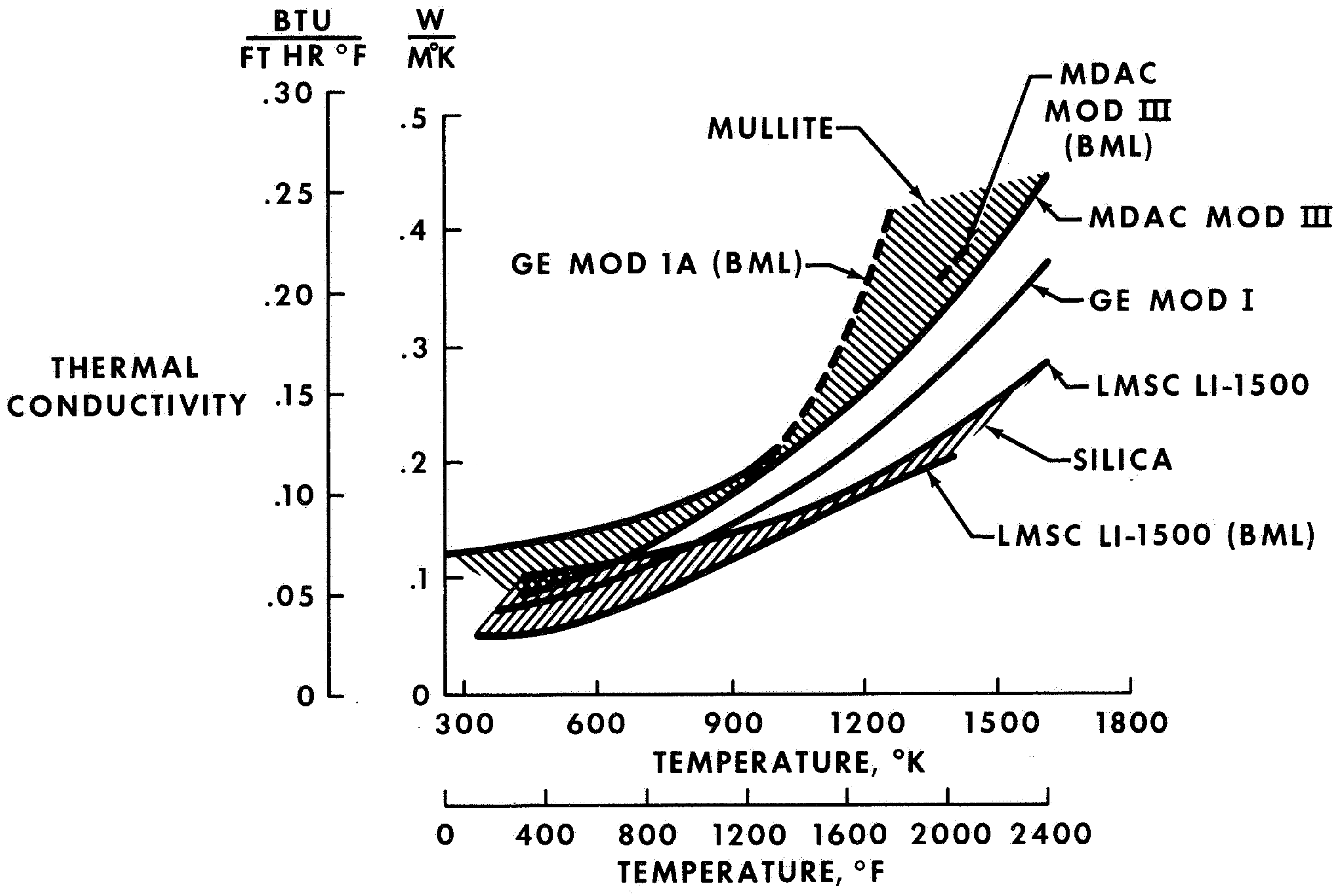


Figure 7

THERMAL CRACKING RESISTANCE

(Figure 8)

To provide some measure of resistance to cracking by thermal stresses during entry, a combination of thermal-mechanical properties as defined in this figure has been utilized to formulate a comparative cracking resistance index for the different materials. A high index value for a material is indicative of a greater resistance to cracking. Although this thermal cracking resistance index is neither dimensionless nor a fundamental property, it indicates how properties combine to influence the tendency of the RSI materials to crack under thermal stresses. Index values have been calculated for each of the RSI materials using average properties and type "B" properties (minimum strength, maximum modulus) at room temperature. Comparison of the indices for silica with those for mullite RSI shows that silica should be far less susceptible to thermal cracking than mullite.

THERMAL CRACKING RESISTANCE
IN-PLANE TENSION
ROOM TEMPERATURE PROPERTIES

PARAMETER $\frac{°K}{\rho C_p} \frac{Fy}{E\alpha} - \frac{M^2 °K}{SEC} \times 10^{-3}$

	AVG PROPERTIES	TYPE B PROPERTIES
GE MULLITE (MOD IA)	15.6	7.1
GE MULLITE (MOD IB)	23.9	14.3
LMSC SILICA (LI-1500)	80.8	22.5
LMSC SILICA (LI-900)	241	144
MDAC MULLITE (MOD III)	17.1	9.8

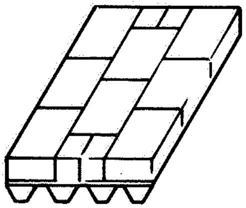
Figure 8

PROTOTYPE TPS PANEL CONFIGURATIONS AND WEIGHT COMPARISONS FOR AREA 2P, ALUMINUM STRUCTURE

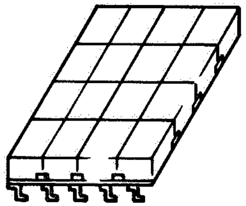
(Figure 9)

This chart shows the total and component weights for the three designs for the Area 2P TPS AL panels delivered under the Phase II technology contracts. The weights of the aluminum primary structure are approximately the same even though the stiffeners on the structures were significantly different. The mullite TPS weights reflect the use of strain isolating foam bonds. This figure also shows the types of gap configurations selected by each contractor. The LMSC panel reflects a butt overlap with a filler strip, the MDAC panel--a straight butt joint, and the GE panel--a butt configuration with a roving fiber filler.

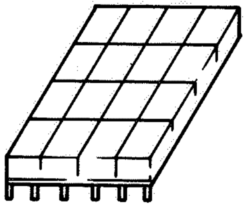
PROTOTYPE TPS PANEL CONFIGURATION AND WEIGHT COMPARISONS FOR AREA 2P, ALUMINUM STRUCTURE



GE
(.20 m × .20 m)AND
(.10 m × .10 m)TILES



LMSC
(.15 m × .15 m) TILES



MDAC
(.15 m × .15 m) TILES

THICKNESS/WEIGHTS

	GE		LMSC		MDAC	
	$m \times 10^{-2}$	Kg/m^2	$m \times 10^{-2}$	Kg/m^2	$m \times 10^{-2}$	Kg/m^2
TPS						
COATING	.043	2.93	.038	1.32	.038	2.39
INSULATION	5.1	9.76	6.4	15.40	8.51	20.40
BOND	2.8	12.20	.23	3.22	.71	3.60
TPS WEIGHT		24.89 (5.1 LB/FT^2)		19.94 (4.08 LB/FT^2)		27.39 (5.42 LB/FT^2)
STRUCTURE	.33	9.28	.29	8.00	.30	8.40
TOTAL WEIGHT		34.17 (7.0 LB/FT^2)		27.94 (5.72 LB/FT^2)		35.79 (7.14 LB/FT^2)

Figure 9

TESTING CONDITIONS AND TESTING SEQUENCE FOR RSI PROTOTYPE PANELS

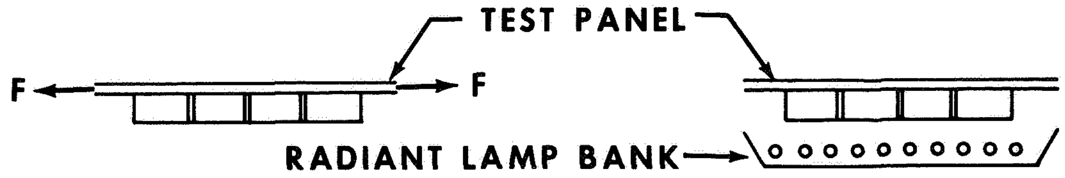
I. INITIAL EXPOSURE

(Figure 10)

The majority of the shuttle orbiter critical environments occur sequentially, and the tests performed reflect this sequence. The initial test consisted of tensile axial loading of the aluminum primary structure. Next, a thermal test was conducted at 1200°K (1700°F) with a room temperature start. The initial thermal test was performed at conditions substantially less than design to check out instrumentation, test procedures, and the interaction between the panel and the induced heating environment.

TEST CONDITIONS AND TESTING SEQUENCE FOR RSI PROTOTYPE PANELS

I INITIAL EXPOSURE



(a) AXIAL LOAD TEST AT ROOM TEMP (b) 1200°K (1700° F) TEST, NO LOAD

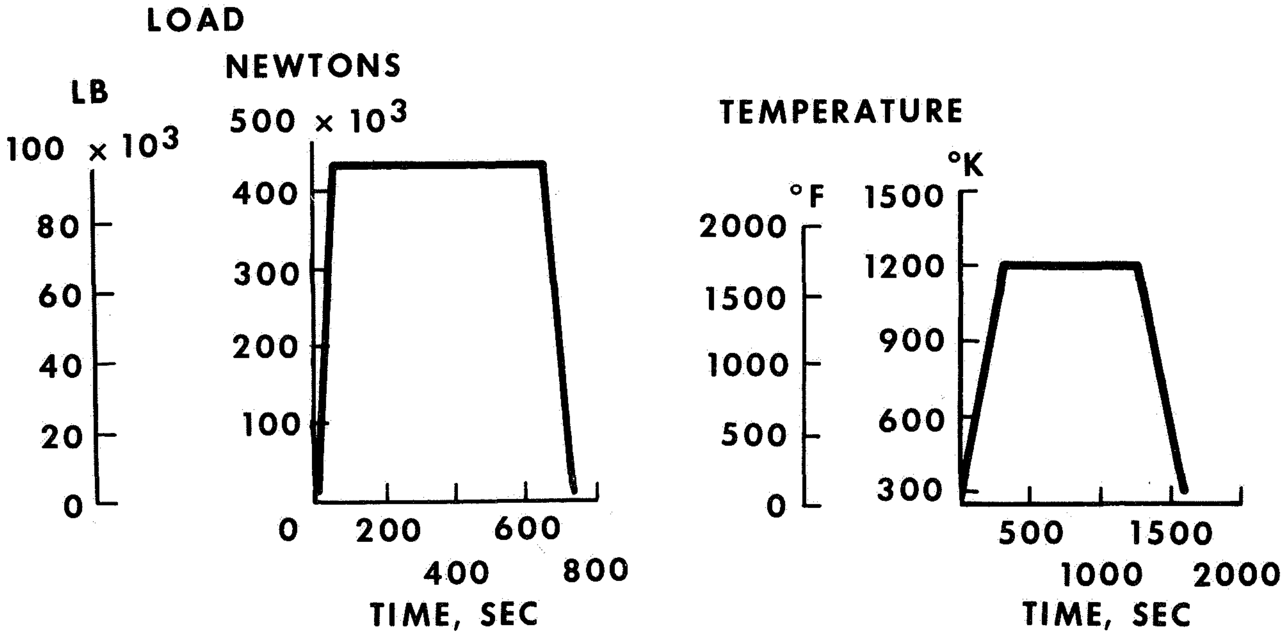


Figure 10

TESTING CONDITIONS AND TESTING SEQUENCE

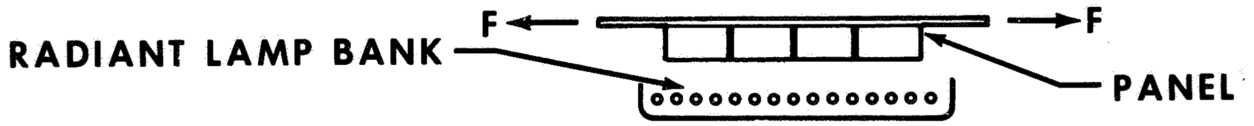
II. FINAL EXPOSURES

(Figure 11 and Figure 12)

The next two figures show the subsequent multiple test environments selected for the RSI thermal structural test program. The sequential tests were conducted in multiples of five cyclic exposures consisting of thermal exposure at design temperature, 1533°K (2300°F), followed by load at atmospheric conditions and/or thermal exposure at design temperature under flight pressure conditions. Acoustic tests consisting of a single exposure for an equivalent test time of five missions followed the thermal tests. The thermal tests at atmospheric conditions were conducted at a cold start temperature of 172°K (-150°F) to permit simulation of full Area 2P heat pulse. Bondline temperatures were monitored during each test to prevent overtemperature of the structure, which was limited to 422°K (300°F) for the aluminum panels and 589°K (600°F) for the titanium panels. The tests were grouped in blocks of five exposures to minimize test article handling and minimize serial time including test preparation in the thermal and acoustic facilities. The atmospheric pressure thermal tests were conducted with standard quartz tube heaters; the reduced pressure tests were conducted in an evacuated chamber using graphite elements in combination with a columbium susceptor plate. The acoustic tests were conducted in a progressive wave tube operating at an overall 160 dB level.

TEST CONDITIONS AND TESTING SEQUENCE

II FINAL EXPOSURES (IN MULTIPLES OF FIVE CYCLES)



(a) 1533°K (2300° F) TEST AT ATMOSPHERIC CONDITIONS, 172°K (-150° F) START, PLUS LOAD

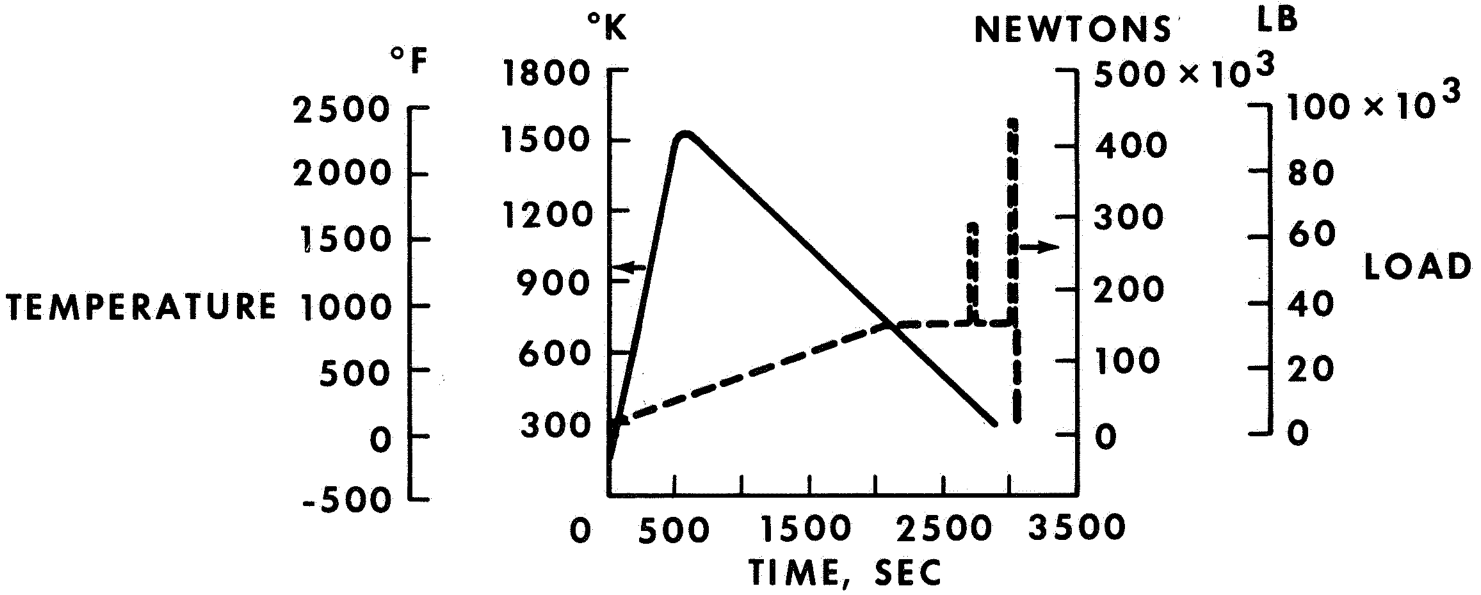
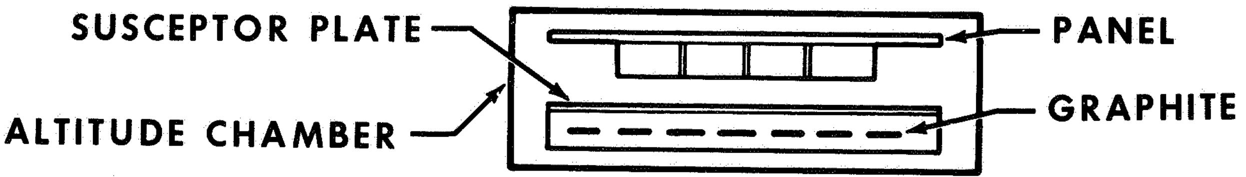


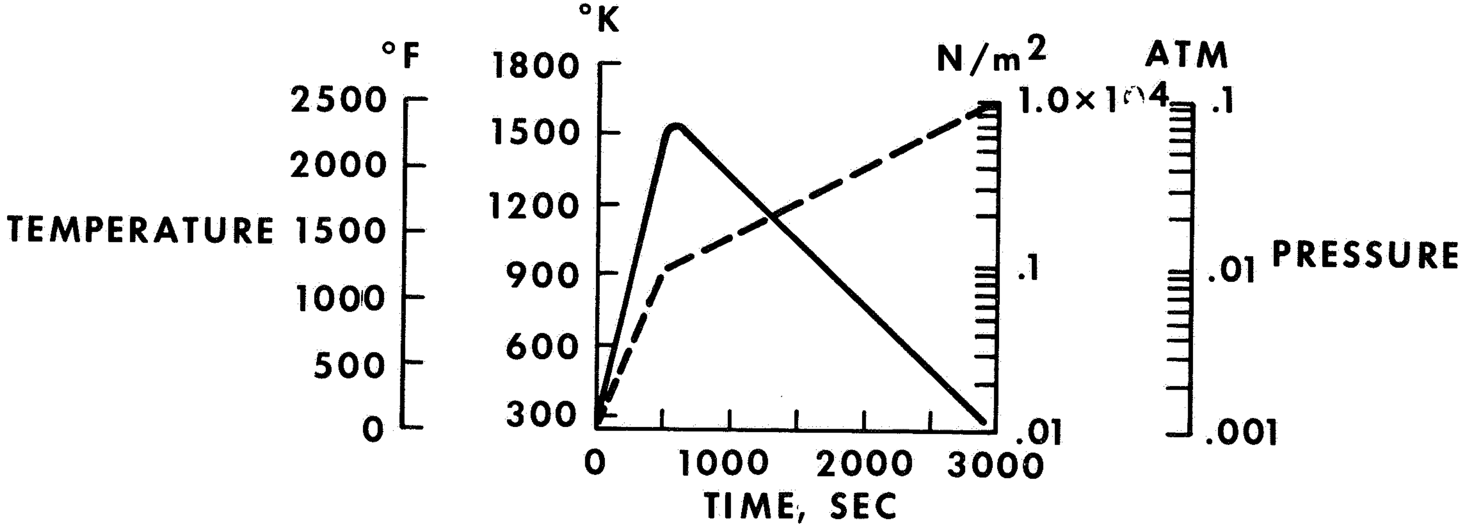
Figure 11

TEST CONDITIONS AND TESTING SEQUENCE

II FINAL EXPOSURES (IN MULTIPLES OF FIVE CYCLES)



(b) 1533°K (2300° F) TEST AT REDUCED PRESSURE, NO LOAD



(c) ACOUSTIC TEST AT ROOM TEMPERATURE × FIFTEEN SECONDS AT 160 dB OASL

Figure 12

IN-DEPTH TEMPERATURE COMPARISONS

(Figure 13)

This figure illustrates typical thermal performance data obtained during thermal tests at atmospheric pressure. The predictions were obtained from a one-dimensional thermal model using the measured surface temperature as a driver and assuming an adiabatic structural backface. The comparisons between the test and analyses shown for the first 1000 seconds into the simulated entry profile indicate that silica possesses the lowest conductivity of the RSI materials, which tends to confirm the guarded hot plate data.

To achieve the correlation between test data and analysis shown for the mullite RSI, MOD I properties for the General Electric MOD IA material, and properties backed out from thermal tests at McDonnell-Douglas for the MOD III material were used.

IN-DEPTH TEMPERATURE COMPARISONS

- AREA 2P
- 172°K (-150°F) INITIAL TEMPERATURE AT ATMOSPHERIC PRESSURE CONDITIONS

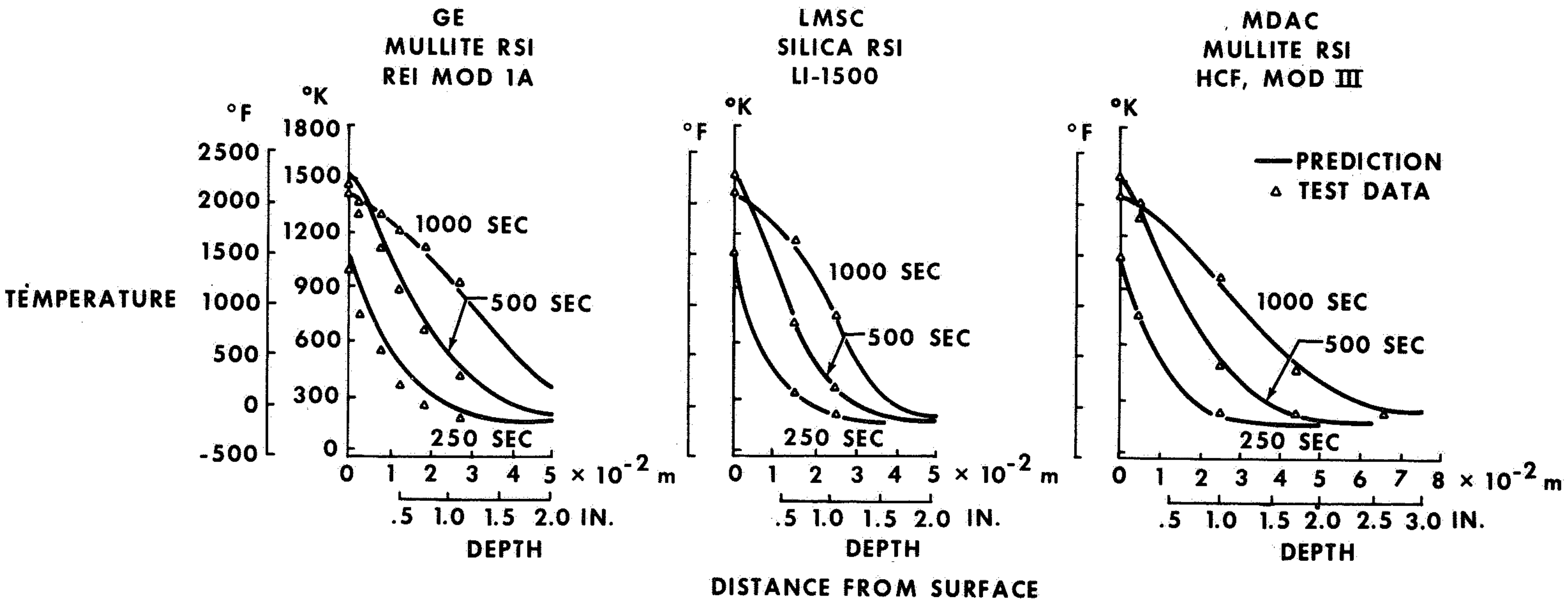


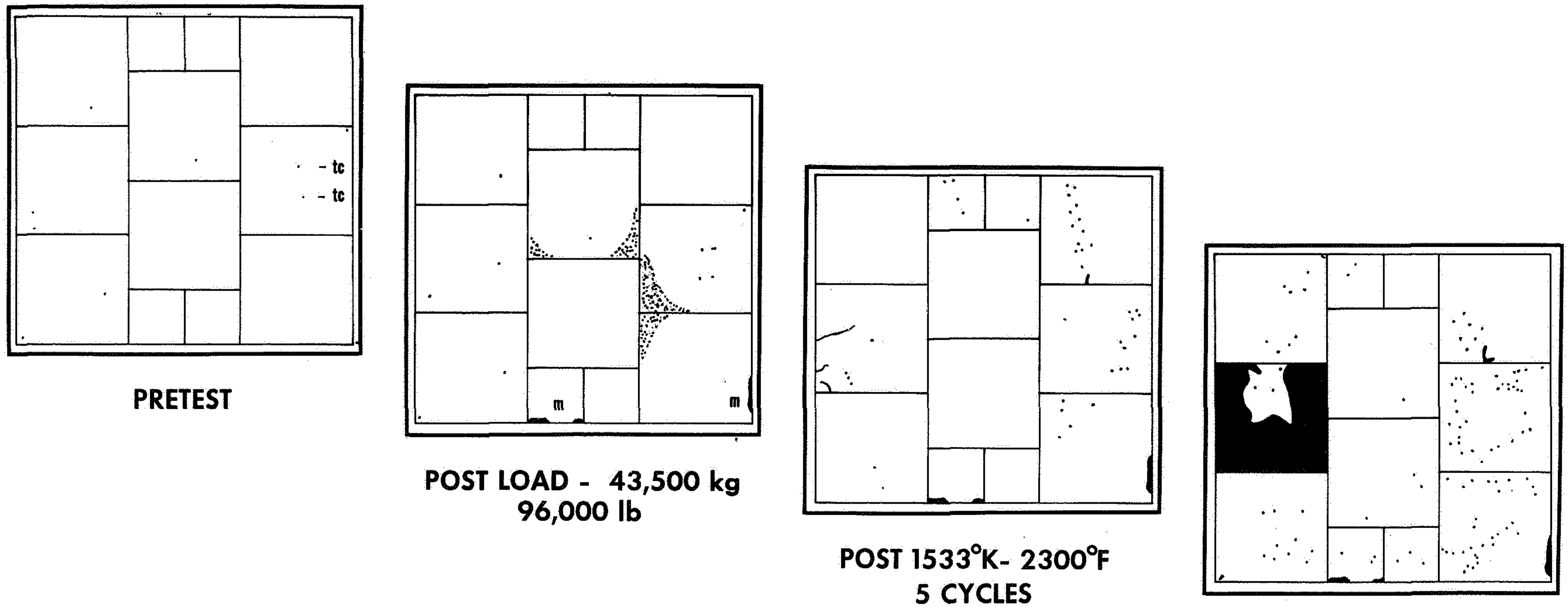
Figure 13

NONDESTRUCTIVE EVALUATION - GENERAL ELECTRIC AREA 2P ALUMINUM PANEL

(Figure 14)

This figure illustrates the RSI panel condition as received, after the axial load test, after five thermal exposures at 1533°K (2300°F) with 172°K (-150°F) start plus axial loading, and after the acoustic environment tests. Some pin holes were observed in several tiles in the as-received condition and after the axial load test. Cracking appeared in several of the RSI tiles after the initial 1200°K (1700°F) heating test. Upon completion of the 1533°K (2300°F) tests, one tile (which has instrumented with thermocouples identified as "tc" on the figure) was cracked extensively and seven other tiles exhibited cracks. The cracked tiles were apparently waterproof based on water drop tests performed in the vicinity of the cracks. During the design temperature tests 1533°K (2300°F) with the 172°K (-150°F) start, it was necessary to use an abbreviated heat pulse to limit temperatures at the RSI/foam bond interface to 533°K (500°F), confirming that the conductivity of the MOD IA material was closer to the MOD I thermal property measurements than to those measured on MOD IA. Subsequent acoustic testing of this panel fractured the instrumented tile; however, the remaining cracked tiles remained intact. Handling damage that occurred during testing is identified as "m" in the figure.

NONDESTRUCTIVE EVALUATION
GENERAL ELECTRIC AREA 2P ALUMINUM PANEL



PRETEST

POST LOAD - 43,500 kg
96,000 lb

POST 1533°K- 2300°F
5 CYCLES

POST ACOUSTIC - 164 dB

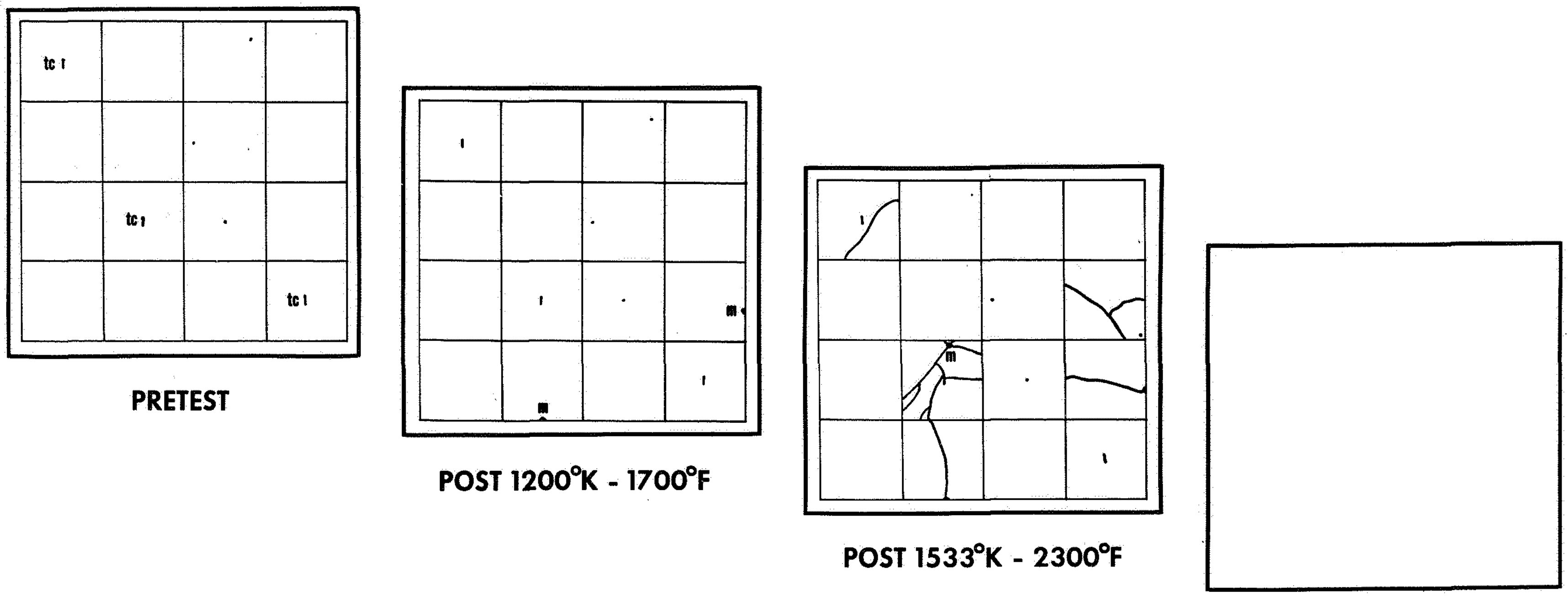
Figure 14

NONDESTRUCTIVE EVALUATION - LOCKHEED AREA 2P ALUMINUM PANEL

(Figure 15)

This figure illustrates the LMSC RSI panel condition as received, after the axial load test, after the thermal test at 1200°F (1700°F), and after initial exposures to 1533°K (2300°F). During the axial load test, excessive deflections occurred at the loaded ends plates of the substrate panel, which resulted in delamination of several tiles from the structure. Since the RSI tiles in the center of the panel were not damaged, the decision was made to acquire limited thermal performance data on this panel. The 1200°K (1700°F) thermal test was conducted and no cracks or anomalies were observed after the 1533°K (2300°F) tests, without load, cracks were observed on five tiles in the array. However, all the cracks appeared to initiate in regions of handling damage or from thermocouple instrumentation in the coating. The panel was then sent back to LMSC for modification of the end fittings. This test article has been returned to MSC and testing is currently in progress. Surface thermocouples and handling damage are identified in the figure as "tc" and "m", respectively.

NONDESTRUCTIVE EVALUATION
LOCKHEED AREA 2P ALUMINUM PANEL



PRETEST

POST 1200°K - 1700°F

POST 1533°K - 2300°F

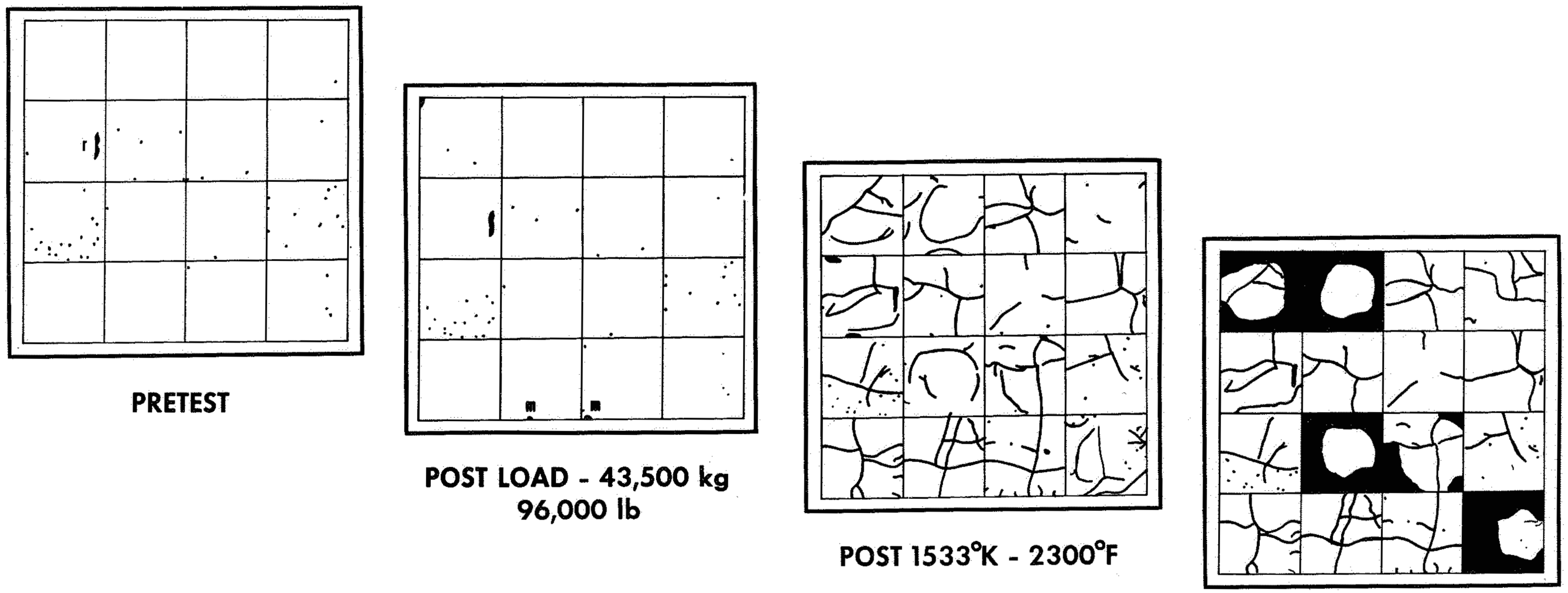
Figure 15

NONDESTRUCTIVE EVALUATION - MCDONNELL DOUGLAS AREA 2P ALUMINUM PANEL

(Figure 16)

This figure shows the panel condition as received, after the axial load test, after the thermal test 1533°K (2300°F) started at 172°K (-150°F) plus axial loading, and after the acoustic tests. Pin holes were observed on several tiles in the as-received condition and after the axial load test. Cracking appeared in every MDAC RSI tile after the initial 1200°K (1700°F) heating test and became progressively worse as the testing continued. Cracking was quite severe on several of the tiles after the final thermal test [172°K (-150°F)]start and maximum design temperature 1533°K (2300°F), and the surface material appeared to have separated from the underlying tile. Subsequent acoustic testing fractured seven of the tiles along the most serious crack zones. These failures precluded further testing of this panel.

NONDESTRUCTIVE EVALUATION
MC DONNELL-DOUGLAS AREA 2P ALUMINUM PANEL



PRETEST

POST LOAD - 43,500 kg
96,000 lb

POST 1533°K - 2300°F

POST ACOUSTIC - 164 dB

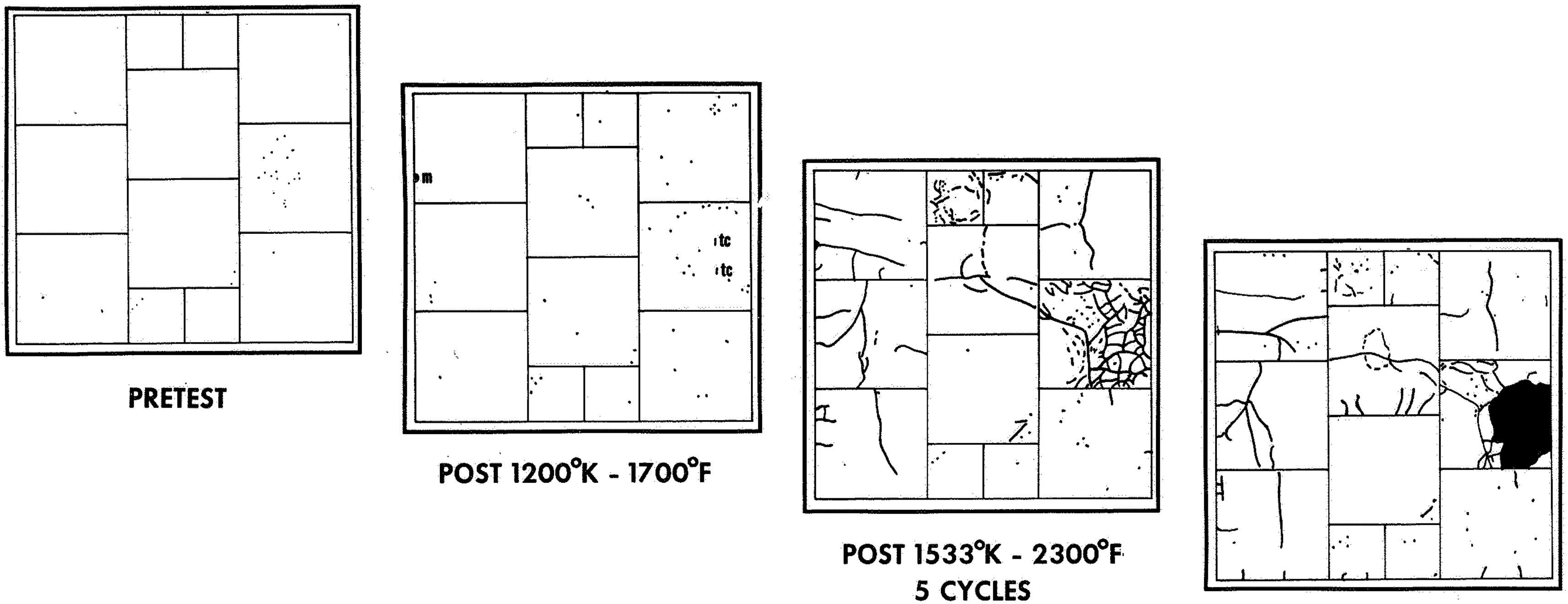
Figure 16

NONDESTRUCTIVE EVALUATION - GENERAL ELECTRIC AREA 2P TITANIUM PANEL

(Figure 17)

During the testing period of the Phase II panels, the graphite heaters and vacuum test equipment became operational at MSC. This permitted radiant heat testing of some of the panels in a realistic simulated flight pressure environment. This figure illustrates the condition of the GE Area 2P titanium panel after completion of a series of acoustic-thermal exposures. The test panel was subjected to an initial acoustic exposure, and no cracks were observable after the test. Thermal testing was then initiated at temperatures of 1200°K (1700°F) and 1533°K (2300°F) at flight pressure conditions. One tile mounted on the barb attachment system (BAS) developed one large crack, and horizontal and vertical cracks were also evident along the sides of the tiles. During these thermal tests, it was necessary to reduce the total heat load (test time) to prevent overtemperature of the RSI/bond interface. The acoustic test performed after the thermal tests resulted in severe delamination and loss of the coating, which removed part of the insulation material from the cracked tile.

NONDESTRUCTIVE EVALUATION
GENERAL ELECTRIC AREA 2P TITANIUM PANEL



PRETEST

POST 1200°K - 1700°F

POST 1533°K - 2300°F
5 CYCLES

POST ACOUSTIC - 164 dB

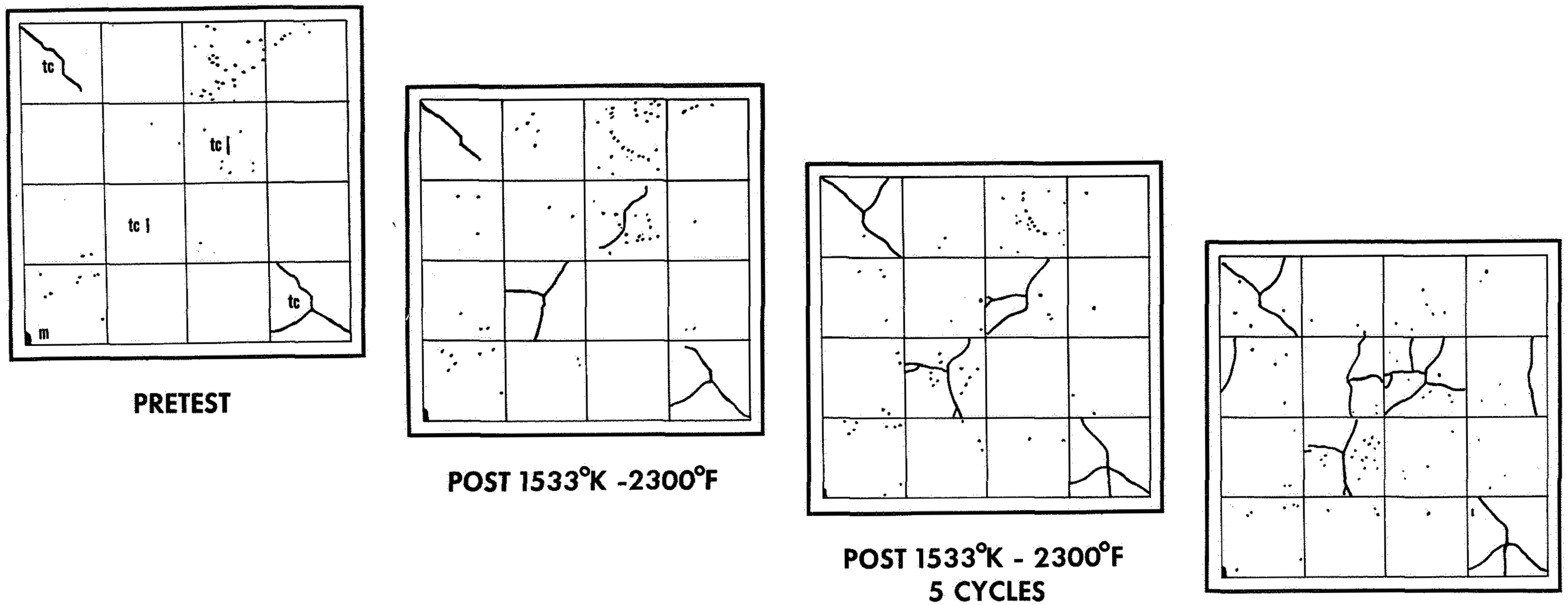
Figure 17

NONDESTRUCTIVE EVALUATION - LOCKHEED AREA 2P TITANIUM PANEL

(Figure 18)

This figure shows the condition of the LMSC Area 2P titanium panel after a series of acoustic thermal exposures. The panel in the as-received condition had several cracks, which tended to propogate during thermal tests at 1533°K (2300°F). Cracks also initiated and propogated from regions of surface thermocouple instrumentation. The panel was subjected to a total of five tests at the Area 2P design temperature level of 1533°K (2300°F) and at flight pressure conditions. The test article was also subjected to acoustic tests, which resulted in further crack formation. However, neither coating delamination nor catastrophic failure of the tiles occurred.

NONDESTRUCTIVE EVALUATION
LOCKHEED AREA 2P TITANIUM PANEL



PRETEST

POST 1533°K -2300°F

**POST 1533°K - 2300°F
5 CYCLES**

POST ACOUSTIC - 164 dB

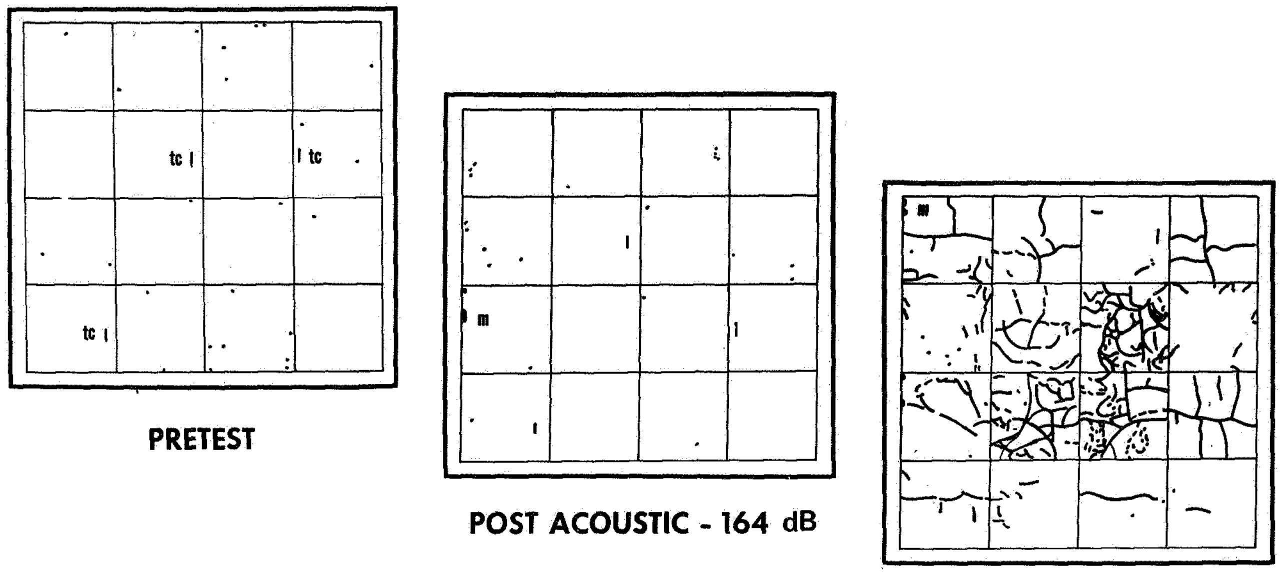
Figure 18

NONDESTRUCTIVE EVALUATION - MCDONNELL DOUGLAS AREA 2P TITANIUM PANEL

(Figure 19)

This figure shows the condition of the MDAC Area 2P titanium panel after a series of acoustic-thermal exposures. The test sequence for the MDAC Area 2P titanium panel was modified by performing the acoustic test initially followed by a 1200°K (1700°F) thermal test at reduced pressure. After the acoustic exposure, no cracks or anomalies were observed. The panel was then subjected to a reduced heat pulse at 1120°K (1558°F), and all 16 tiles cracked. All testing of the MDAC panels were suspended after these tests. This figure shows the panel condition after exposure to the various tests.

NONDESTRUCTIVE EVALUATION
MC DONNELL - DOUGLAS AREA 2P TITANIUM PANEL



PRETEST

POST ACOUSTIC - 164 dB

POST 1120°K - 1558°F

Figure 19

CONCLUDING REMARKS

- PROTOTYPE PANEL DESIGNS USING RSI TECHNOLOGY HEATING ENVIRONMENTS ARE REPRESENTATIVE OF CURRENT SHUTTLE BASELINE REQUIREMENTS
- FURTHER THERMAL CONDUCTIVITY EVALUATIONS OF RSI MATERIALS IN REPRESENTATIVE FLIGHT ENVIRONMENTS ARE REQUIRED. THERMAL CONDUCTIVITY OF MULLITE RSI IS HIGHER THAN SILICA RSI, BASED ON THERMAL RESPONSE DATA
- SURFACE THERMOCOUPLE INSTRUMENTATION AND LOCAL DAMAGED AREAS CREATE STRESS CONCENTRATORS AND CRACKS APPEAR TO INITIATE AND PROPAGATE FROM THESE REGIONS
- ACOUSTIC EXCITATION OF CRACKED SILICA TILES DO NOT LEAD TO CATASTROPHIC FAILURE SUCH AS SPALLATION OR TILE LOSS
- CRACKS IN THE MULLITE MATERIALS IDENTIFIED AFTER THERMAL EXPOSURE CAN LEAD TO FRACTURING OF THE COATING AND SURFACE INSULATION MATERIAL AFTER ACOUSTIC EXCITATION

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