SILICA RSI
ENTRY SIMULATION TESTS

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SYMBOLS

C_2	Constant in Plank's Law, 1.4387 cm deg Kelvin
H_t	Total enthalpy, joules per kilogram
K	Apparent thermal conductivity, watts per meter degree Kelvin
P_t	Total pressure behind normal shock, Newtons per meter^2
T	Temperature, degrees Kelvin
q or q_{cw}	Cold wall heat rate, watts per meter^2
V_∞	Indicates flow direction
ϵ	Spectral normal emittance
μ	Micron, 10^{-6} meter
ρ	Spectral normal reflectance

Subscripts:

λ	At a specified wavelength

RESULTS OF DEVELOPMENT TESTING LMSC SILICA RSI

(Figure 1)

Silica RSI has been under development at LMSC for the past several years. Extensive test experience has resulted, but only those more significant tests accomplished the past year are reported here. In summarizing these tests, the presentation is divided in two parts. The simulated reentry testing is presented here; the more specialized environmental testing is presented in Volume II of these Proceedings in the paper by S. J. Housten.

RESULTS OF DEVELOPMENT TESTING OF LMSC SILICA RSI

SIMULATED REENTRY TESTING

- TESTS BY LMSC, NASA/MSC, NASA/ARC
- MULTICYCLE – RADIANT AND CONVECTIVE
- ACCUMULATED TEST EXPOSURE TO DEMONSTRATE PERFORMANCE AND STABILITY

SPECIALIZED ENVIRONMENTAL TESTING

- LAUNCH CONDITIONS
- ORBIT CONDITIONS
- REENTRY – SPECIALIZED CONDITIONS

Figure 1

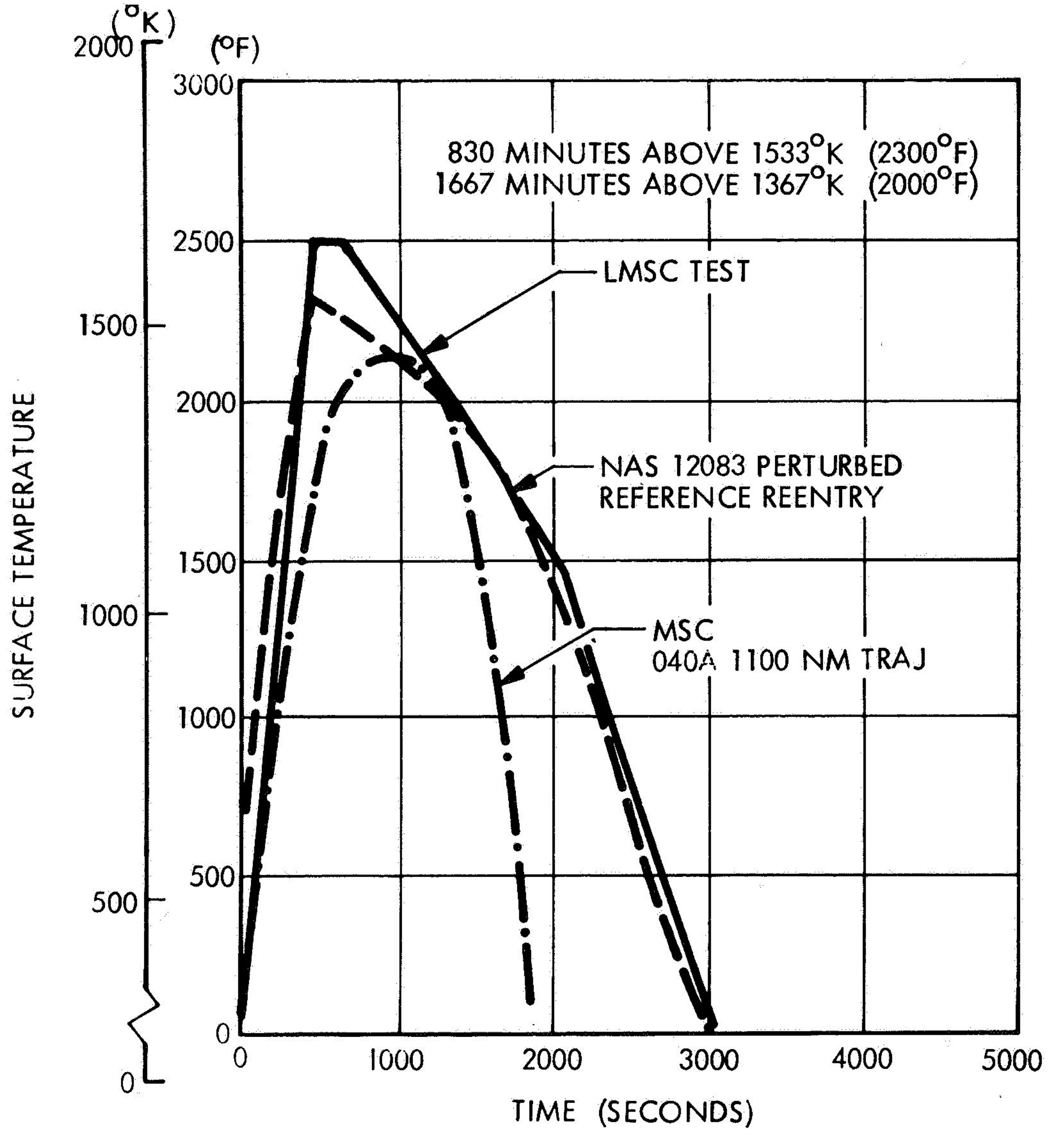
LI-1500/0042 COATING 100-CYCLE TEST PROGRAM

(Figure 2)

One of the primary requirements of the orbiter TPS is that of reuse for 100 missions. In October of 1971, LMSC conducted a 100-cycle radiant heat test on six 10 x 10 x 6.3 cm (4 x 4 x 2.5 in.) LI-1500 specimens selected from the numerous coatings being evaluated under the Material Improvement Contract (NAS 9-12137), Ref. 1. As a result of these tests a new coating was baselined for the silica RSI. This coating, designated 0042, consists of a silicon carbide emittance agent in a borosilicate matrix. This coating system proved so successful that it has been used exclusively on the LMSC silica RSI since October 1971.

As shown, the imposed heat pulse (controlled by thermocouples installed directly below the coating) dwelled at 1648°K (2500°F) for 2.5 minutes per cycle. The total time at 1648°K (2500°F) was 4 hours with 14 hours at temperatures greater than 1533°K (2300°F). The time above 1533°K (2300°F) is equivalent to 336 missions when compared to the reference heat pulse (Area 2P). It should be noted that the total heat load resulting from this heat pulse greatly exceeds that of the reentry trajectories currently being considered for the orbiter. These tests were performed at LMSC under NAS 9-12083, Ref. 2.

LI-1500/0042 COATING 100 CYCLE TEST PROGRAM



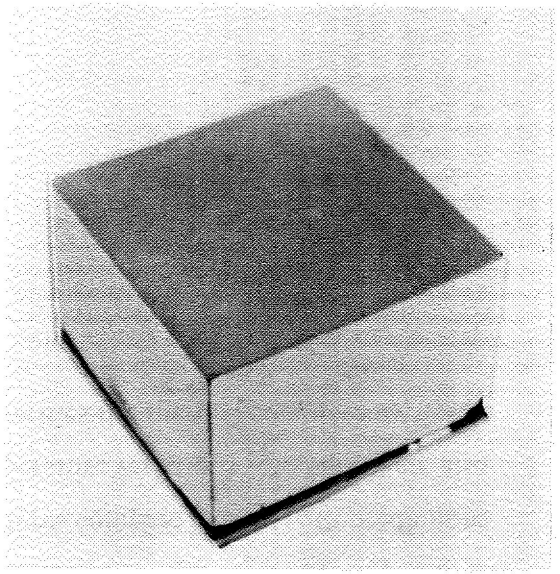


Figure 2

TEMPERATURE HISTORIES FOR SPECIMEN TT42-6
100-CYCLE TESTS
(Figure 3)

The test samples discussed in the previous chart were also instrumented with thermocouples both in depth and on the aluminum substrates. Thermal predictions are shown along with measured temperatures for two representative cycles. The predictions are based on a one-dimensional thermal model and utilize the LI-1500 thermal conductivity and specific heat design values developed in late 1970 and reported in the Phase I Final Report (Ref. 3). The maximum in-depth temperatures compare closely with predictions and were repeatable throughout the tests. It is interesting to note that the calculated temperature variations with time were also closely predicted. The tests were performed at atmospheric pressure, and this agreement verifies the thermal conductivity design values for this pressure.

TEMPERATURE HISTORIES FOR SPECIMEN TT 42-6

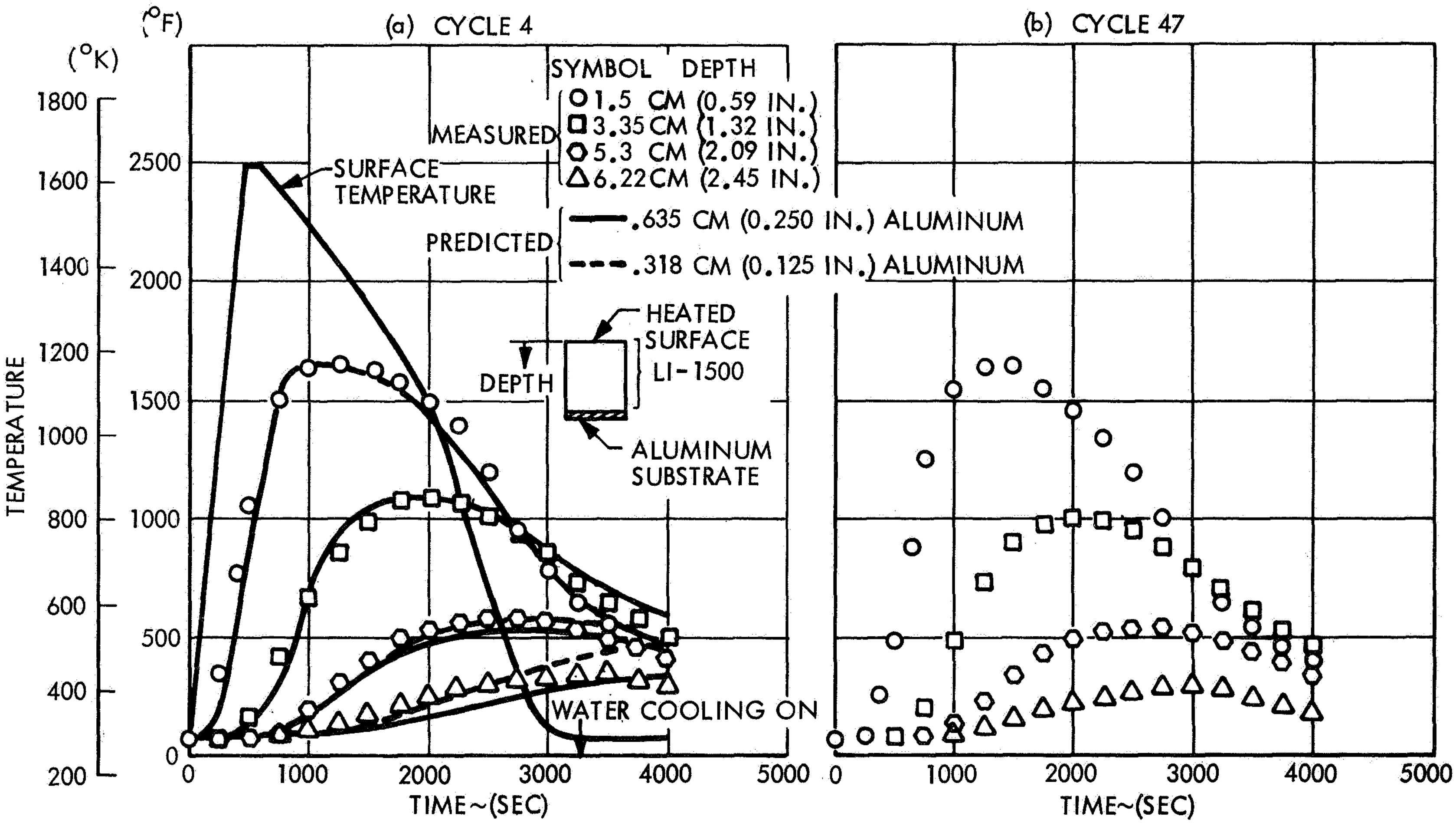


Figure 3

COMPARISON OF MEASURED AND PREDICTED PEAK TEMPERATURES

100-CYCLE TESTS - SPECIMEN TT 42-6

(Figure 4)

Variation of in-depth measured temperatures for the entire 100 cycles is compared with the predicted thermal gradient. At all locations the measured values are less than predictions, illustrating that the LI-1500 conductivity is conservative. Thermal and dimensional stability of the LI-1500 were also demonstrated for the severe thermal conditions of this test. The change in pre- and post-test length and width was less than 0.05 percent, which is well within the accuracy of the measuring device, 0.005 out of 9.9 cm (0.002 in. out of 3.900 in.).

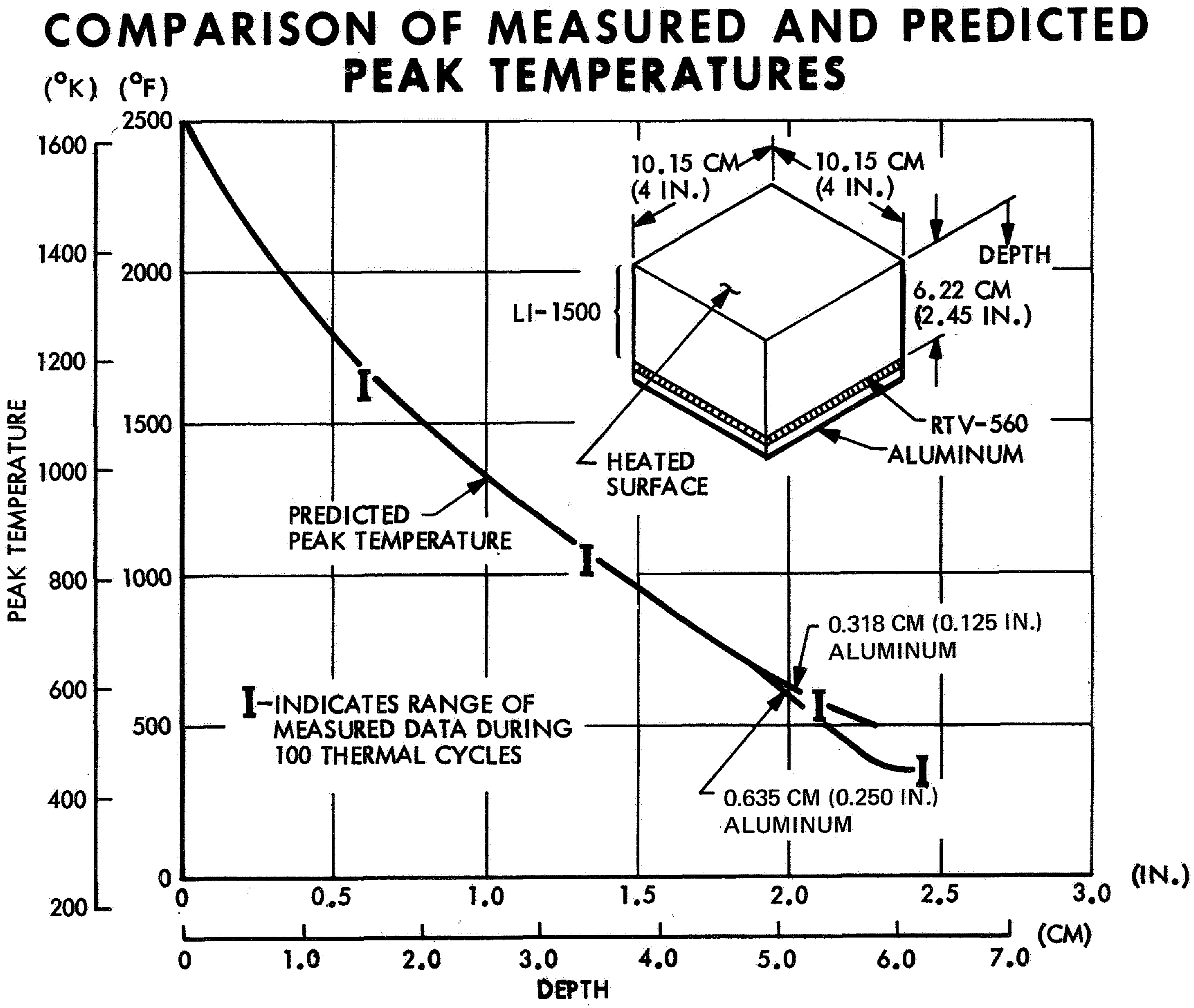

COMPARISON OF MEASURED AND PREDICTED PEAK TEMPERATURES
(°K) (°F)
PEAK TEMPERATURE
1600
1400
1200
1000
800
600
400
200
2500
2000
1500
1000
500
0
10.15 CM (4 IN.)
10.15 CM (4 IN.)
DEPTH
6.22 CM (2.45 IN.)
LI-1500
RTV-560
ALUMINUM
HEATED SURFACE
PREDICTED PEAK TEMPERATURE
0.318 CM (0.125 IN.) ALUMINUM
I–INDICATES RANGE OF MEASURED DATA DURING 100 THERMAL CYCLES
0.635 CM (0.250 IN.) ALUMINUM
0
0.5
1.0
1.5
2.0
2.5
3.0
(IN.)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
(CM)
DEPTH

Figure 4

DESIGN CURVES SHOWING VARIATION OF LI-1500 THERMAL CONDUCTIVITY WITH TEMPERATURE AND PRESSURE

(Figure 5)

LI-1500 thermal conductivity interim design curves developed in late 1970 and reported in Ref. 3 are shown. The rapid increase in thermal conductivity at about 10 mm Hg is attributed to the increasing significance of the gaseous conduction portion of the apparent thermal conductivity. The use of an apparent thermal conductivity, which includes the effects of conduction along fibers, gaseous convection between fibers, and radiation between fibers, is justified for materials like silica, which have a very small fiber diameter (about 0.5 to 1.5 μ) and a corresponding large value for the scattering coefficient. This simplified approach allows use of the Fourier heat conduction law, which can be easily used with finite difference solutions to size the TPS and predict structural thermal response.

These thermal conductivity design curves were utilized along with the specific heat values listed in Ref. 3, Vol. I, for the temperature predictions shown in succeeding charts.

DESIGN CURVES SHOWING VARIATION OF LI-1500 THERMAL CONDUCTIVITY WITH TEMPERATURE AND PRESSURE

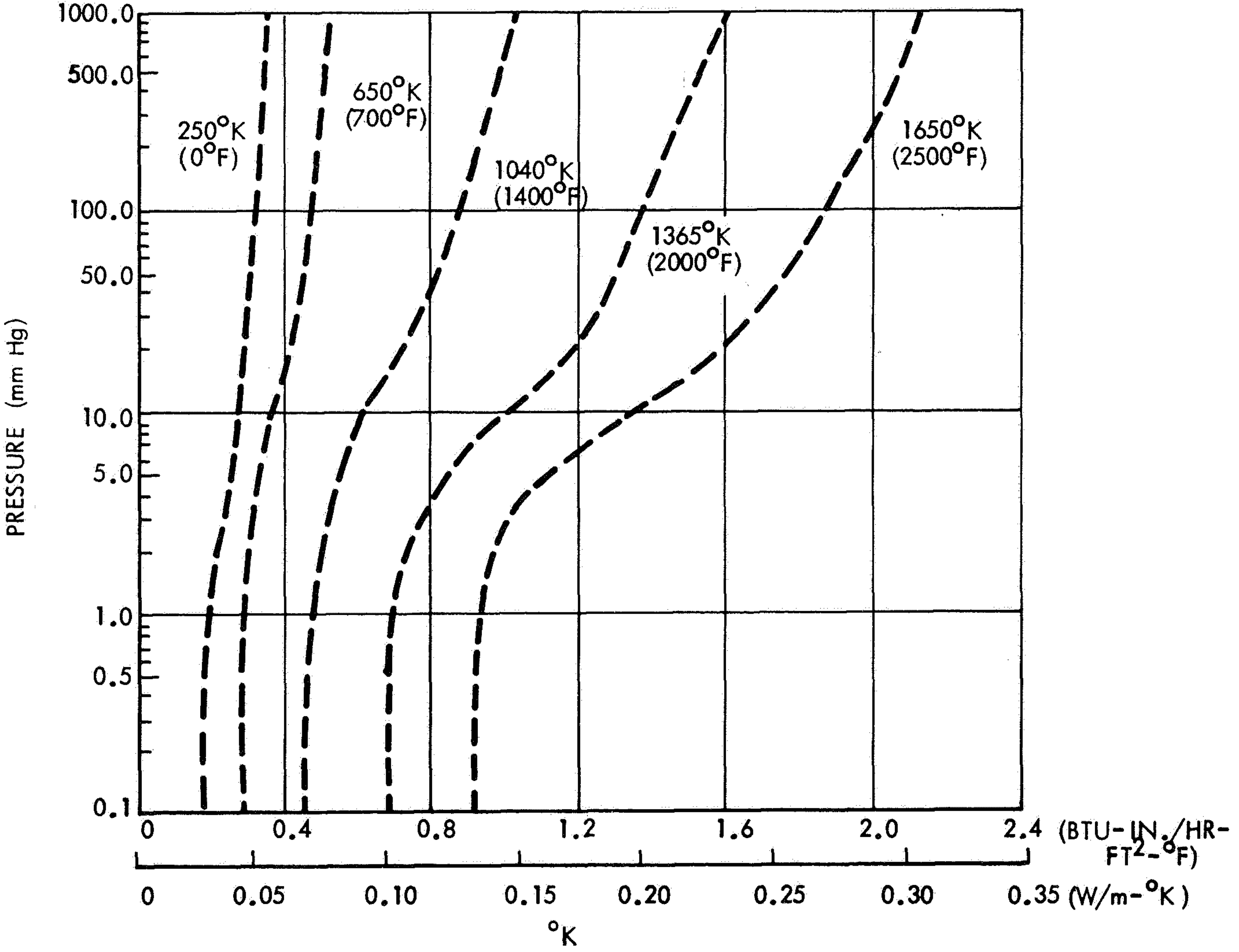


Figure 5

100-CYCLE TESTS

(Figure 6)

LMSC has been experimentally and analytically evaluating reduced density silica RSI (i.e., less than 240 kg/m^3 (15 lb/ft^3)) for several years. This work led to the introduction of LI-900, with a density of 144 kg/m^3 (9 lb/ft^3) during the recently completed Material Improvement Contract (NAS 9-12137).

The current Phase III Development Contract (NAS 9-12856) is providing more detailed characterization of this material.

To demonstrate reuse capability, two LI-900 samples with two LI-1500 standards were subjected to a 100-cycle test sequence at LMSC in October 1972. The samples were 12.7 x 12.7 x 5 cm (5 x 5 x 2 in.) bonded with 0.0254 cm (0.010 in.) of RTV 560 to an 0.0203 cm (0.080 in.) thick RL1973 foam pad, which was subsequently bonded with 0.0254 cm (0.010 in.) of RTV 560 to 0.317 cm (0.125 in.) to aluminum plates. All samples were coated on the top and 4.44 cm (1.75 in.) down the sides with the 0042 coating. The NAS 9-12856 reference heat pulse (Area 2P) was used for the test cycles.

100-CYCLE TESTS

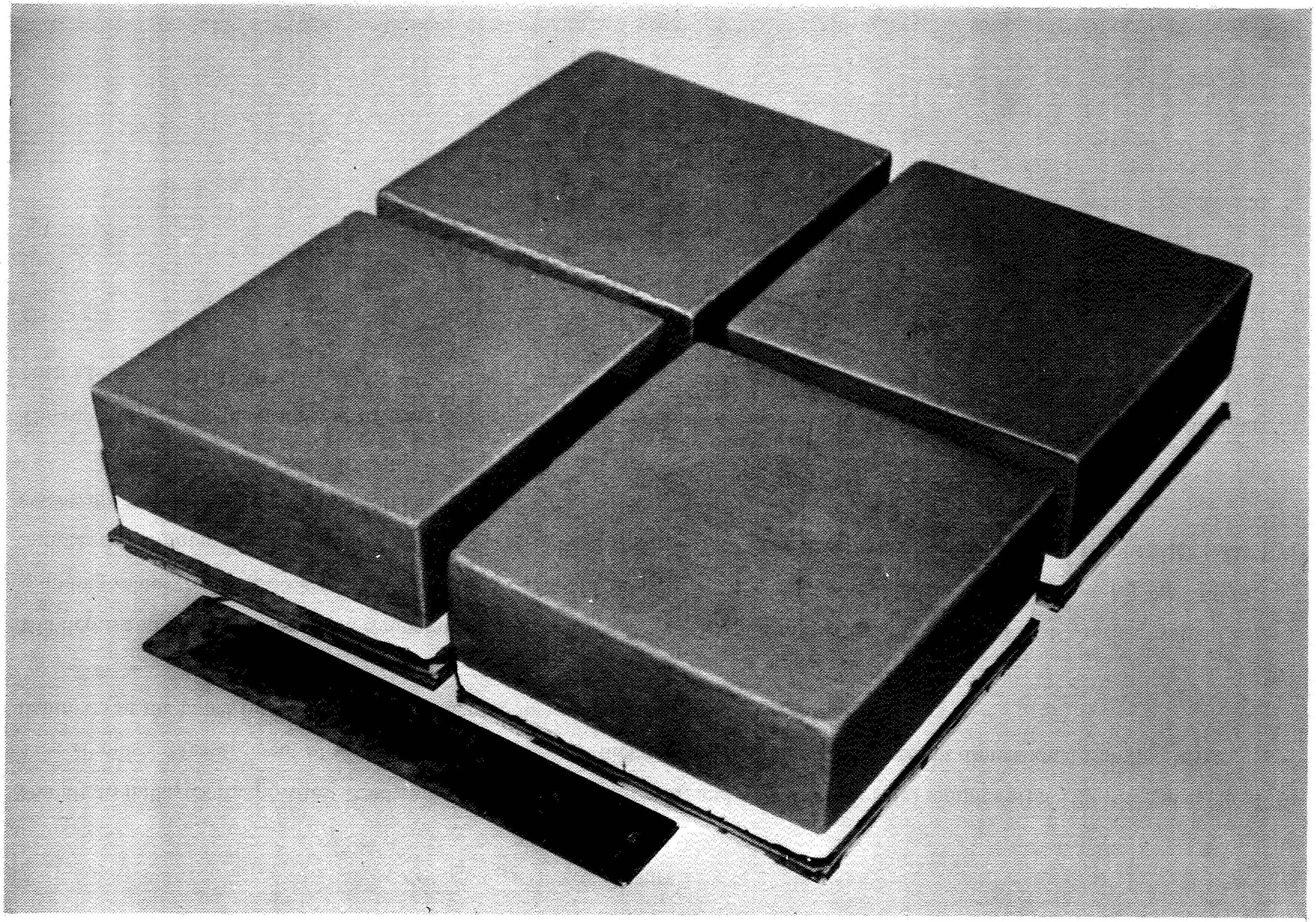


Figure 6

POST-TEST PHOTO OF LI-1500 AND LI-900

(Figure 7)

The photo indicates the post-test condition of the LI-900 (right side) and LI-1500 (left side) samples after 100 thermal cycle of the Area 2P pulse. Measurement of sample length, width, and thickness for tiles indicated excellent dimensional stability. (See Figure 25 in the paper by K. J. Forsberg presented in Volume III of these Proceedings.)

Mid-depth and backface maximum temperatures for the LI-900 were 1015°K (1370°F) and 489°K (420°F), respectively. Corresponding values for LI-1500 were 921°K (1200°F) and 472°K (390°F). The moderate increase in temperature for the LI-900 samples is attributed primarily to the lower heat capacity of this material, since the thermal conductivity up to 1143°K (1600°F) is essentially the same as that of LI-1500 (see Figure 8).

The repeatability of the measured temperatures over the 100 cycles demonstrates the consistent thermal performance capability of both LI-900 and LI-1500.

POST-TEST PHOTO OF LI-1500 AND LI-900

(100 CYCLES AT AREA 2 P HEATING – OCTOBER 1972)

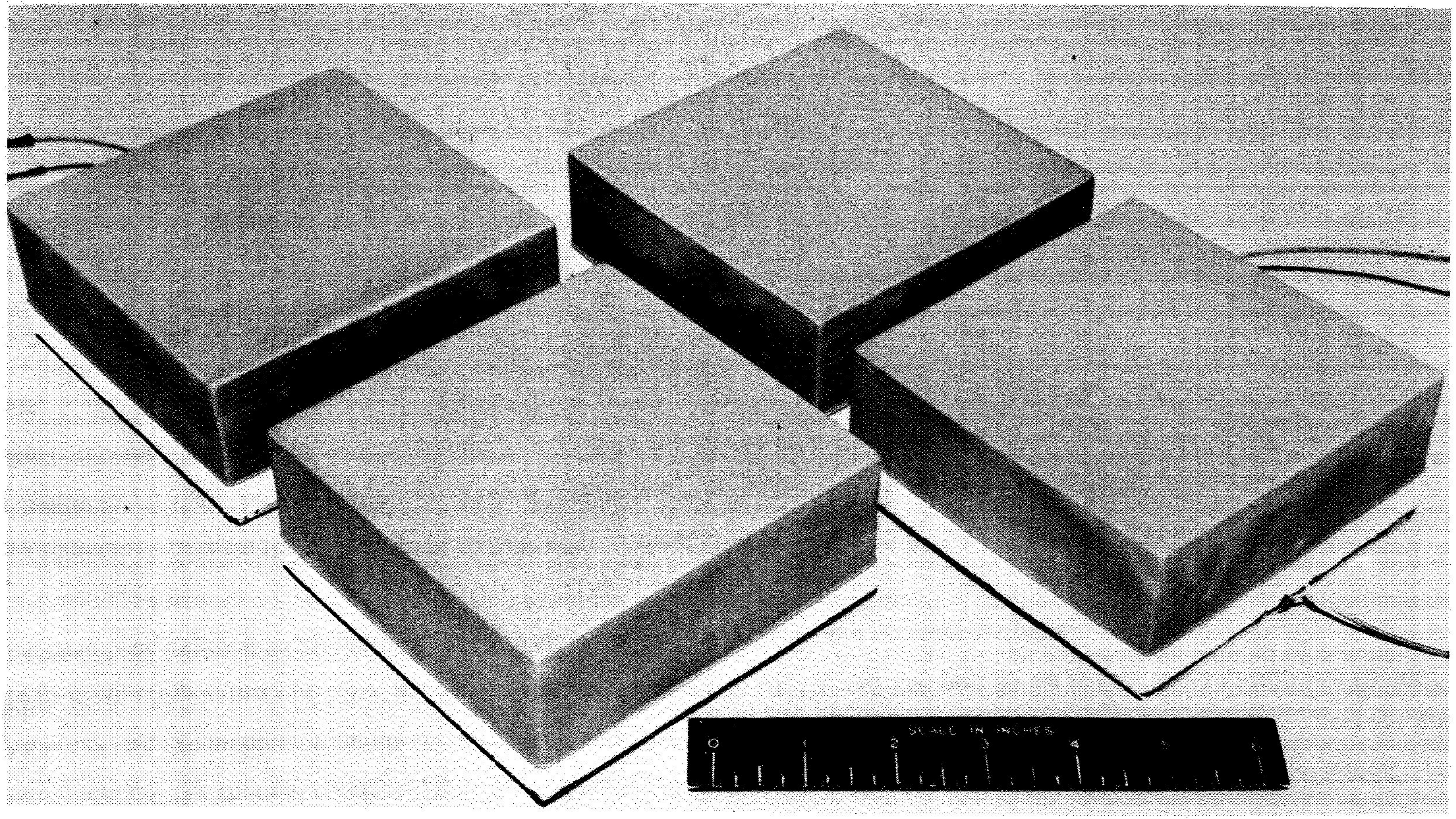


Figure 7

LI-900 CONDUCTIVITY DATA

(Figure 8)

Measurements of the thermal conductivity of LI-900 are being performed under the Phase III TPS Contract from NASA/MSC (NAS 9-12856). These measurements are currently being performed using a Dynatech 17.8 and 20.3 cm (7 and 8 in.) guarded hot plate to mean temperatures of 1367°K (2000°F) and pressures of 1, 10, 50, and 760 mm Hg on as-fabricated LI-900 and LI-900, which have been exposed to 20 thermal cycles of the Area 2P temperature and pressure histories.

Measurements to date on the as-fabricated LI-900 when compared to the LI-1500 design curves (Ref. 3) indicate the LI-900 values are slightly lower than the LI-1500 design curve at low pressures and slightly higher than LI-1500 design curve at 760 mm Hg (1 atm) pressure. The differences between the LI-900 data and the LI-1500 design curves are within the uncertainty of the measurements.

LI-900 CONDUCTIVITY DATA

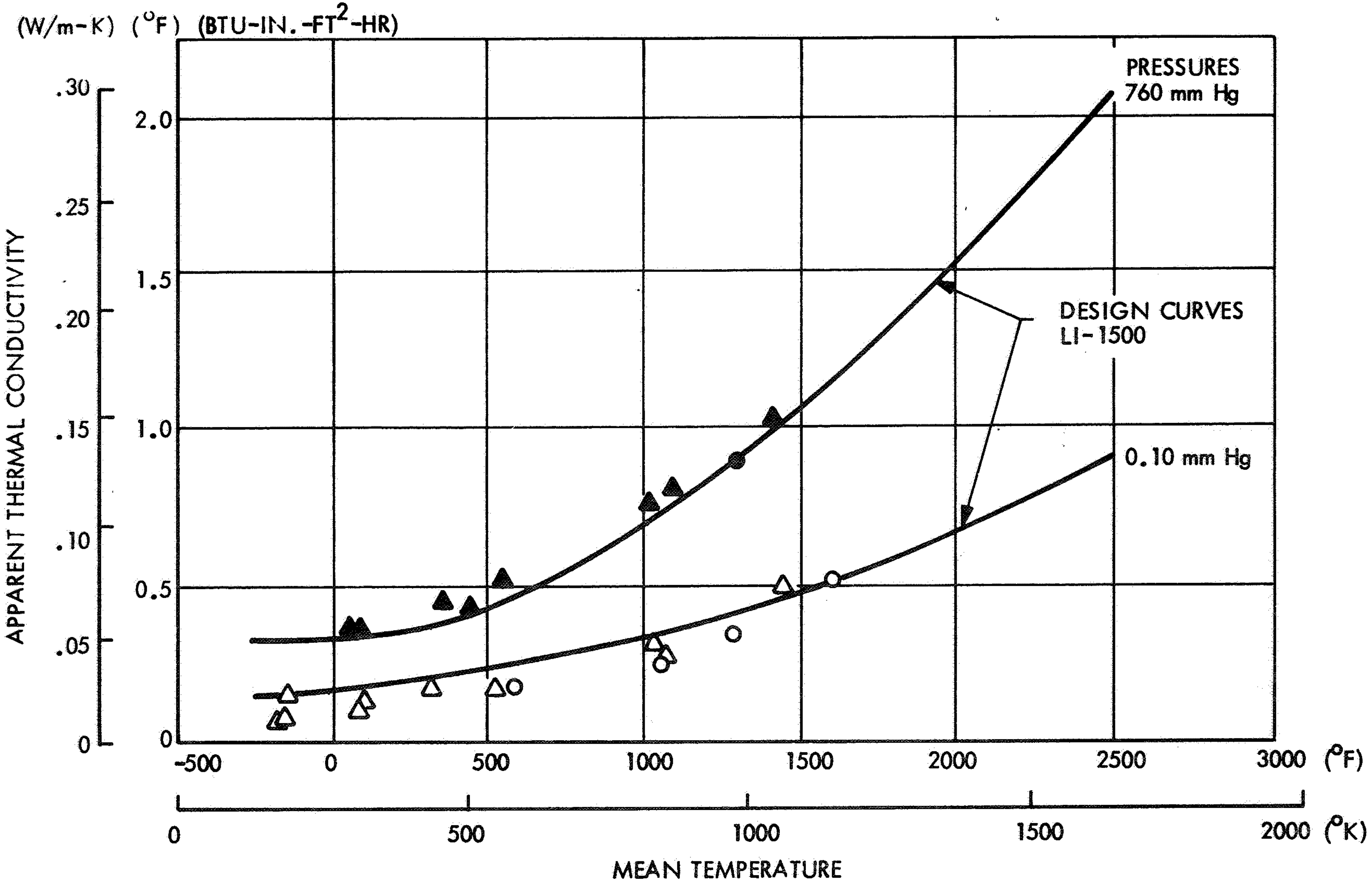


Figure 8

PREDICTABLE THERMAL PERFORMANCE

(Figure 9)

A realistic weight for the Orbiter TPS must be known as early as possible in the Shuttle Program, since it affects both program cost and orbiter weight growth. TPS weight is a direct function of the assumed variation of thermal conductivity with both pressure and temperature. The test results presented in this chart were performed by NASA/ARC personnel in their 2-MW arc-plasma facility with LI-1500 specimens supplied under the Phase II TPS development contract. A 10 cm dia. x 5 cm (4 in. dia. x 2 in.) thick LI-1500 sample (cut from the TT 70-3) coated on the top with 0042 coating was placed in a 20.3 cm (8 in.) dia flat face cylindrical model holder. The test procedure and results are discussed in the paper by D. A. Stewart also presented in this Volume of the Proceedings.

The predictions were based on a one-dimensional thermal model and an adiabatic backface, as will be all predictions shown in succeeding charts. Good agreement between predicted and measured temperature is shown and indicates that the low pressure LI-1500 thermal conductivity design values are slightly conservative but sufficient for TPS sizing purposes.

PREDICTABLE THERMAL PERFORMANCE

TEST PERFORMED IN NASA/ARC ARC-PLASMA FACILITY – RUN 16

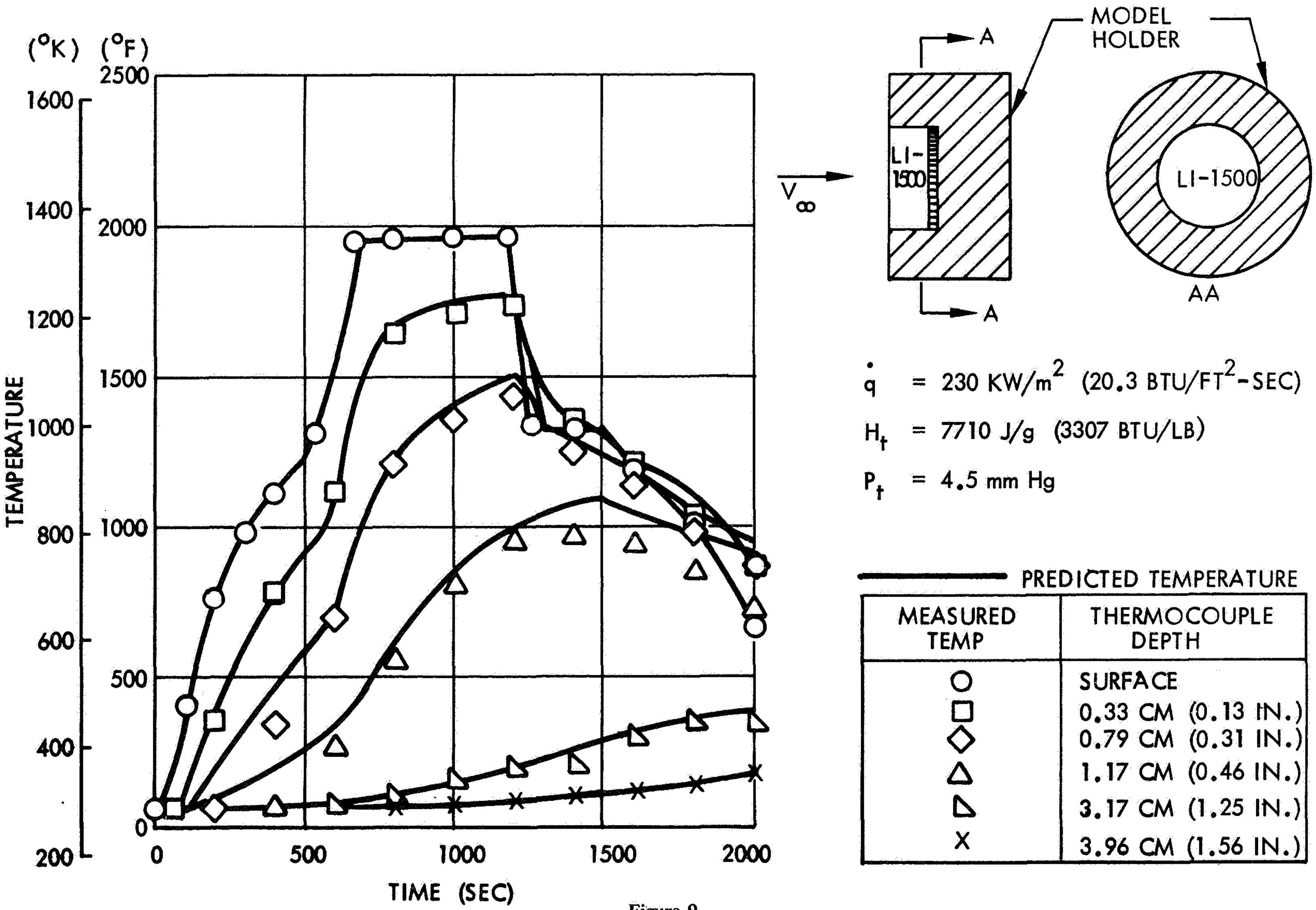


Figure 9

0042 COATING IS WATERPROOF AFTER NASA-ARC TESTS

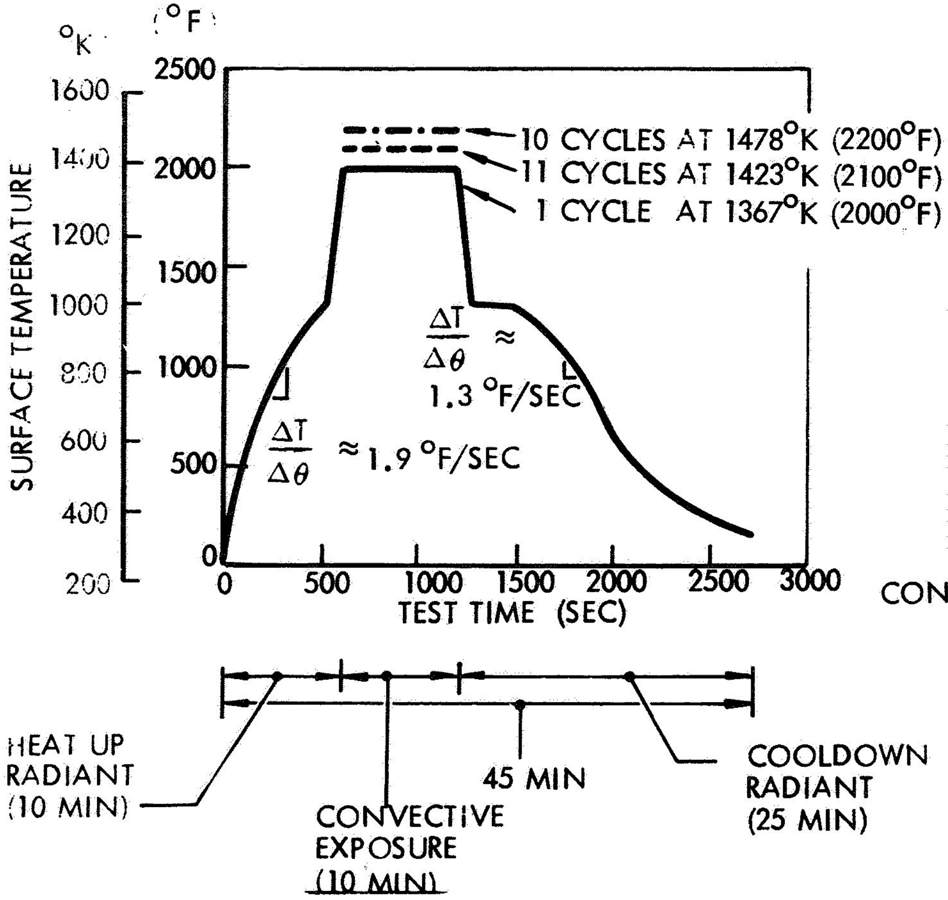
(Figure 10)

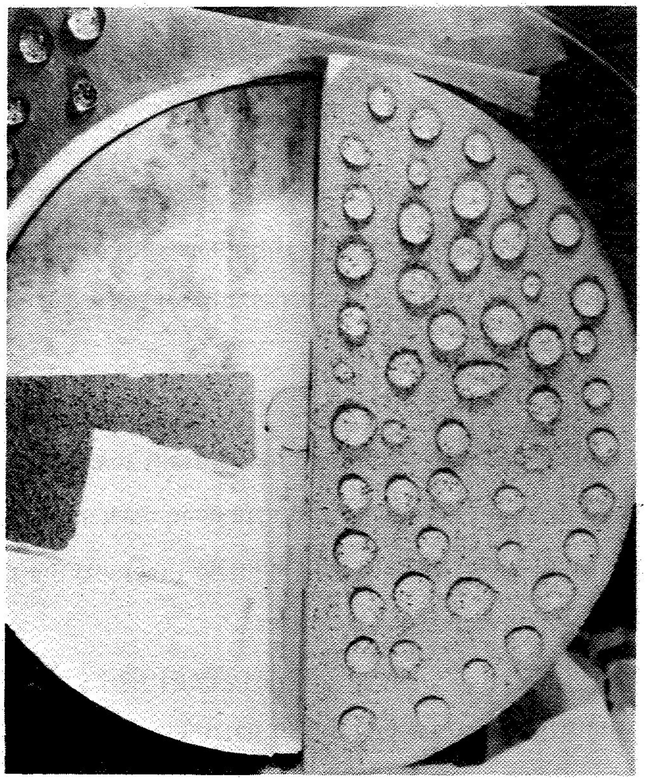
The surface temperature history for the previous chart is depicted here along with a photo of the LI-1500 sample after it was exposed to a total of 22 cycles in the NASA-ARC 2-MW facility. As shown, the test consisted of both radiant and convective heating to simulate an Area 2 entry heat pulse. The heatup rate of 1.05°K/sec (1.9°F/sec) and cooldown rate of 6.5°K/sec (1.3°F) are listed for comparison purposes with the Area 2 rates, which were 2.5°K/sec (4.5°F) for heatup and about 1.05°K/sec for cooldown. Further tests in both arc-plasma and radiant facilities should attempt to bound the thermal shock parameter to determine the thermal shock sensitivity of all RSI candidate materials. This can be accomplished by exposing RSI samples to a range of heatup rates that are representative of entries from all anticipated shuttle orbits. Preliminary estimates indicate that these heatup rates, which depend on initial entry angle, entry angle of attack, boundary layer transition criteria, and turbulent heat transfer method, range from about 1.67°K/sec (3°F) to 3.9°K/sec (7°F) for a 185 km (100 nm) orbit to 5.5 - 8.3°K/sec (10 - 15°F) for a 310 or 580 km (270 or 500 nm) orbit.

A water drop test (where drops of tap water are placed on the 0042 surface coating for 45 minutes) was used to determine if the 0042 coating was waterproof. The results, as illustrated by the beaded water in the photo, indicate no surface cracks or water absorption after 22 thermal cycles. In terms of time at peak temperature for an Area 2 type entry pulse these tests were equivalent to 50 to 55 entries from 185 km (100 nm) orbits.

0042 COATING IS WATERPROOF AFTER NASA-ARC TESTS

DATA SOURCE: NASA-ARC 2.0 MW FACILITY
F. J. DeMERITTE STATUS REPORT 23 MAY 1972





CONCLUSION:

0042 COATING IS WATERPROOF AND DOES NOT CRACK AFTER;

1.83 HR AT T_{SUR} = 1423°K (2100°F)

OR

1.67 HR AT T_{SUR} = 1478°K (2200°F

50-55 EQUIVALENT FLIGHTS TO AREA 2 HEATING

Figure 10

RSI MATERIAL THERMAL PERFORMANCE

(Figure 11)

This figure presents the temperature distribution through samples of LI-1500, G.E. Mullite (MOD I), and MDAC HCF to illustrate the difference in thermal performance between Mullite and Silica. All materials were supplied to NASA/MSC under parallel Phase II RSI development contracts, which ended in January 1972. The samples are the same thickness and the data were taken from tests performed at NASA/ARC, Mountain View, California, in January 1972 and informally reported in the Space Shuttle Structures and Materials Working Group Monthly Status Report for February (15 Jan 1972 to 15 Feb 1972) 1972.

A comparison of measured and predicted temperatures for all materials is shown for 1000 seconds into the test. The shape of the temperature distribution through the Mullite indicates that steady-state conditions have been attained. The non-linear-temperature variation for LI-1500 (Silica) indicates a non-steady-state condition and hence a lower thermal conductivitiy. All predictions are based on the same boundary conditions and a one-dimensional thermal model.

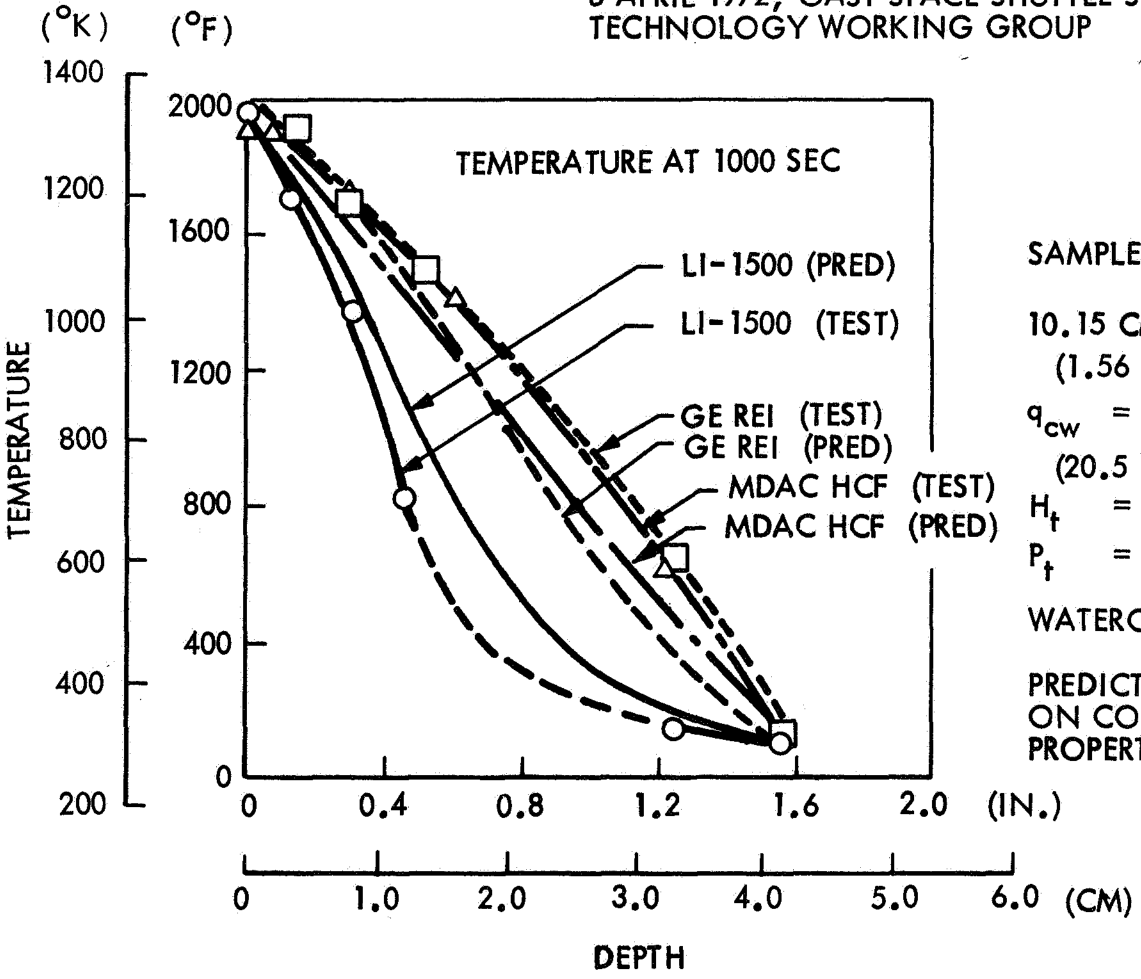
The comparisons indicate that the LI-1500 design thermal conductivity (Ref. 2 or 3) at low pressure is conservative, while the Mullite thermal conductivity design values (Ref. 4 and 5) are overly optimistic since the calculations predict lower temperatures than the measured data.

RSI MATERIAL THERMAL PERFORMANCE

COMPARISON OF MEASURED AND PREDICTED TEMPERATURES DURING PLASMA ARC TESTS

TESTS WERE PERFORMED IN NASA AMES RESEARCH CENTER 3 MW PLASMA ARC FACILITY

REFERENCE: MONTHLY STATUS REPORT FOR FEBRUARY (15 JAN 1972 TO 15 FEB 1972), 3 APRIL 1972, OAST SPACE SHUTTLE STRUCTURES AND MATERIALS TECHNOLOGY WORKING GROUP



SAMPLE SIZE:

10.15 CM (4 IN.) DIA × 3.96 CM (1.56 IN.) THICK

q_{cw} = 23.3 W/CM^2-SEC (20.5 BTU/FT^2-SEC)

H_t = 7700 J/g (3300 BTU/LB)

P_t = 4.6 mm Hg

WATERCOOLED BACKFACE

PREDICTED VALUES BASED ON CONTRACTOR MATERIAL PROPERTIES

Figure 11

042 COATING IS WATERPROOF AFTER NASA-MSC TESTS

(Figure 12)

Arc-plasma tests were also performed by NASA/MSC on LI-1500 samples delivered under the Phase II Development Contract (Ref. 2). These tests were performed in their 1.5-MW facility in May through June 1972 (Personal communication with D. J. Tillian discussing an internal NASA/MSC Memo by R. E. Vale). The 10 cm (4 in.) diameter sample was placed in a 12.7 cm (5 in.) dia water-cooled copper holder and tested in a stagnation flow attitude to a heat rate 25 W/cm^2 (22 Btu/ft^2 -sec), and a surface pressure of about 1.6 mm Hg. The sample (TT67-2A) was exposed to a pulse consisting of both radiant and convective heating to simulate Area 2P heating. The sample was precooled to 116°K (-250°F) with LN$_2$ and then exposed to peak surface temperature of about 1553°K (2340°F) over a 50 min interval. The sample was exposed to 35 cycles of the pulse shown in the chart. After exposure the sample was cut into three segments with the one shown here provided to LMSC for post test analysis.

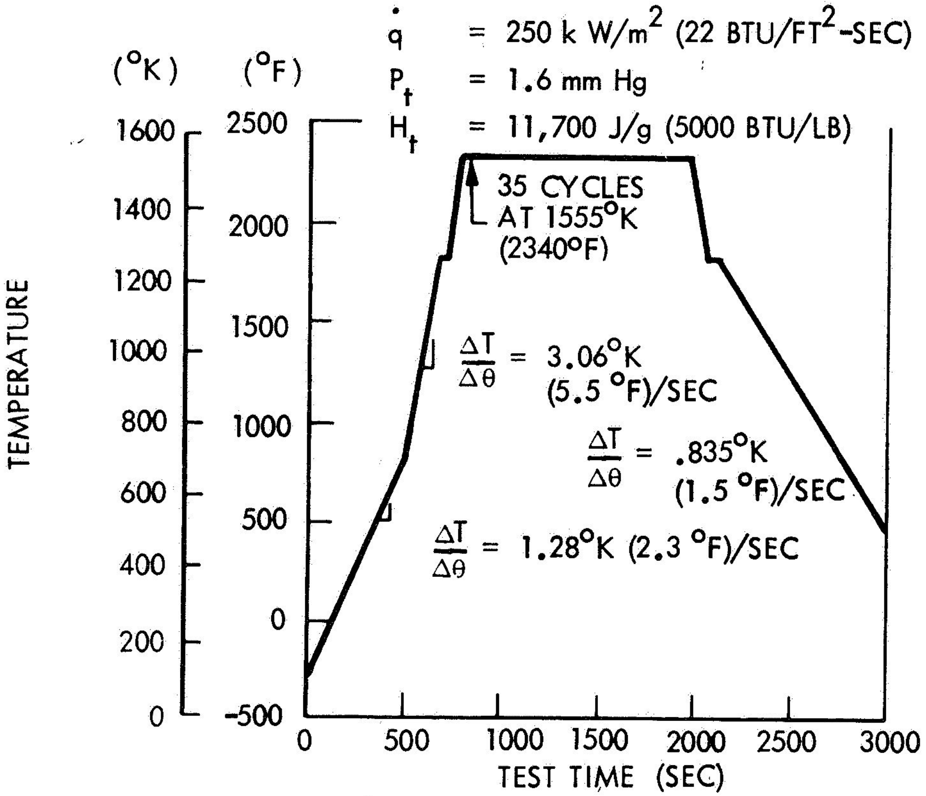
A simple water drop test was used to determine the waterproof nature of the coating after the test. While the water wetted the surface in some areas and beaded (water drops) in others, it did not work into the material. Hence, the coating was considered waterproof with no apparent cracks after 35 thermal cycles..

Similar results were reported by Battelle (Ref. 6), where they indicated the LMSC, MDAC, and GE surface coatings spread water easily after exposure to heat treatment but it did not work into the surface coatings. However, the mullite material after heat treatment rapidly absorbed water while the silica material resisted water absorption.

In terms of time at peak temperature (11.6 cumulative hours at 1553°K) (2340°F), the 35 test cycles correspond to 336 equivalent entries from a 100 nm orbit using an Area 2P peak temperature of 1533°K (2300°F).

0042 COATING IS WATERPROOF AFTER NASA-MSC TESTS

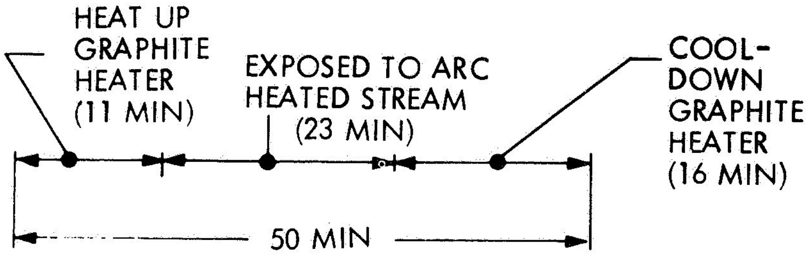
DATA SOURCE: NASA-MSC 1.5 MW FACILITY
R. E. VALE MEMO 27 JUL 1972

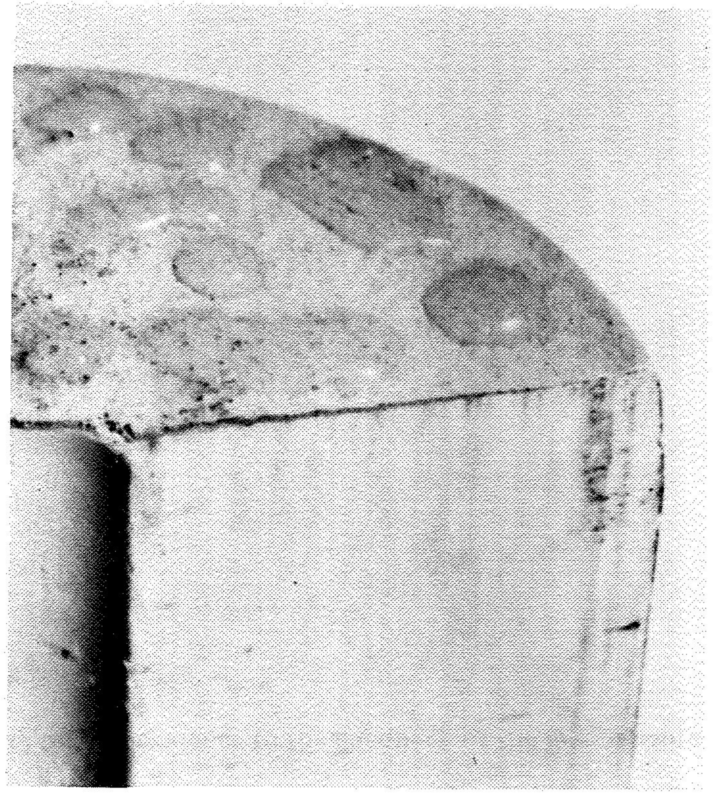


$\dot{q}$ = 250 k W/m^2 (22 BTU/FT^2-SEC)

P_t = 1.6 mm Hg

H_t = 11,700 J/g (5000 BTU/LB)





CONCLUSION:

0042 COATING IS WATERPROOF AND DOES NOT CRACK AFTER,

11.6 HR AT T_{SUR} = 1555°K (2340°F)

OR

350 EQUIVALENT FLIGHTS TO AREA 2P HEATING

Figure 12

PREDICTABLE THERMAL RESPONSE

(Figure 13)

This chart presents a comparison of predicted and measured temperature for one cycle of the 35 cycles in Figure 12. The LI-1500 sample 10 cm dia x 5 cm thick (4 in. x 2 in.) was instrumented in-depth with 10 thermocouples, six on the centerline and four 3.17 cm (1.25 in.) off the centerline. The six centerline thermocouples were used for this comparison. A one-dimensional thermal model was used for the predictions, with the first in-depth thermocouple as the driving temperature and an adiabatic backface. Comparisons of the predicted and measured data indicate good agreement and supply further evidence to the adequacy of the low-pressure thermal conductivity design values discussed earlier.

PREDICTABLE THERMAL RESPONSE

TEST PERFORMED BY NASA/ARC IN 5.08 x 20.32 CM (2 x 8 IN.) TURBULENT DUCT — RUN 11

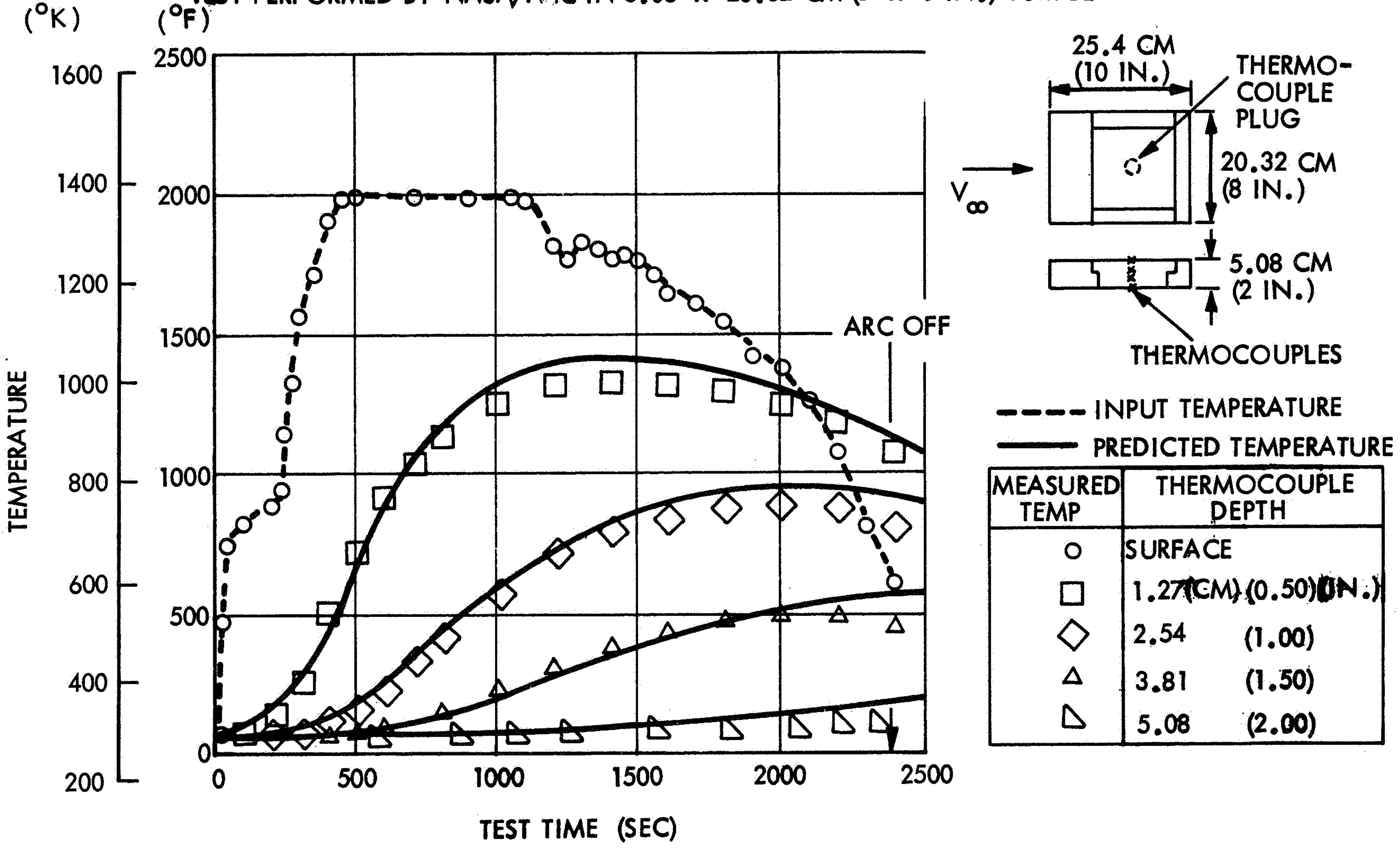


Figure 13

PREDICTABLE THERMAL RESPONSE

(Figure 14)

In addition to the stagnation flow tests of LI-1500 performed at NASA/ARC and NASA/MSC, F. J. Centalanzi et al. (Section 14 of this Volume) discussed results obtained when 20.3 x 25.4 cm (8 x 10 in.) RSI models consisting of a 15.2 x 15.2 x 5 cm (6 x 6 x 2 in.) tiles surrounded by various guard tiles were exposed to a high energy 11,700 J/g (5000 Btu/lb) high shear 13,790 N/m^2 (~2 psi) turbulent boundary layer. A test of this type is more representative of Shuttle Orbiter conditions during entry, since most of the heating may occur in a turbulent boundary layer.

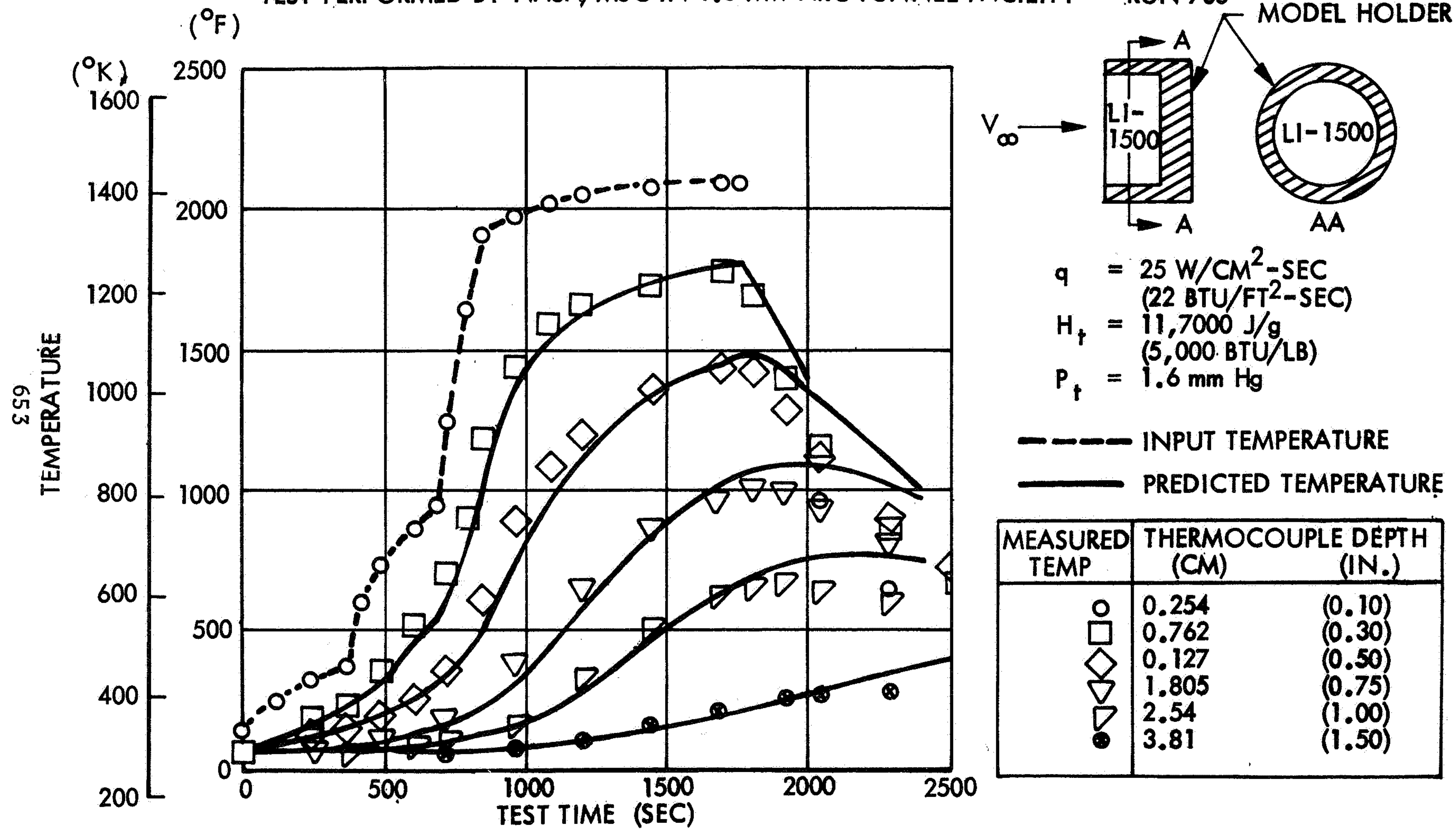
The LI-1500 model (a deliverable discussed in Ref. 2) was instrumented in the gaps between tiles and in the center of the 15.2 x 15.2 x 5 cm (6 x 6 x 2 in.) tile. This run simulated an Area 2 heat pulse with a peak surface temperature of 1367°K (2000°F). The surface pressure varied from 6 to 55 mm Hg. The prediction used bivariant interpolation to determine the appropriate thermal conductivity values as a function of pressure and temperature. The pressure within the LI-1500 was assumed equal to the surface pressure.

The predicted and measured data show good agreement and indicate that the LI-1500 design values are conservative and resulting weight predictions using these values for the Shuttle Orbiter may be slightly high.

These tests also provided some unanticipated gap/step heating results in that local melting of a downstream LI-1500 closure strip occurred in the vicinity of a tee-slot. The closure strip resulted in a 50-mil forward facing step. Based on correlations of wind tunnel and flight heating data, the closure strip experienced a peak heating rate of at least 3.5 times the undisturbed value, which produced a temperature greater than 1925°K (3000°F). This situation is not expected to occur in flight because of constraints on the allowable forward facing steps and larger turbulent boundary layer thicknesses.

PREDICTABLE THERMAL RESPONSE

TEST PERFORMED BY NASA/MSC IN 1.5 MW ARC TUNNEL FACILITY – RUN 703



q = 25 W/CM^2-SEC
(22 BTU/FT^2-SEC)
H_t = 11,7000 J/g
(5,000 BTU/LB)
P_t = 1.6 mm Hg

– – – – INPUT TEMPERATURE
—— PREDICTED TEMPERATURE

MEASURED TEMP	THERMOCOUPLE DEPTH (CM)	(IN.)
○	0.254	(0.10)
□	0.762	(0.30)
◇	0.127	(0.50)
▽	1.805	(0.75)
◸	2.54	(1.00)
⊗	3.81	(1.50)

Figure 14

PROTOTYPE PANEL THERMAL RESPONSE

(Figure 15)

To verify the adequacy of various competitor RSI designs for the Shuttle Orbiter, NASA/MSC under the Phase II contracts had GE, LMSC, and MDAC supply full-scale prototype panels with RSI attached. The panels were 60.8 x 60.8 cm (2 x 2 ft) and had a sufficient amount of RSI material to limit the maximum panel temperature to 420°F (300°F) during exposure to a simulated Area 2P entry temperature and pressure history. G. Strouhal and D. J. Tillian (Section 27 of these Proceedings) present a more thorough history of the RSI development contracts and NASA requirements for the Orbiter Thermal Protection System.

The results discussed here are for LMSC Area 2P Aluminum Panel (TT62). The panel contained 24 LI-1500 tiles bonded with about 0.24 to 0.40 cm of RTV-560 adhesive to the aluminum. All tiles were 6.4 cm thick, 8 had surface dimensions of 15 x 15 cm, 8 were about 10 x 15 cm and 8 were about 5 x 15 cm. The panel was instrumented with 22 thermocouples – 4 below the surface of the 0042 coating, 3 in depth, and 15 on the aluminum panel. The gaps between tiles, which represent the LMSC joint filler strip design for the orbiter, were between 0.127 to 0.254 cm. The panel was tested in NASA/MSC radiant/vacuum facility.

As of November 1972, this panel has gone through 25 cycles of a simulated Area 2P environment. The thermal performance, as measured by the thermocouples, was repeatable within the uncertainty of the measurements. The panel has gone through 4 acoustic tests in NASA/MSC progressive wave facility of the Component Acoustic Laboratory. Each acoustic test had a duration of 150 sec, which is equivalent to 5 Shuttle liftoffs. An acoustic test was performed prior to thermal cycling, and after 5, 15, and 25 cycles. Although no visible damage was noted on the 0042 surface coating or the LI-1500 and no tiles were separated or fell off the panel, NDEs with acetalaldehyde performed prior to and after the acoustic tests indicated various micro-cracks in the 0042 coating (see Section 24 of these Proceedings). Hence, even though these microcracks were present, and in some cases propagated either during or subsequent to the thermal or acoustic cycles, the LI-1500 system performed satisfactorily in that no tiles were fractured.

Comparison of the predicted and measured temperature histories indicates that the LI-1500 design thermal conductivity curves are sufficient for TPS sizing where the pressure varies from 10^3 to 10^5 N/m^2 (10^{-2} to 1.0 atm) and the temperature varies from room temperature to 1535°K (2300°F). The temperature predictions were included in the Phase II final report (Ref. 2) dated 2 Jan 1972 and were verified by these test results in October through November 1972.

Additional thermal and acoustic tests were performed by NASA/MSC on a LMSCI titanium panel (TT69) with sixteen 15 x 15 x 3.4 cm (6 x 6 x 1.35 in.) LI-1500 tiles bonded with 0.24 to 0.40 cm (0.090 to 0.160 in.) of RTV-560 to the titanium. A total of ten Area 2P entry cycles and three acoustic tests were performed successfully on this panel. The temperature data were predictable and repeatable and no tiles were lost in the acoustic tests.

PROTOTYPE PANEL THERMAL RESPONSE

TESTS PERFORMED BY NASA/MSC IN RADIANT HEAT/VACUUM TEST FACILITY

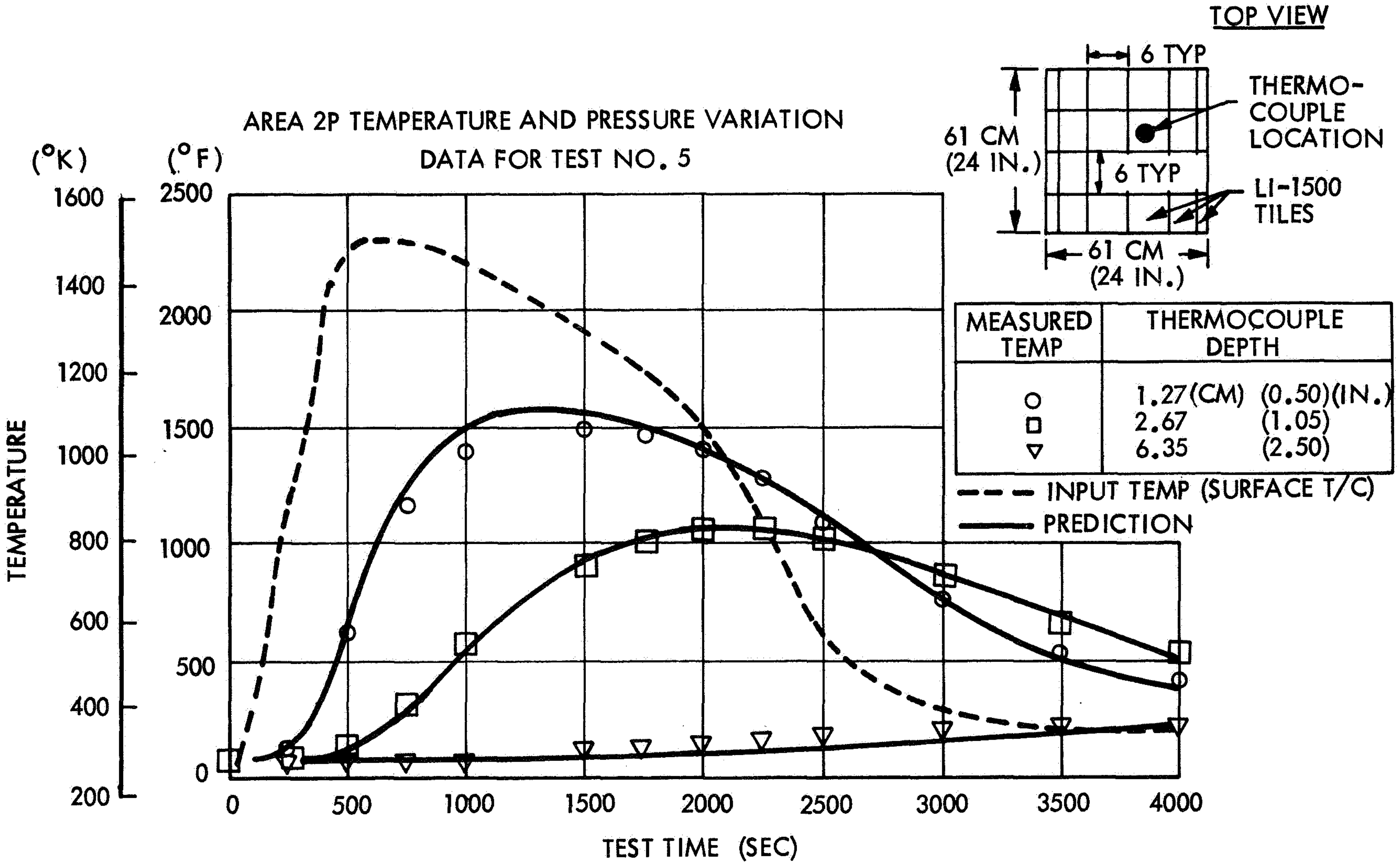


Figure 15

LI-1500 THERMAL CONDUCTIVITY COMPARISON

(Figure 16)

Comparisons of the LI-1500 design thermal conductivity at a pressure of 1.0 and 760 mm Hg are shown with conductivity values obtained by Dr. D. Curry of NASA/MSC. Dr. Curry and S. Williams in Ref. 7 discuss a nonlinear least-squares technique of "backing-out" thermal conductivity curves from transient test data. Data shown were taken from Ref. 7 and were obtained on LI-1500 samples manufactured in 1970 and tested at low pressure in NASA/MSC 1.5 MW plasma arc facility. One atmosphere pressure data were obtained from an LI-1500 sample (TT5C) tested at LMSC in November 1970. Additional thermal conductivity data, using the nonlinear least-squares technique, were obtained from the LI-1500 measured temperature data presented in Figure 13 (Personal communication with D. M. Curry on September 11, 1972).

At low pressure the conductivity values from the least-squares method are slightly lower than the LI-1500 design curves (Figure 5). At atmospheric pressure the values from the least squares method are higher than the design curve at low temperatures [73 percent at 255°K (0°F)] and slightly lower at high temperature [10 percent at 1366°K (2000°F)]. The high least-squares values from 255 to 978°K (0 to 1300°F) are questionable due to the good agreement with the aluminum panel measured temperature shown in Figure 15 and the titanium panel (TT69) and other comparisons for 10^5 N/m^2 (1 atm) pressure tests performed at NASA/MSC and LMSC. The comparisons between the least-squares values and the guarded hot plate values lend credibility to the nonlinear least-squares method of obtaining thermal conductivity from transient test data.

LI-1500 THERMAL CONDUCTIVITY COMPARISON

NONLINEAR LEAST SQUARES METHOD

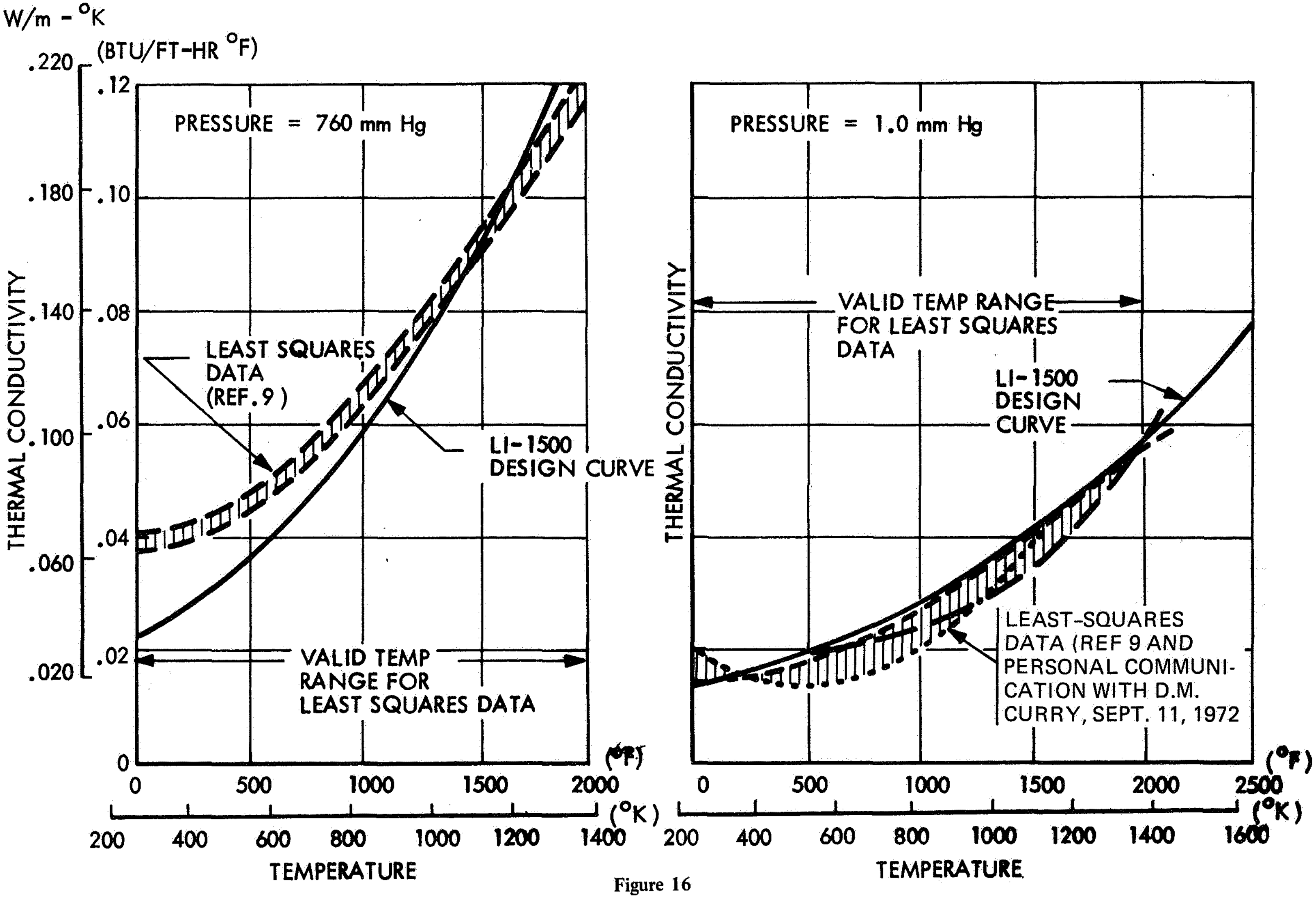


Figure 16

COMPARISON OF 0042 EMITTANCE DATA

(Figure 17)

Values for the total normal emittance of the 0042 coating from various sources computed from spectral reflectance data and emittance data are shown. The data exhibit a wide disparity in total normal emittance (values for total hemispherical emittance can be obtained from sources such as Jakob, Ref. 8). For a heat rate of 25 W/cm^2 (22 Btu/ft^2-sec), an emittance of 0.9 yields a surface temperature of about 1490°K (2220°F), using an emittance of 0.6, corresponding to the NASA/LaRC data, would yield a temperature of about 1640°K (2500°F). Hence a surface temperature difference of about 411°K (280°F) could exist if the uncertainty in coating emittance is similar to that shown on the chart.

The integrated LMSC and TRW spectral data yield a total emittance that varies little with temperature. The Langley data show total emittance decreasing with increasing temperature and with lower absolute values. Battelle data, based on a total radiometric measurement, are in reasonable agreement with the Langley data, and the Ames data fall in between. From the comments made in Figure 18 regarding temperature measurement, the Battelle and Langley data may both be in error for this coating because of true surface temperature measurement inaccuracies.

COMPARISON OF 0042 EMITTANCE DATA

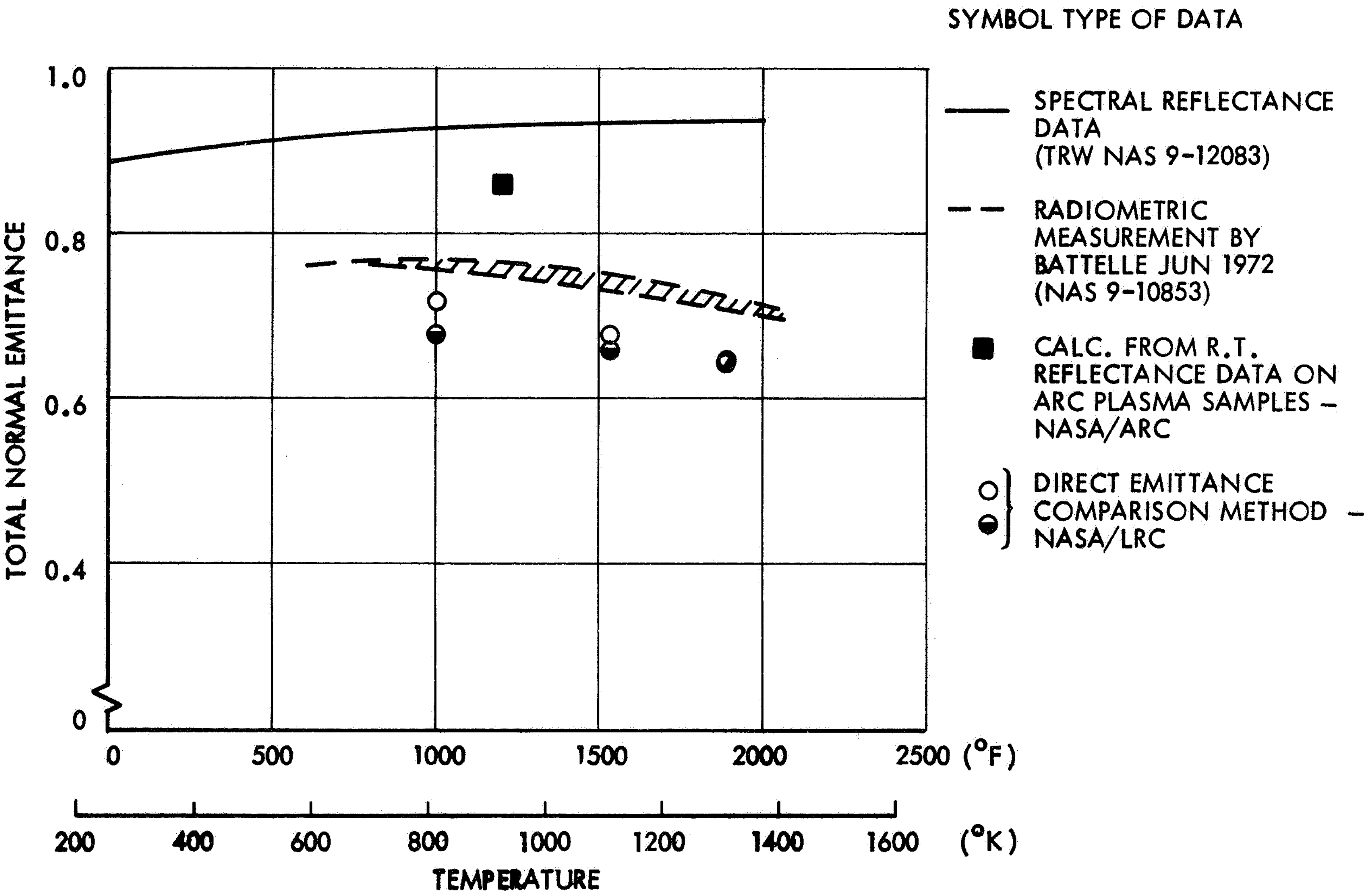


Figure 17

COMPARISON OF SPECTRAL NORMAL EMITTANCE

(Figure 18)

Spectral emittance data (in air) for the 0042 coating from several sources are shown. Direct measurements of spectral emittance were made by Langley using a comparison of radiances from the coating and a reference (standard or cavity) by the Furnace Enclosed Sample/Reference method (Ref. 9). Spectral emittance values are also shown that were computed from spectral reflectance measurements at LMSC and TRW. Emittance is inferred from reflectance data using the relationship $\epsilon_\lambda = (1 - \rho_\lambda)$ assuming the coating is opaque. This assumption was verified by the TRW measurements by using both a low reflectance oxidized metal (Inconel) and a high reflectance plantinum strip to back the sample. Measurements made at 1, 2.2, and 5μ with both backing surfaces were within 0.01 verifying that transparency is not a significant source of error in using the reflectance-emittance relationship.

The large discrepancies between the two sets of data can be attributed to (1) specimen differences, (2) measurement errors, or (3) a combination of both. As the LMSC data (reflectance) on the Langley specimen (sent to LMSC in July 1972) after emittance testing are essentially in agreement with both earlier LMSC measurements and the TRW data (Ref. 2, Vol. I, pp. 4-33), the specimen-to-specimen differences are considered to be minimal. Concerning measurement error, the coating was found to be opaque so the reflectance-emittance relationship is valid.

Sample emission is not a primary source of error in the TRW measurement method since for reflectance measurements temperature determination does not enter into the method other than to assign a temperature at which reflectance is measured. A primary source of measurement error for the direct emittance data (NASA/LRC) lies in the temperature measurement since the accuracy is strongly dependent on the accuracy to which surface temperature is known.

Using Plank's law the spectral emittance error can be expressed as:

$$\left.\frac{\Delta\epsilon_\lambda}{\epsilon_\lambda}\right._{T} = \frac{(e^{C_2/\lambda T} \; \frac{C_2}{\lambda T} \; \frac{\Delta T}{T}}{e^{C_2/\lambda T} - 1}$$

An estimate was made of the potential for surface temperature error in the Langley data by comparing their spectral data with the TRW data, and computing the temperature difference that would be required for both sets of data to agree. The following results show the magnitude of this temperature difference (ΔT) for two measurement temperatures.

ϵ_λ (μ)	T (^{o}K)	ΔT (^{o}K)	T (^{o}K)	ΔT (^{o}K)
3.5	1307	106	813	59
5.0	1307	110	813	56
8.0	1307	107	813	63
12.0	1307	93	813	68

From these consistent temperature differences at several wavelengths it appears that the actual surface temperatures for the Langley data are lower than their indicated temperatures, and it is suggested that they reevaluate the measurement procedure for surfaces placed on very low thermal diffusivity substrates.

COMPARISON OF SPECTRAL NORMAL EMITTANCE

LMSC–0042 COATING

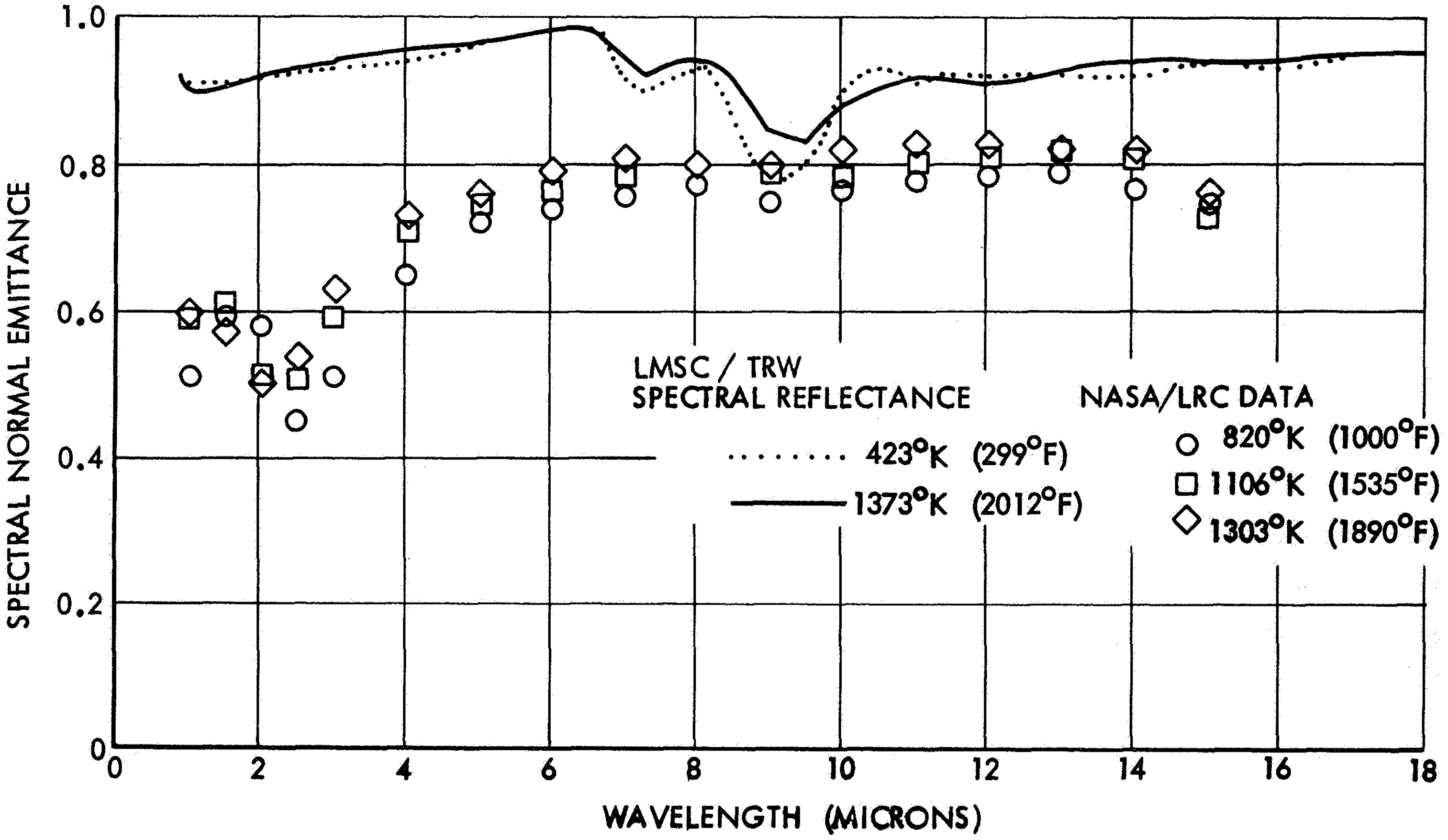


Figure 18

CONCLUSIONS – LMSC SILICA

(Figure 19)

Simulated reentry heating of the all-silica RSI under a variety of conditions including arc-jet and radiant lamp facilities for up to 100 simulated flight cycles has demonstrated consistent thermal performance capability. This consistency has been evident in testing of this material from 1967 to the present. Additionally, LMSC has successfully predicted (pre-test) this performance since 1967 on the basis of both LMSC and NASA-generated thermophysical material property data. This consistent predictability, along with the demonstrated coating integrity and dimensional stability to 1645°K (2500°F), serves to validate the earlier LMSC selection of the all-silica material for the RSI application.

This consistent predictable performance provides the confidence base for designing an Orbiter Thermal Protection System with the all-silica RSI.

CONCLUSIONS — LMSC SILICA

MULTICYCLE REENTRY HEATING TESTS HAVE DEMONSTRATED:

- CONSISTENT THERMAL PERFORMANCE CAPABILITY
- PREDICTABLE THERMAL PERFORMANCE BASED ON NASA GENERATED DATA
- COATING INTEGRITY
- DIMENSIONAL STABILITY TO 1648°K (2500°F)

Figure 19

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