NASA Contractor Report 159367

Thermal Conductivity of René 41 Honeycomb Panels

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V. Deriugin

Boeing Aerospace Company

Seattle, Washington

Contract NAS1-14213
DECEMBER 1980

NASA

National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

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FOREWORD

This report presents the results of a program designed to obtain effective thermal conductivity data on Rene'41 honeycomb panels carried out by the Boeing Aerospace Company under Contract NAS1-14213 from August 1979 through February 1981. The NASA contract monitor was John L. Shideler of NASA Langley Research Center, Loads and Aeroelasticity Division, Thermal Structures Branch.

The work was performed by the Advanced Space Transportation organization of the Boeing Aerospace Company at its Kent Space Center. The cryogenic testing was accomplished at the Wyle Laboratories, NORCO, California.

Study manager was Mr. V. Deriugin under the administration of Mr. A. K. Hepler.

The elevated temperature tests were conducted using the Boeing Aerospace Company Materials and Processes Laboratory Heat Flow Meter and the comparative Thermal Conductivity Instrument under the direction of Dr. M. Taylor who also provided the Rene'41 honeycomb panel thermal conductivity values at elevated temperatures.

The cryogenic specimens were redesigned by Mr. G. Dishman and fabricated by Mr. N. Munsey.

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SUMMARY

Effective thermal conductivities of Rene'41 panels were determined analytically and experimentally for temperature ranges between 20.4K ($-423^{o}F$) and 1186K ($1675^{o}F$). The cryogenic data were obtained using a cryostat whereas the high temperature data were obtained in a heat flow meter and a comparative thermal conductivity instrument. Comparisons between experimental data and analysis were developed. The cryogenic test (Wyle Laboratory) results indicated discrepancies between analysis and experimental data of a relative magnitude that was not found during the low and high temperature testing at Boeing. A rationale based on analysis is provided to resolve this discrepancy. Analytical methods appear to provide adequate definition of the honeycomb panel effective thermal conductivity. Additional tests for obtaining a broader design data base in both the low and the high temperature regimes are desirable.

INTRODUCTION

Thermal properties of structural components of advanced transportation systems undergoing rapid heating or cooling cycles directly affect the temperature distribution and the heat flow into a structure. Excessive transients and/or heat loads may result in unacceptable stresses and/or local temperatures adversely affecting payload capability and service life of a vehicle system. Requirements of additional thermal protection (insulation, heat sinking, etc.) usually lead to weight escalation and payload reduction.

Recent developments in advanced structural systems have demonstrated the advantages of honeycomb construction due to its capability of playing a triple functional role bridging thermal and structural disciplines, and at the same time providing lightweight structure (see for example Reference 1). The triple role consists of being an insulator (thermal protection) a fuel container (tank) and an integral structural part of a vehicle (body or wing).

Candidate aluminum brazed titanium honeycomb with a capability up to 1000°F has been designed and tested in the course of development of the SST (Supersonic Transport) vehicle yielding thermal property data including panel conductivities (Ref. 2). Such honeycomb panels can also be used on the upper portions and in the moderate heating areas of advanced space transportation systems such as the SSTO/RASV (Single Stage to Orbit/Reuseable Aerodynamic Space Vehicle). Areas of higher heating, like lower surfaces, require application of superalloys, such as Rene'41. Conductivities of Rene'41 honeycomb panels are required for accurate vehicle design. This program is designed to measure effective conductivities at both cryogenic and elevated surface temperatures covering the range between 20.4K (-423°F) and 1186K (1675°F). A cryostat was used for the cryogenic range, whereas a heat flow meter and a comparative thermal conductivity instrument yielded the data for elevated temperatures.

SYMBOLS

A	area
ΔA	cross-sectional area of conduction path through core material
$\frac{\rho_c}{\rho}$	solidity, $\frac{\Delta A}{A}$
d	cell diameter
e	thermopile output
$f(\lambda, \epsilon)$	view factor function
k	thermal conductivity
l	core height
P	power
Q	rate of heat transfer per unit area
s	sensitivity of heat flow meter
t	thickness
T	Temperature
ΔT	temperature difference
Δx	sample or reference material standard thickness
ϵ	emissivity
λ	ratio of core height to cell diameter, l/d
ρ	density of core material
ρ_c	core density
σ	Stefan-Boltzmann constant

SYMBOLS

<u>Subscripts:</u>

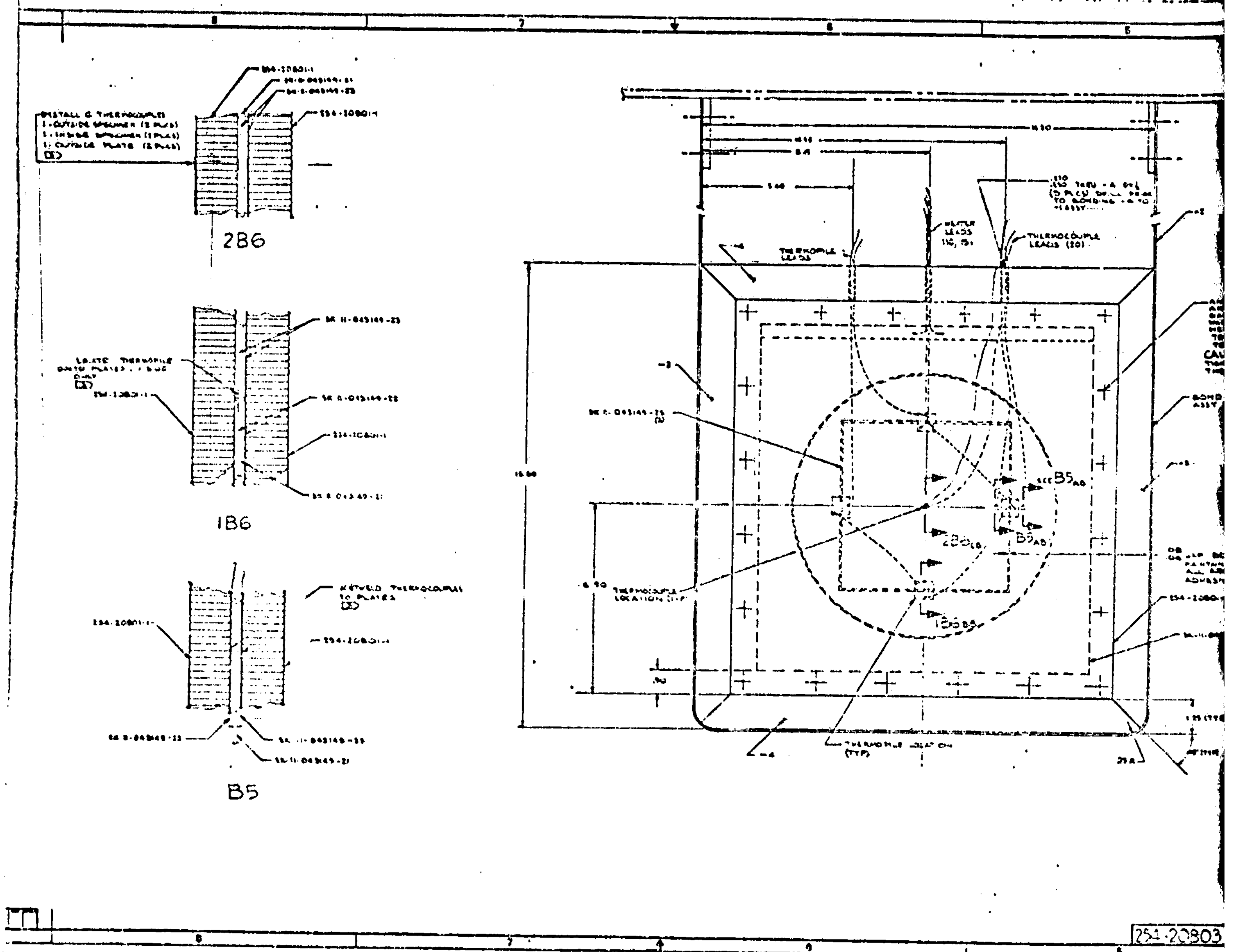
A	air
ave	average
C	cold face
c	core
F	face
H	hot face
M	metal
m	mean
Nom	nominal
R	radiant
T	test
MEAS	measured
PRED	predicted

THERMAL CONDUCTIVITY OF RENE'41 HONEYCOMB PANELS AT CRYOGENIC TEMPERATURES

This portion of the test was conducted at Wyle Laboratories, Norco, California using a Boeing built cryostat.

Test Specimens

Two test specimens were fabricated by Boeing with the intent of testing one specimen and having a second one as a backup. The test specimens consisted of two 350.52 X 363.22 X 30.48 mm (13.8 X 14.3 X 1.2 in.) Rene'41 honeycomb panels enclosing in sandwich fashion two 304.8 X 304.8 mm (12 X 12 inch) heaters and two aluminum heat distribution plates appropriately instrumented in order to be able to determine the temperature drop through the thickness of the honeycomb panels for deriving the respective effective conductivities of the panels from the known power input to the heaters. The specimen drawings are shown in Figure 1. The location and the numbers of the thermocouples are shown in Figures 2 and 3. Each of the heaters was an HR 1710 MINCO thermofoil etched circuit electric heater (Figure 4) with two separate electrical circuits. One circuit was for the test section which covered a 152.4 X 152.4 mm (6 X 6 inch) area at the center of the specimen. The other circuit was for a 152.4 mm (6 inch) wide guard section which surrounded the test section. The guard section had a 25.4 mm (1 inch) wide border region with a 10% higher watt density along the periphery as shown in Figure 4. The watt density of the heaters was rated at approximately 1.085 W/cm^2 ($7W/in^2$) with 100% overload capability. The honeycomb panels were bolted together along the periphery. A circular notch was cut into the inside faces of the honeycomb panels to prevent excessive bending and/or crushing of the honeycomb core due to the high temperature gradients. A



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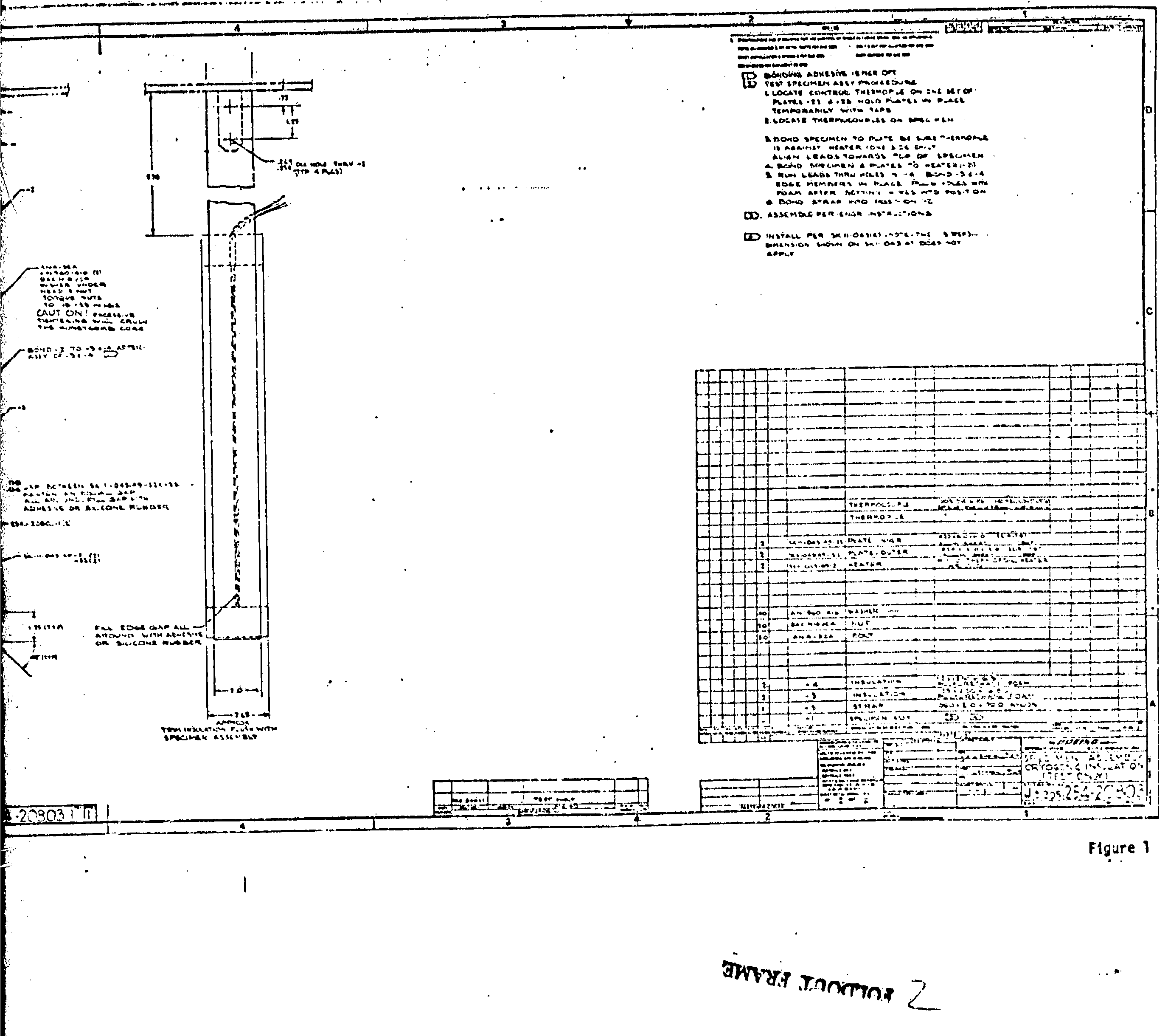

Figure 1

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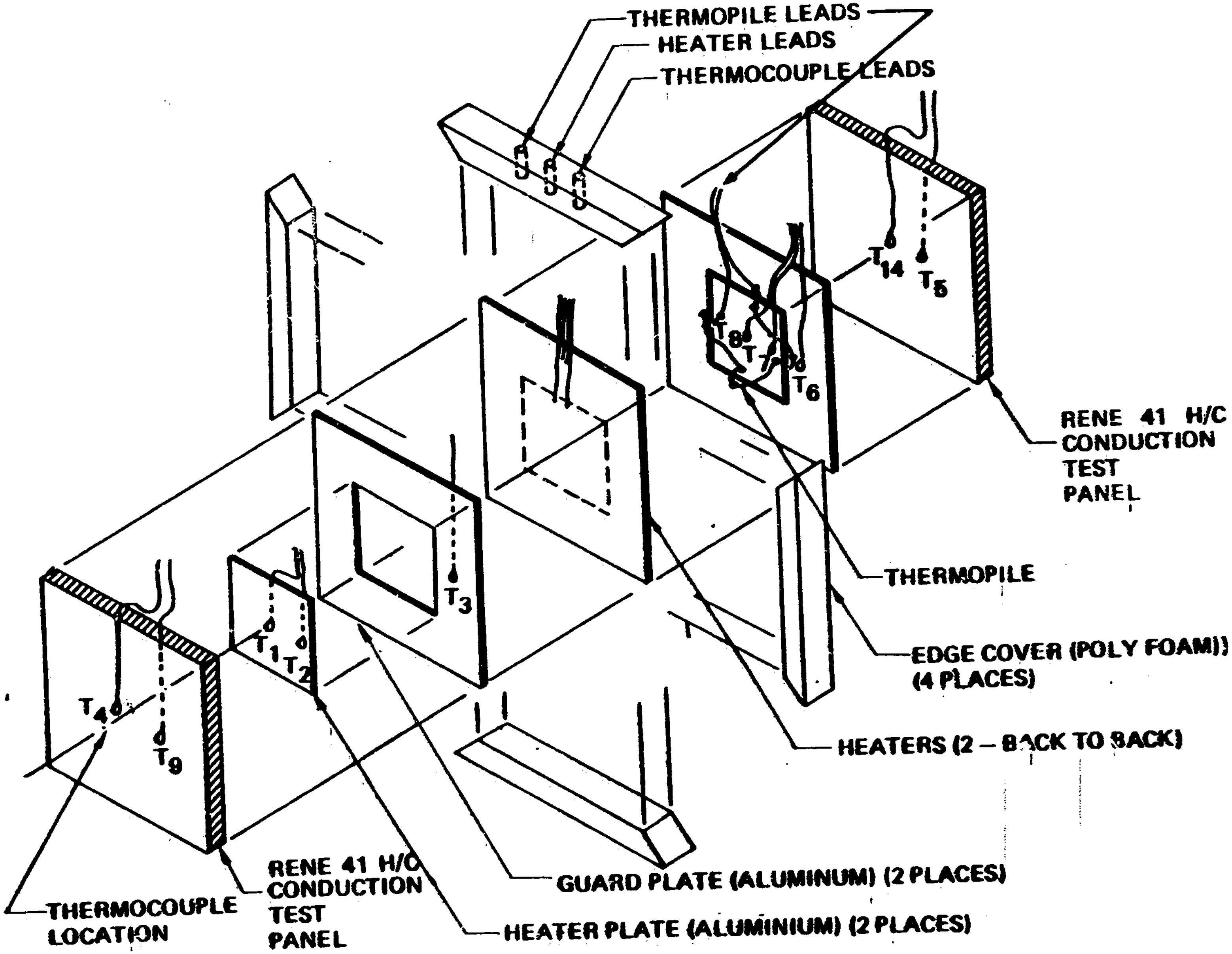

Figure 2: Test Specimen - Conduction Test Panel Assembly

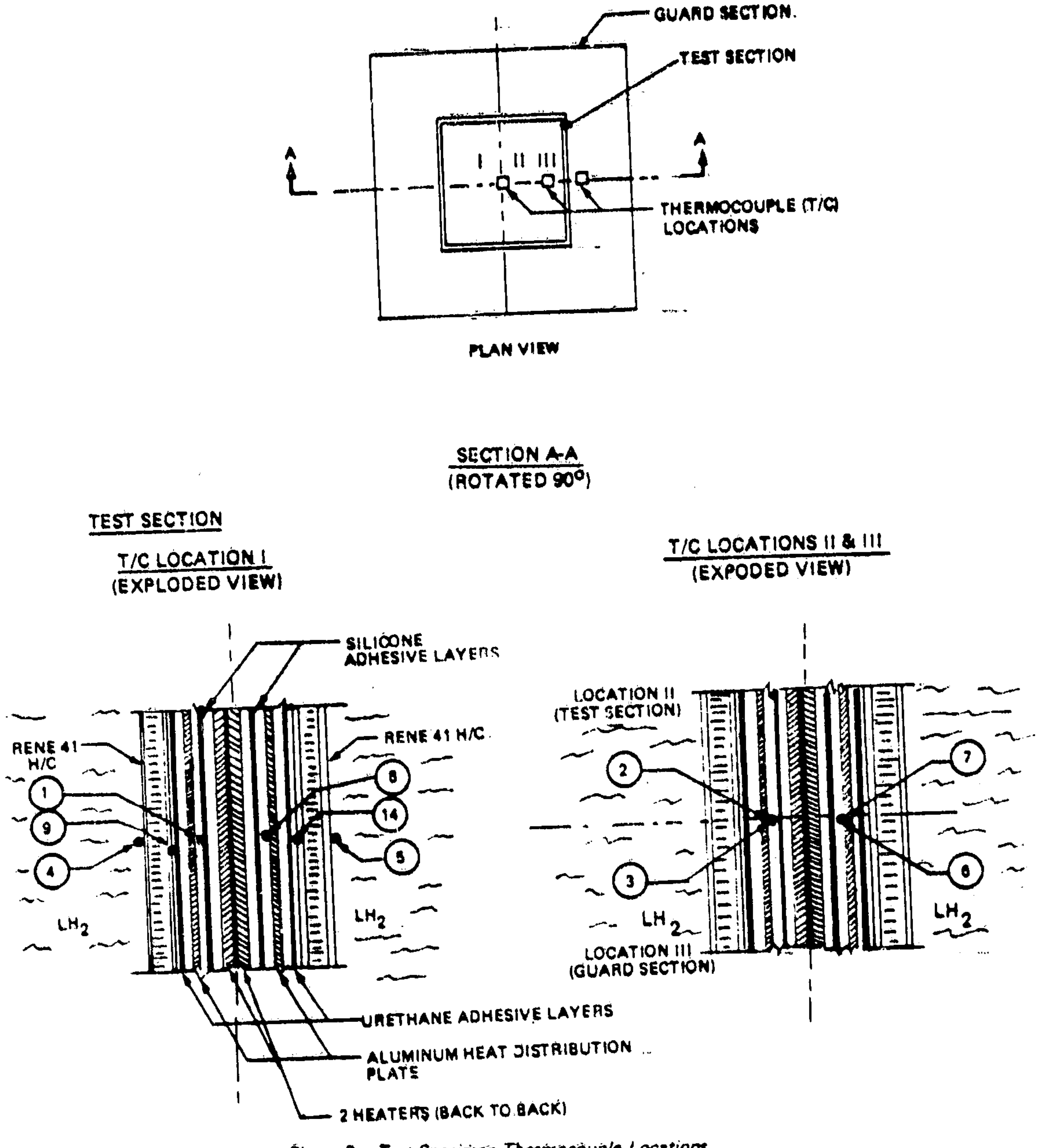

Figure 3: Test Specimen Thermocouple Locations

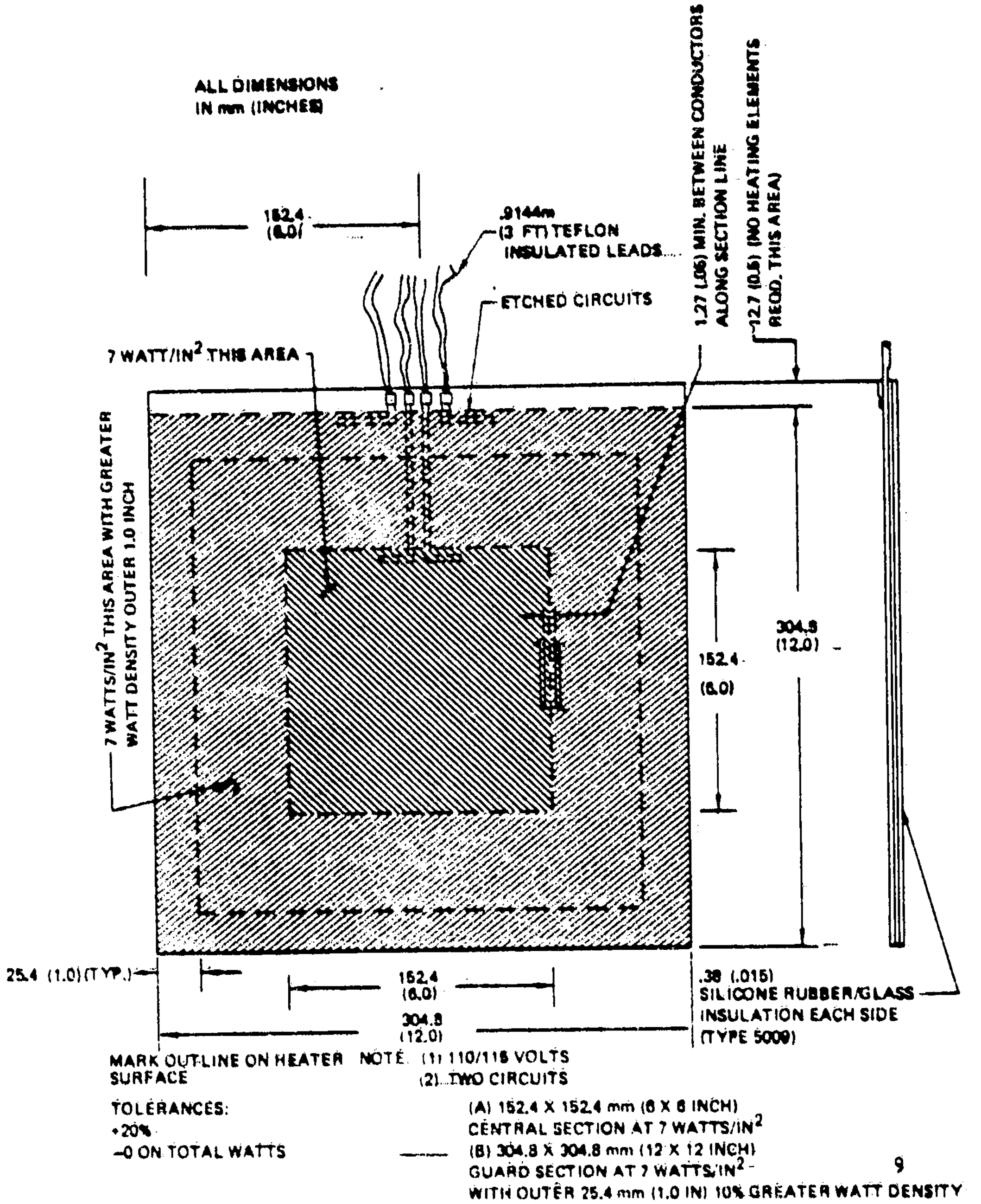

Figure 4: HR 1710 MINCO Thermo Foil Etched Circuit Heater

31.2 mm (1.25 in.) thick polyurethane foam insulation layer was placed around the outside edge of the heater/honeycomb panel assembly in order to insulate it from the liquid hydrogen surrounding the test specimen during the test and to prevent hydrogen penetration between the layers of the test specimen assembly. In addition to the temperature instrumentation, a thermopile was installed in order to measure the temperature drop between the test and the guard section.

Description of Cryostat

The cryostat used for the test is shown in Figures 5, 6 and 7. It consists of a Dewar type pail with appropriate fittings for filling and venting and a cover containing the required through fittings for electrical wiring using Deutsch plugs for power, thermocouple and thermopile connections. The cover also contains support clips for hanging the test specimen. The cryostat has a vacuum jacket for insulation with an appropriate fitting for drawing the required vacuum. A liquid level sensor located inside the cryostat with carbon resistors as sensing elements can be used for determining the liquid hydrogen levels during test.

Test Setup

The general test setup is shown schematically in Figure 8. A photograph of the test setup on the test pad at Wyle Laboratories is seen in Figure 9 showing the suspended test specimen and the wiring block containing the thermocouple reference junction kept at liquid hydrogen temperature, $T_{ref} = 20.4K$ ($-423^{o}F$).

The instrumentation setup is shown in Figure 10. Table 1 lists the equipment used in the Test (Reference 3).

The power was supplied using two variable power sources - Variac AC (115V) with 500 W capacity for the test section and 2000 W capacity for the guard section.

CRYOSTAT

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CRYOSTAT & LID - INTERIOR

Figure 5: Cryostat

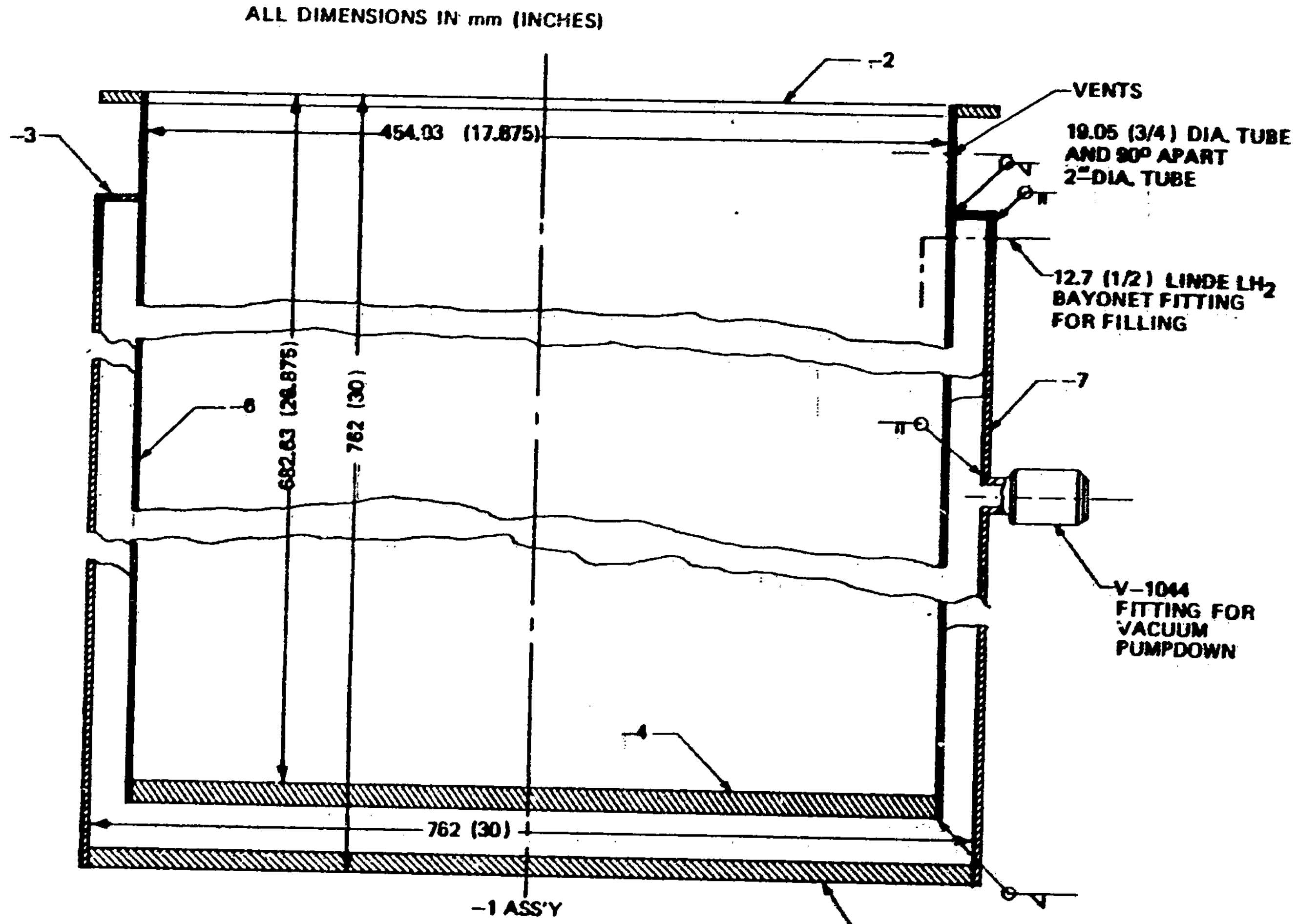


Figure 6: Cryostat Assembly

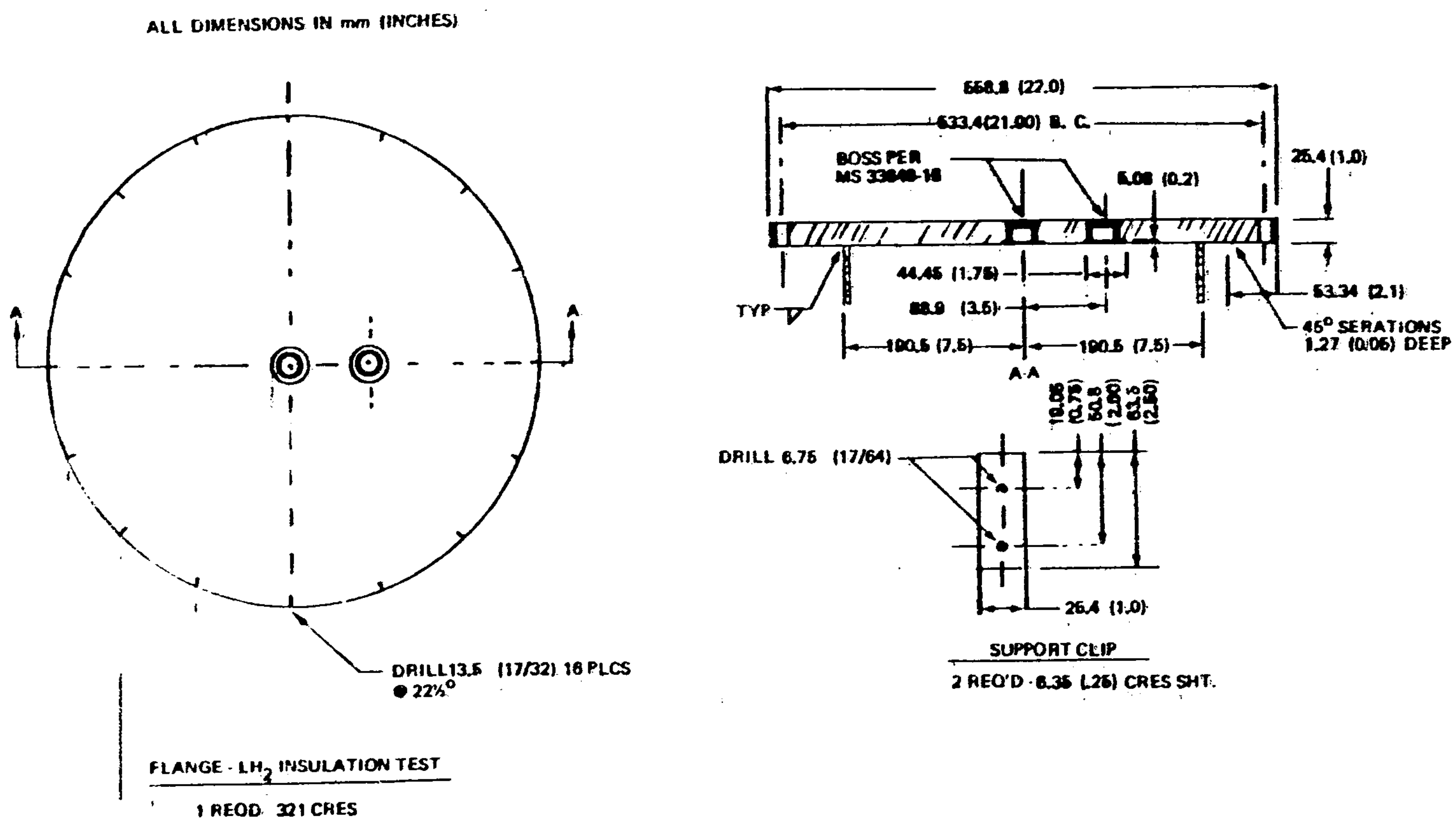


Figure 7: Cryostat Cover Assembly

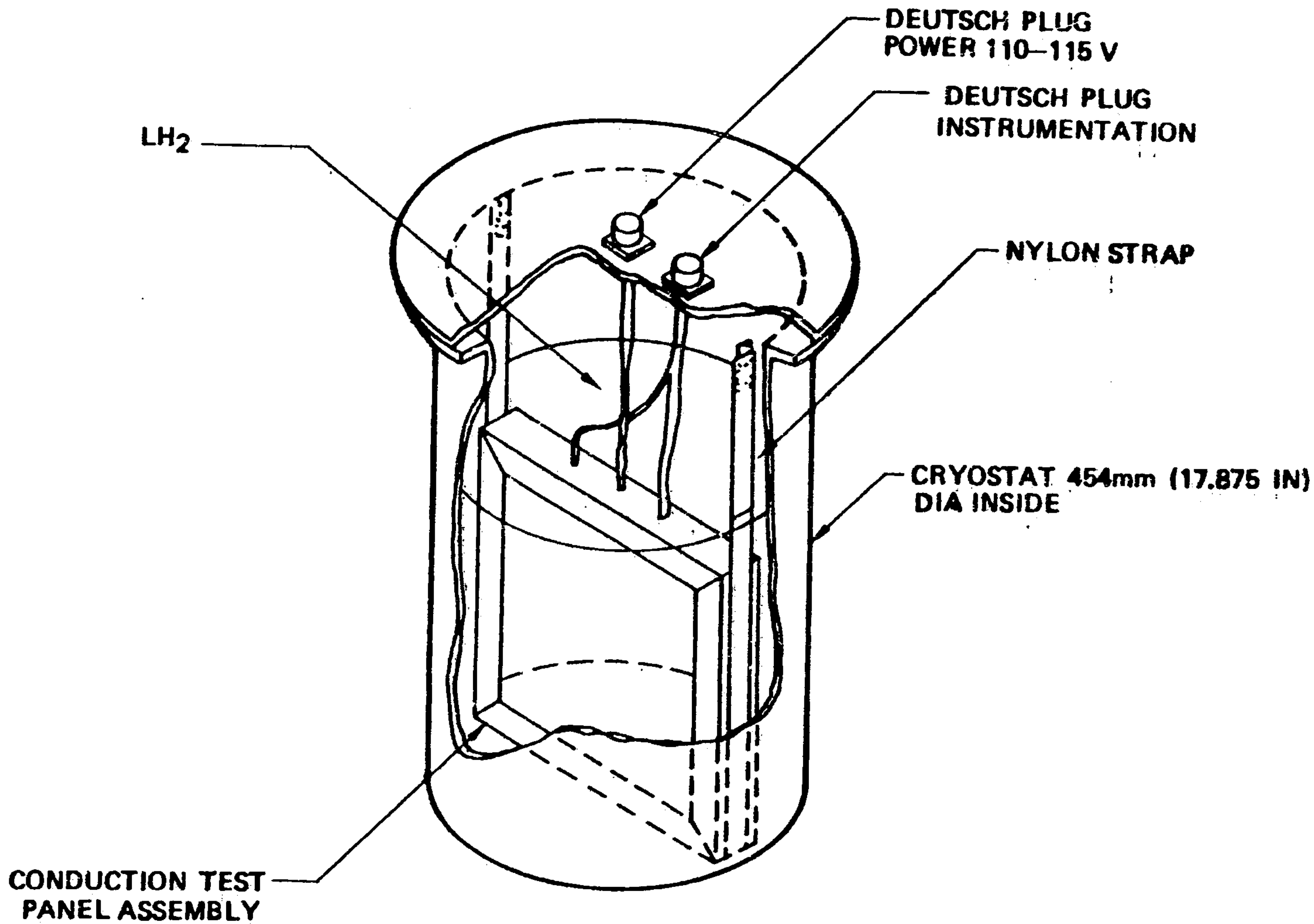


Figure 8: Conduction Test Panel Installation

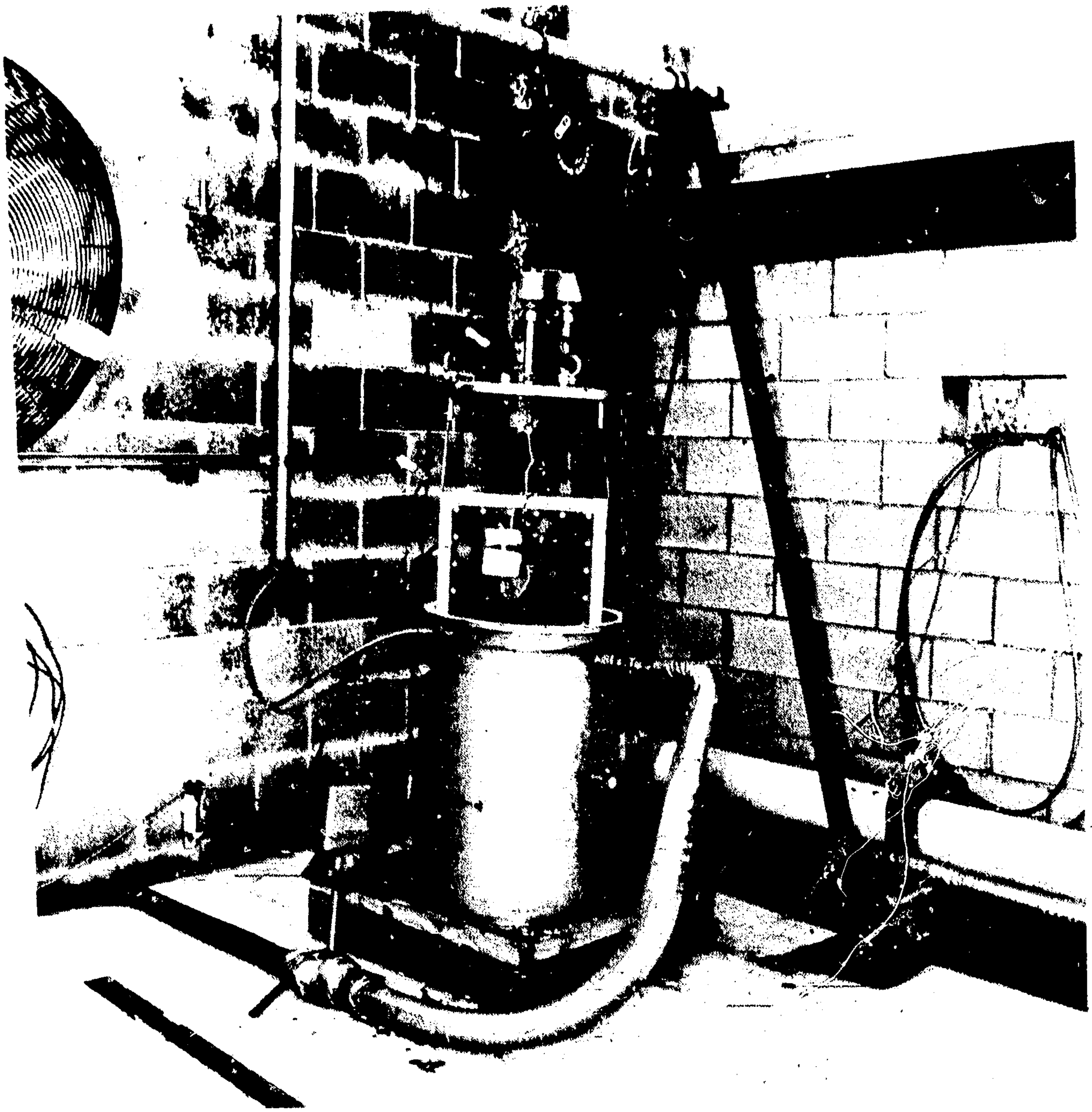


Figure 9: Test Setup - René 41 Honeycomb Panel (Reference 3)

WYLE LABORATORIES

DATA SHEET

Project No. 57103

Page No. 2

CUSTOMER BOEING AEROSPACE CO.

Test Title: CRYOGENIC CONDUCTIVITY TEST

Specimen RENE' 41 HONEYCOMB PANEL

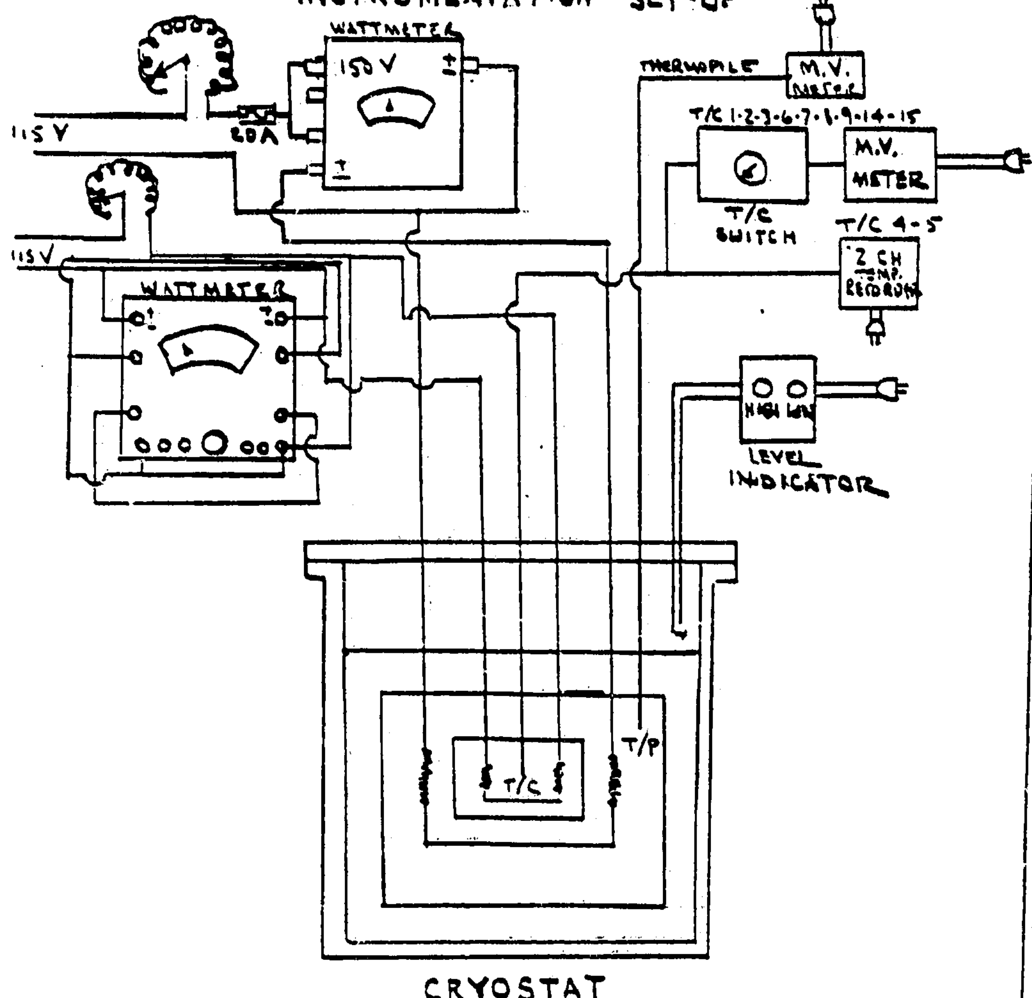
DWG Part No. 254-20843

Job No. 57103

S/N NONE

Date 9/29/80

INSTRUMENTATION SET-UP



(REFERENCE 3)

FIGURE 10

QC Form Approval

SHEET ____ OF ____

(REFERENCE 3)

WYLE LABORATORIES

SPECIMEN RENE'41 HONEYCOMB PANEL
CUSTOMER Boeing
DWG PART NO 354-20805
S/N NONE
TEST CRYOGENIC CONDUCTIVITY TEST

JOB NO FS. 57193
DATE 4-23-80
TEST BY B. Sewell
WITNESS VAL DERIUGIN

EQUIPMENT	MANUFACTURER	MODEL NO.	RANGE	WYLE NO	CALIBRATION LAST	CALIBRATION DUE	ACCY
Digital Thermometer	Fluke	2100A	-320° to +1830°F	7586	1-7-80	7-6-80	±.2%
Wattmeter	Weston	329	0-1000 watts	8569	4-21-80	8-24-80	±.5%
Wattmeter	Weston	400	0-3000 watts	8570	4-21-80	8-24-80	±3/4%
Digital Voltmeter	Fluke	8800A	± 200 MV	7986	3-9-80	3-8-81	±.01%
Reference Junction	Pace	12TP	150°	31456	11-29-79	5-28-80	±.5%
Chart Recorder	Heath	SR-206	0-500 VDC	8003	System	Calibration	

TABLE 1

EQUIPMENT LIST FOR CRYOGENIC CONDUCTIVITY TEST

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Test Procedure

The test specimen was installed in the cryostat and the instrumentation checked. The cryostat was purged with helium. LH_2 was slowly admitted first flashing to GH_2 and cooling the cryostat and specimen. Sufficient power was applied to the heaters to keep the inside panel surfaces (hot wall) at a minimum temperature on the order 88.76K (-300°F). The power level to the heaters was then gradually increased to the desired hot wall temperature levels by manually changing the settings on the Variacs for both the test and the guard section. Data were taken after achieving steady state temperatures and after achieving a near zero reading on a voltmeter monitoring the thermopile. A zero reading indicates no heat exchange across the boundary between the test section and the guard section. The nominal and the actual temperature levels achieved during the test are shown in Table 2.

Test Data

The temperatures of the specimen surfaces exposed to the liquid hydrogen were recorded on a strip chart recorder. Temperatures from all other test unit thermocouples were read using a digital voltmeter with a stepping switch. The power inputs were read from two wattmeters, one for the test section and the other for the guard section. A schematic of the thermocouple locations is given in Figure 3. The data obtained and the times of the readings are shown in Table 2.

The nominal temperature readings were obtained in millivolts and transformed to temperatures using a curve (Figure 11) computed from thermocouple reference tables for Chromel (Ni-Cr Alloy) - Constantan (Cu - Ni Alloy) - (Type E) thermocouples (NBC Monograph 125). Numerical table values were used later for better accuracy during the actual data reduction.

TABLE 2: TEST DATA - WYLE LABORATORIES - CRYOGENIC CONDUCTIVITY TEST

APRIL 29, 1980

TIME HR/MIN	TOTAL POWER (WATT) TEST SECTION HEATERS	TOTAL POWER (WATT) GUARD SECTION HEATERS	NOMINAL TEMP. K (°F)	THERMOCOUPLES 1 K (°F)	2 K (°F)	3 K (°F)	4/5 K (°F)	6 K (°F)	7 K (°F)	8 K (°F)	9 K (°F)	14 K (°F)	REMARKS
11:43	START TEST												
12:45	20	155	88.76 (-300)	88.51 (-300.44)	91.05 (-295.87)	87.85 (-301.63)	20.42 (-423)	90.03 (-297.71)	92.41 (-293.43)	90.37 (-297.09)	87.50 (-302.26)	89.58 (-298.51)	
1:30	45	315	144.31 (-200)	147.41 (-194.43)	150.46 (-188.94)	144.52 (-199.62)	20.42 (-423)	147.53 (-194.21)	152.93 (-184.48)	150.55 (-188.77)	145.53 (-197.80)	149.09 (-191.39)	
2:15	70	465	199.87 (-100)	201.42 (-97.20)	204.43 (-91.78)	197.44 (-104.36)	20.42 (-423)	201.37 (-97.30)	208.01 (-85.35)	205.68 (-89.54)	198.16 (-103.07)	203.34 (-93.75)	
3:00	95	595	255.42 (0)	249.56 (-10.56)	252.37 (-5.49)	243.24 (-21.93)	20.98/22.09 (-422/-420)	247.80 (-13.72)	257.08 (2.98)	255.56 (.25)	244.78 (-19.16)	252.44 (-5.36)	
3:30	135	765	310.98 (100)	308.20 (95.00)	309.58 (97.49)	298.20 (77.00)	20.98/22.09 (-422/-420)	303.27 (86.13)	313.15 (103.91)	316.27 (109.53)	300.77 (81.63)	311.89 (101.65)	
4:20	180	930	366.53 (200)	361.16 (190.32)	360.26 (188.70)	344.60 (160.52)	22.09/23.2 (-420/-418)	349.96 (170.16)	362.99 (193.62)	368.20 (203.00)	350.13 (170.47)	361.49 (190.92)	
4:55	230	1120	422.09 (300)	419.86 (295.98)	419.83 (295.93)	402.36 (264.48)	22.09/23.20 (-420/-418)	409.38 (277.13)	423.49 (302.52)	428.49 (311.53)	405.21 (269.61)	417.64 (291.99)	
5:25	257	1240	444.31 (340)	449.46 (349.26)	450.28 (350.75)	430.73 (315.55)	22.09/23.20 (-420/-418)	437.29 (327.36)	454.57 (358.47)	461.88 (371.63)	433.66 (320.82)	446.61 (344.14)	MAX. POWER AVAILABLE WITH 115V

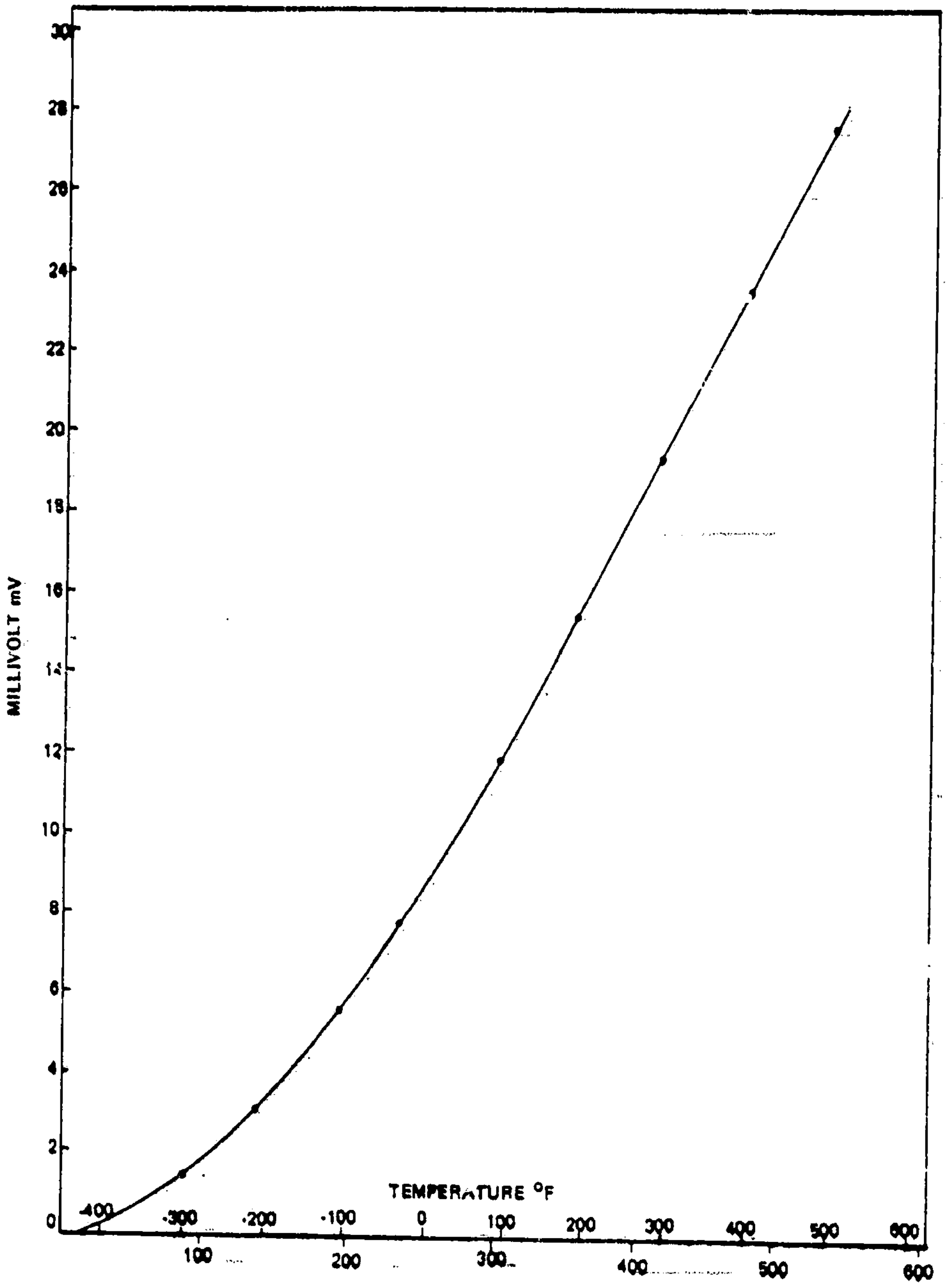

Figure 11 Temperature Curve Using a LH_2 Reference Temperature 20.4K (-423.4°F)

Data Analysis

The data were analyzed using average values for the hot wall and cold wall temperatures obtained from thermocouples 9 and 14 (hot wall) and 4 and 5 (cold wall) for each test point identified by the respective nominal temperature. The effective conductivities were obtained from the relations:

$$k = \frac{P x l}{2 A_T x \ \Delta T} = \frac{.03048}{(2)(.023226)} \ \frac{P}{\Delta T_{AVE}} = .6562 \ \frac{P}{\Delta T_{AVE}} \quad \frac{W}{m \ K}$$

$$\left(= 8.196 \ \frac{P}{\Delta T_{AVE}} \quad \frac{Btu \ in}{ft^2 \ hr \ {}^oR}\right)$$

P = total power to both heaters - W $(1W = 3.415 \ \frac{Btu}{hr})$

k = effective thermal conductivity - $\frac{W}{m \ K}$ $\left(\frac{Btu \ in}{ft^2 \ hr \ {}^oR}\right)$

l = honeycomb panel thickness = .03048m (1.2 in.)

A_T = honeycomb panel test area = .023226 m^2 (0.25 ft^2)

ΔT_{AVE} = average temperature drop through honeycomb panel K (^oR)

Thermal Conductivity Values

The effective thermal conductivities obtained from this analysis are listed in Table 3.

TABLE 3: EFFECTIVE THERMAL CONDUCTIVITY OF RENE'41 HONEYCOMB PANELS AT CRYOGENIC TEMPERATURES

T_{NOM} K (°F)	$T_{H_{AVE}}$ K (°F)	$T_{C_{AVE}}$ K (°F)	T_m K (°F)	ΔT_{AVE} K (°F)	K_{MEAS} $\frac{W}{m\,K}$ $\frac{(Btu\ in)}{(ft^2 hr\,^oR)}$	K_{PRED} $\frac{W}{m\,K}$ $\frac{(Btu\ in)}{(ft^2 hr\,^oR)}$	$\frac{K_{MEAS}}{K_{PRED}}$
88.76 (-300)	88.54 (-300.39)	20.42 (-423)	54.48 (-361.7)	68.12 (122.62)	.193 (1.338)	.108 (.747)	1.79
144.31 (-200)	147.31 (-194.60)	20.42 (-423)	83.86 (-308.8)	126.89 (228.41)	.233 (1.615)	.118 (.819)	1.97
199.87 (-100)	200.75 (-98.41)	20.42 (-423)	110.59 (-260.7)	180.33 (324.59)	.255 (1.768)	.129 (.894)	1.98
255.42 (0)	248.61 (-12.26)	21.53 (-421)	135.09 (-216.6)	227.08 (408.74)	.275 (1.906)	.140 (.972)	1.96
310.98 (100)	306.33 (91.64)	21.53 (-421)	163.92 (-164.7)	284.80 (512.64)	.311 (2.159)	.155 (1.078)	2.00
366.53 (200)	355.81 (180.70)	22.64 (-419)	189.22 (-119.2)	333.17 (599.70)	.355 (2.461)	.171 (1.186)	2.07
422.09 (300)	411.42 (280.80)	22.64 (-419)	217.03 (-69.1)	388.78 (699.80)	.388 (2.696)	.191 (1.325)	2.03
444.31 (340)	440.13 (332.48)	22.64 (-419)	231.37 (-43.3)	417.49 (751.48)	.404 (2.803)	.202 (1.405)	2.00

TEST PANEL CHARACTERISTICS

Panel Thickness	l = 30.48 mm	(1.2 in.)
Core Density	ρ_c = 124.94 kg/m^3	(7.8 lb/ft^3)
Core Foil Thickness	t_c = .064 mm	(.0025 in.)
Cell Diameter	d = 9.53 mm	(.375 in.)
Face Sheet Thickness	t_F = .51 mm	(.02 in.)

Analytical Check of Thermal Conductivity Values

In order to check the measured effective conductivities, an independent analysis was conducted using the approach by R. T. Swann and C. M. Pittman presented in NASA TN D-714. The equation for the heat transfer through a honeycomb panel can be written in the form:

$$Q = \underbrace{\frac{k_M}{T}\frac{\Delta A}{A}(T_H - T_C)}_{\text{Solid Conduction}} + \underbrace{\frac{k_A}{T}(T_H - T_C)}_{\text{Air Conduction}}$$

$$+ [0.664\,(\lambda + 0.3)^{-0.69}\ \underbrace{\epsilon^{1.63}(\lambda+1)^{-0.89}}_{\text{Radiation}}\sigma(T_H^4 - T_C^4)]$$

The net effective conductivity can be expressed as:

$$k = k_M \frac{\Delta A}{A} + k_A\left(1 - \frac{\Delta A}{A}\right) + k_R$$

For Rene'41 the material conductivity can be written in the form:

$k_M = a_1 + a_2 T_m$ where $a_1 = .0114$ and $a_2 = 1.61 \times 10^{-5}$ to

obtain k_M in $\dfrac{\text{Btu in}}{\text{ft}^2\text{sec}^o\text{R}}$

$$T_m = \frac{T_H + T_C}{2}\ (^oR)$$

$$k_A = \frac{1}{\left(e^{\frac{-49.736}{T_m}} \times 44.1.72 + T_m\right)} \times 3.8 \times 10^{-6} \times T_m^{\ 1.5}$$

$$k_R = f(\lambda, \epsilon)\ \sigma\ 1\ (T_H + T_C)\ (T_H^{\ 2} + T_C^{\ 2})$$

$$f(\lambda, \epsilon) = 0.664(\lambda + 0.3)^{-0.69}\ \epsilon^{1.63}\ (\lambda + 1)^{-0.89}$$

$$\lambda = 1/d = 3.2;\ \frac{\Delta A}{A} = \frac{\rho_{core}}{\rho_{Rene'41}} = .01515;\ \epsilon = .8$$

The results of the computations of effective thermal conductivity are shown in Table 3. Also shown is a comparison of measured and predicted values. The ratio of measured to predicted values is shown to be on the order of two. A detailed review of the data and test procedures did not yield a plausible explanation of this discrepancy.

Since, however, the power input readings were obtained from a wattmeter, and the values which were read were multiplied by a factor of two, according to the instructions on the wattmeter, it could be speculated that the read off values should have been taken at face value. Wyle test personnel have rejected this explanation.

An assessment was made of the magnitude of possible error introduced by heat loss across the boundary between the test and the guard section due to temperature gradients actually measured by thermocouples 2, 3, 6 and 7 as opposed to the nominal near-zero gradient conditions indicated by the thermopile readings. The last test point at the highest hot surface temperature was chosen for this estimate (see Tables 2 and 3). Mean temperatures were used for determining material conductivities between thermocouples 2 and 7 and 3 and 6 respectively (see Figure 3). An average value was used for the temperature gradients between the test and the guard section thermocouples. Applying the Fourier conduction equation across the boundary between test and guard section, a maximum error of 7% was estimated for P = 257W and 14% assuming one half of this power value. This error is significantly below the discrepancy by a factor of two observed between test data and predictions.

In order to try to resolve this puzzle, three additional (low temperature) points were added to the elevated temperature tests conducted using a heat flow meter. These tests are discussed in the next section. The test results showed to be within 6% of predictions which seems to bear out the suspicion that the power input readings were overestimated by a factor of two. A plot of the measured values and a curve of the predicted values shown in Figure 14 lend credence to such an explanation. In order to obtain a firmer data base, additional cryogenic conductivity tests of René'41 honeycomb panels are required.

THERMAL CONDUCTIVITY OF RENE'41 HONEYCOMB PANELS AT ELEVATED TEMPERATURES

This portion of the test was conducted at the Boeing Aerospace Company Materials and Processes Laboratory in Renton, Washington.

HEAT FLOW METER TEST

Test Specimens

Two test specimens were fabricated by Boeing with the intent of having one backup specimen. The test specimens consisted of 177.8 X 177.8 X 30.48 mm (7 X 7 X 1.2 inch) Rene'41 honeycomb panels using the same honeycomb configuration as that used for the cryogenic test described above.

Test Setup

The measurements for obtaining thermal conductivities were made using the heat flow meter apparatus shown in Figure 12. It meets the requirements of Specification ASTM C-518, "Standard Method of Test for Thermal Conductivity of Materials by Means of the Heat Flow Meter". The test zone of the apparatus was 127 X 127 mm (5 X 5 in.) with a 25.4 mm (1 in.) wide peripheral zone acting as a guard section. The guard section was adjusted to minimize radial heat flow, using the output of thermocouples to monitor the temperature differential between the test zone and the guard heater zone. The surface temperatures of the test sample were measured using three thermocouples placed back to back on each surface. The heat flow was monitored using a thermopile placed in the heat

Figure 12. [illegible]

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sink. The thermopile output and the thermocouple outputs were monitored using a Dynscience Digital Multimeter. A schematic section of the test setup is shown in Figure 13.

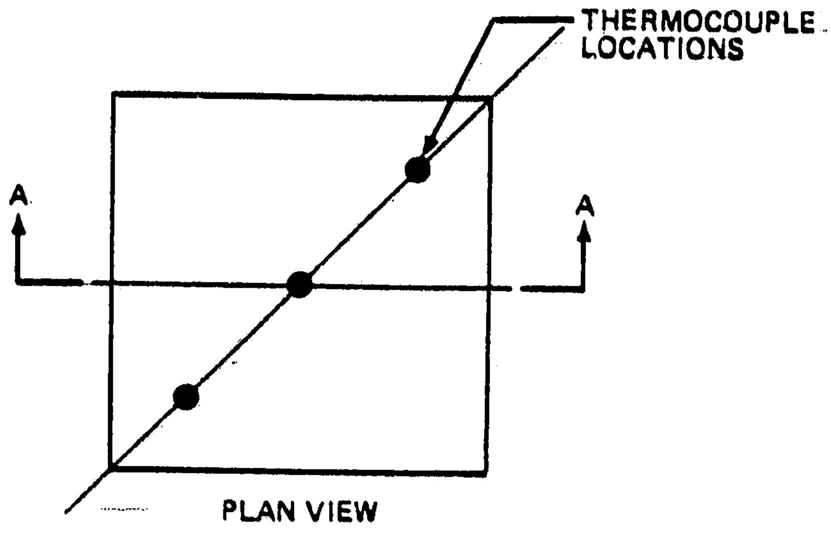
Test Procedure

The thermal conductivity was determined first at the lower temperatures above room temperature, then the intermediate, and finally, at the highest temperatures the equipment was capable of.

In order to obtain the highest hot face temperatures, the cold face insulation was increased to effectively raise the cold face temperature and produce a smaller ΔT between the hot face and the cold face than would ordinarily exist (see Figure 13).

Three additional test points below room temperature level were introduced later in the test plan in order to obtain some test points at mean temperatures closer to the test series conducted in the cryostat. This was done in the hope of resolving the discrepancy between test data and analytical predictions in the low temperature range. The backup specimen was used for this portion of the test.

It must be pointed out that this method - ASTM Method C-518 - is recommended for determination of the thermal conductivity of homogeneous materials whose conductances do not exceed (2.0 Btu/hr-ft^2 - ^{o}F). Although, the conductances did exceed the stated value at the higher temperatures, it is believed that the technique used avoided errors due to high conductance by using insulation and by closely monitoring the lateral heat flow.



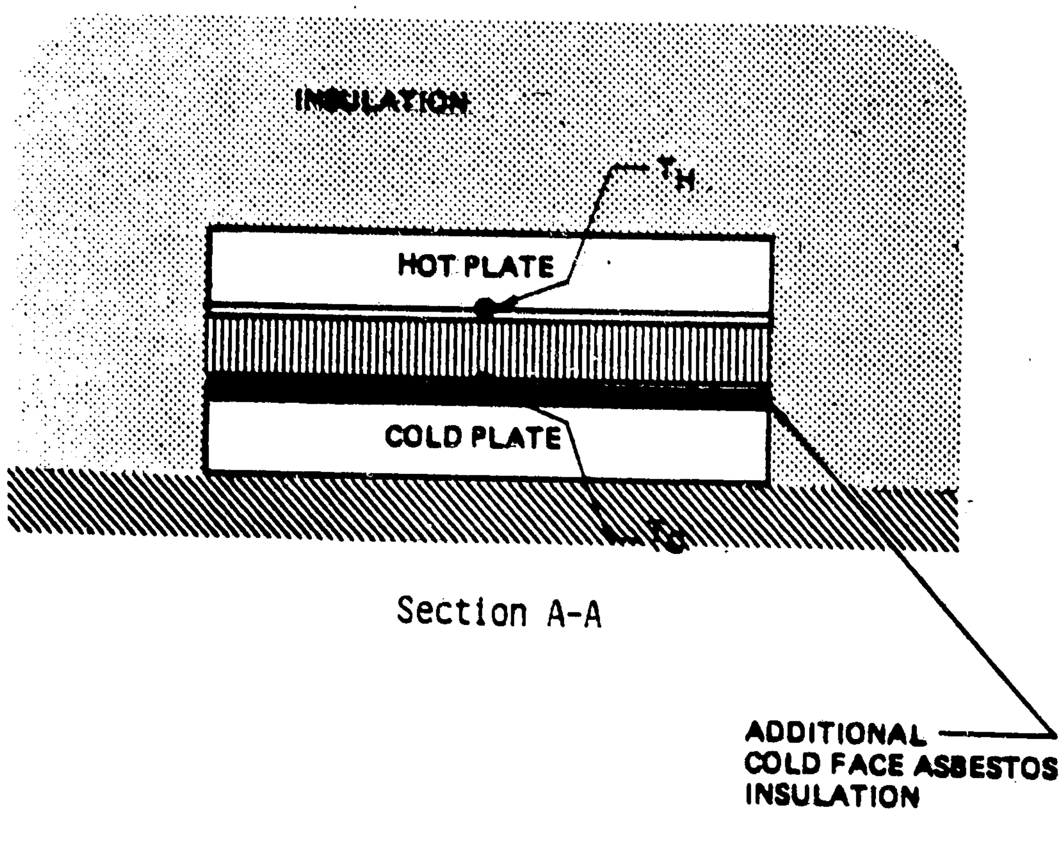


Figure 13: Schematic Test Setup in Heat Flow Meter (ASTM C-518)

Data Analysis

The thermal conductivity, was calculated from the test data using the following equation:

$$K = set/\Delta T$$

where: s = sensitivity of Heat Flow Meter, $19.81 \frac{W}{m^2\ hr\ mV}$ $\left(6.3 \frac{Btu}{ft^2\ hr\ mV}\right)$

e = thermopile Output, mV

t = specimen thickness, m (inch)

ΔT = temperature difference across the specimen, K (^{o}R)

The surface temperature used in the calculation was the arithmetic average of the three values recorded for each surface. The specimen thickness was the arithmetic average of at least five measurements made using a micrometer.

Thermal Conductivity Values

The computed effective conductivity values are shown in Table 4 and plotted in Figure 14.

COMPARATIVE THERMAL CONDUCTIVITY INSTRUMENT TEST

The limitations of the heat flow meter precluded testing at temperatures much above 992K (1200^{o}F). A comparative thermal conductivity instrument was used for achieving the 1144K (1600^{o}F) range.

Test Specimens

Two 50.8 mm (2 inch) diameter test samples were fabricated (one for backup) with the same honeycomb configuration used for the cryogenic and the heat flow meter tests.

TABLE 4: EFFECTIVE CONDUCTIVITY OF RENE'41 HONEYCOMB PANELS AT ELEVATED TEMPERATURES USING A HEAT FLOW METER

T_{NOM} K (^oF)	$T_{H_{AVE}}$ K (^oF)	$T_{C_{AVE}}$ K (^oF)	T_M K (^oF)	ΔT_{AVE} K (^oF)	K_{MEAS} $\frac{W}{m\ K}$ $\left(\frac{Btu\ in}{ft^2 hr ^oR}\right)$	K_{PRED} $\frac{W}{m\ K}$ $\left(\frac{Btu\ in}{ft^2 hr ^oR}\right)$	$\frac{K_{MEAS}}{K_{PRED}}$
269.31 (25)	268.76 (24)	259.31 (7)	264.04 (16)	9.45 (17)	.219 (1.52)	.206 (1.43)	.941
291.53 (65)	291.53 (65)	260.98 (10)	276.26 (38)	30.55 (55)	.208 (1.44)	.213 (1.48)	.973
310.98 (100)	312.09 (102)	264.87 (17)	288.48 (59)	47.22 (85)	.219 (1.52)	.223 (1.55)	.981
477.64 (400)	482.64 (409)	322.09 (120)	402.37 (264)	160.55 (289)	.327 (2.27)	.334 (2.32)	.978
616.53 (650)	616.53 (650)	554.87 (539)	585.70 (595)	61.66 (111)	.578 (4.01)	.624 (4.33)	.926
616.53 (650)	621.53 (659)	563.2 (554)	592.37 (607)	58.33 (106)	.602 (4.18)	.638 (4.43)	.944
699.87 (800)	698.76 (798)	634.87 (683)	668.20 (741)	63.89 (115)	.744 (5.16)	.816 (5.66)	.912
838.76 (1050)	842.64 (1057)	780.98 (946)	811.81 (1002)	61.66 (108)	1.316 (9.13)	1.278 (8.87)	1.029
922.09 (1200)	937.64 (1228)	880.98 (1126)	909.31 (1177)	56.66 (102)	1.844 (12.80)	1.689 (11.72)	1.092

TEST PANEL CHARACTERISTICS

Panel Thickness	l =	30.48 mm	(1.2 in.)
Core Density	ρ_c =	124.94 kg/m^3	(7.8 lb/ft^3)
Core Foil Thickness	t_c =	.064 mm	(.0025 in.)
Cell Diameter	d =	9.53 mm	(.375 in)
Face Sheet Thickness	t_F =	.51 mm	(.02 in)

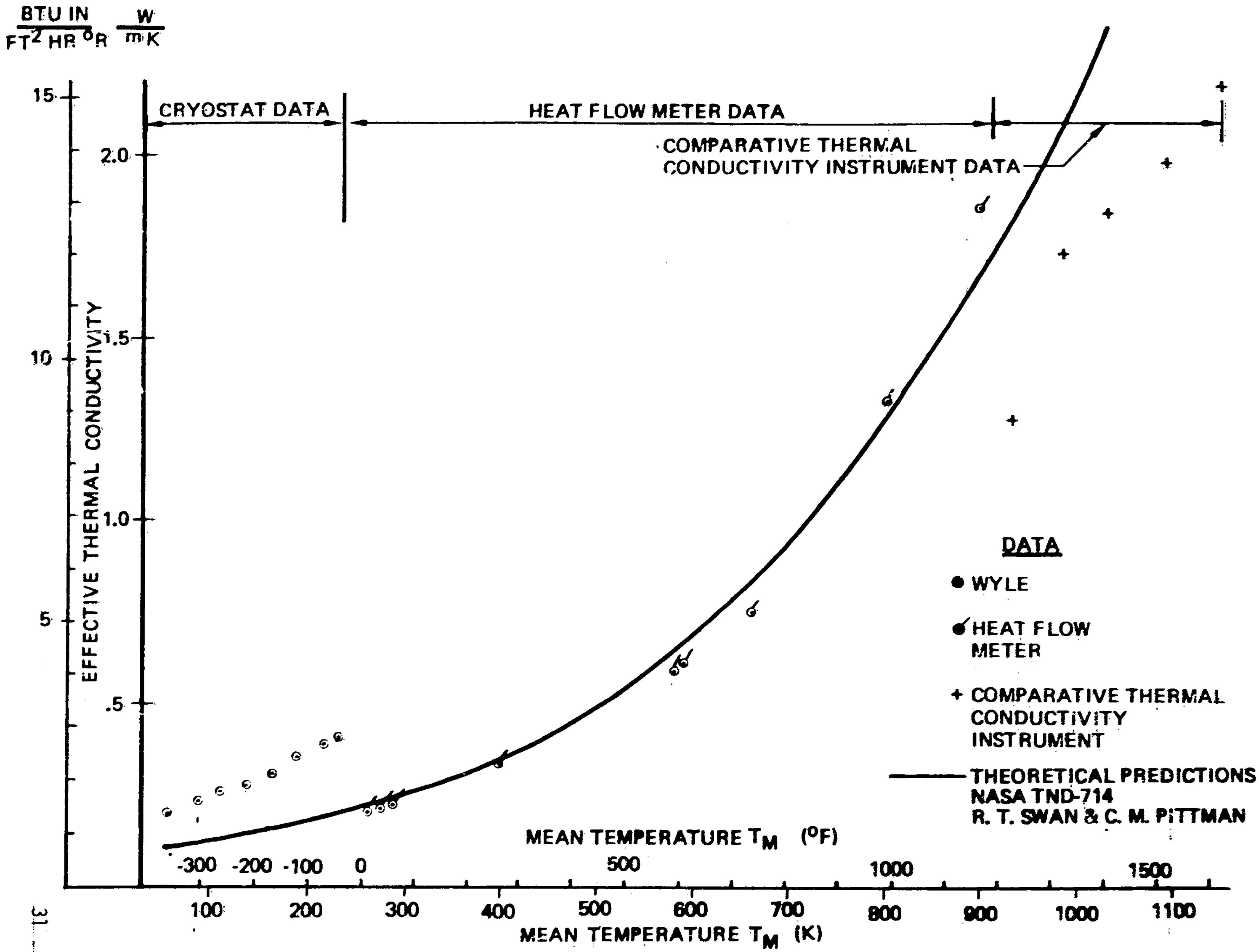


Figure 14: Effective Thermal Conductivities of Rene 41 Honeycomb Panels

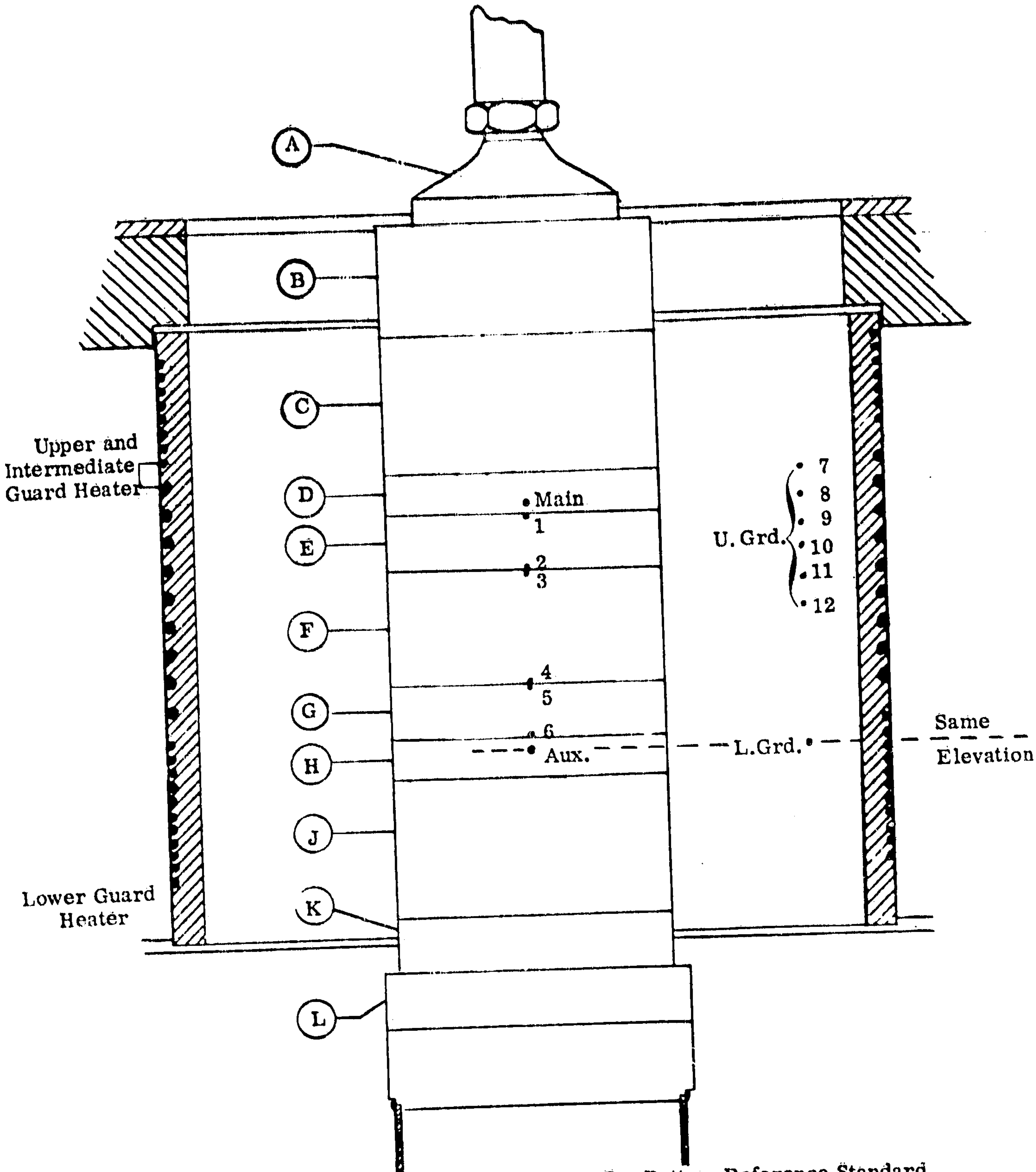
Test Setup

A Dynatech Corp. Model TCFCM-N20 Comparative Thermal Conductivity Instrument was used in which the thermal conductivity of the sample was compared to the thermal conductivity of two known reference materials. Thermal conductivity can be determined by measuring the temperature difference between two points in a material when heat flows from one point to another. When the heat flow is kept the same for two materials, one of known thermal conductivity ($k_{reference}$) and one of unknown thermal conductivity (k_{sample}) the respective temperature drops ΔT, across a thickness Δx are related as follows:

$$(k\ \Delta T/\Delta x)_{sample} = (k\ \Delta T/\Delta x)_{reference}$$

The condition of equal heat flux was obtained by placing a test sample between two reference materials of equal cross-section in intimate contact with each other and holding the three pieces between a heater and a heat sink. To ensure a consistent and uniform heat flux through the sample and reference materials appropriate guard heaters were used to eliminate heat losses (or gains) which would occur along the sides wherever the temperatures of the surroundings do not exactly match those along the test stack.

To avoid non-uniform heat flux between the thermocouples, caused by an irregular interface contact, the surfaces of the sample and the reference material were polished. Radial heat transfer is reduced in the apparatus by placing the test stack inside a cylindrical furnace with a linear temperature gradient along the length of the furnace. The end temperatures match those at adjacent points in the test stack. The space between the furnace tube and the stack is filled with Celite insulating powder. A schematic of the test setup showing the test stack is seen in Figure 15.



A. Pressure Pad
B. Insulation
C. Main Heater
D. Surface Plate
E. Top Reference Standard
F. Test Sample
G. Bottom Reference Standard
H. Surface Plate
J. Auxiliary Heater
K. Spacer
L. Heat Sink
• Thermocouples

FIGURE 15

COMPARATIVE THERMAL CONDUCTIVITY INSTRUMENT
TEST STACK FOR TESTS USING PYREX OR PYROCERAM REFERENCE STANDARDS

Test Procedure

To obtain the most accurate results, the polished test sample was sandwiched between two identical reference materials (Pyroceram 9606). An NBS calibration curve for Pyroceram 9606 conductivity was supplied with the instrument. The choice of reference standard for a particular test depends on the expected thermal conductance of the test specimen. It is desirable to have a temperature difference across the sample comparable to that across the reference standards.

The thermal conductivity was determined starting at a nominal temperature 922K (1200°F). The temperature was then raised in steps to 1144K (1600°F). Measured were the temperatures of the top and the bottom reference. The bottom temperature of the top reference material was then used as $T_{H_{AVE}}$ and the top temperature of the bottom reference material as $T_{C_{AVE}}$ for obtaining the temperature gradient across the test sample. This was done in order to eliminate possible errors connected with installing thermocouples in thin-walled materials on specimens required to be in intimate surface contact with the reference standards.

All temperatures were allowed to stabilize within $\pm$ 1K (1.8°F) before readings were taken.

Data Analysis

The thermal conductivity was calculated from the temperature readings using the following equation:

$$k_{\text{sample}} = \frac{1}{2}\left(\frac{\Delta x}{\Delta T}\right)_{\text{sample}}\left[\left(k\,\frac{\Delta T}{\Delta x}\right)_{\substack{\text{top}\\ \text{reference}}} + \left(k\,\frac{\Delta T}{\Delta x}\right)_{\substack{\text{bottom}\\ \text{reference}}}\right]$$

The thermal conductivity of each reference standard was taken at the respective average temperature from the Pyroceram 9606 calibration curve supplied with the instrument.

Thermal Conductivity Values

The computed effective conductivity values are shown in Table 5. (See also Figure 14).

ANALYTICAL CHECK OF THERMAL CONDUCTIVITY VALUES

Analytical predictions show excellent correlation with the conductivities calculated from the test data obtained using the heat flow meter (see Table 4). Particularly interesting is the good correlation at the three low temperature points selected specifically for this purpose.

A good overall feel of the quality of the data/analysis correlation can be obtained from Figure 14, which shows unusually good correlation of this type of data with predictions, if the explanation for the factor of two discrepancy in the cryogenic regime is accepted as valid.

Correlation of data obtained from the comparative thermal conductivity instrument measurements shows that the data fall up to 30% below theoretical predictions (see Table 5 and Figure 14) exhibiting otherwise reasonable trends. More data are required in order to establish statistical validity.

Table 5: Effective Conductivity of Rene'41 Honeycomb Panels at Elevated Temperatures Using a Comparative Thermal Conductivity Instrument

T_{NOM} K (^oF)	$T_{H_{AVE}}$ K (^oF)	$T_{C_{AVE}}$ K (^oF)	T_M K (^oF)	ΔT_{AVE}	K_{MEAS} $\frac{W}{m\ ^oK}$ $\left(\frac{Btu\ in.}{ft^2\ hr\ ^oR}\right)$	K_{PRED} $\frac{W}{m\ ^oK}$ $\left(\frac{Btu\ in.}{ft^2\ hr\ ^oR}\right)$	$\frac{K_{MEAS}}{K_{PRED}}$
922 (1200)	972 (1290)	889 (1141)	931 (1216)	83 (149)	1.278 (8.869)	1.792 (12.434)	.713
977 (1300)	1018 (1373)	971 (1288)	995 (1331)	47 (85)	1.715 (11.901)	2.121 (14.720)	.808
1033 (1400)	1074 (1474)	999 (1339)	1037 (1407)	75 (135)	1.826 (12.672)	2.365 (16.410)	.772
1089 (1500)	1133 (1580)	1060 (1449)	1097 (1515)	73 (131)	1.992 (13.824)	2.744 (19.040)	.726
1144 (1600)	1186 (1675)	1117 (1551)	1151 (1613)	69 (124)	2.187 (15.177)	3.124 (21.680)	.700

For Test Panel Characteristics See Table 4.

CONCLUSIONS AND RECOMMENDATIONS

(1) Good correlation was found between measured and predicted values for Rene'41 honeycomb thermal conductivities at elevated temperatures.

(2) Test data from the cryostat are higher by a factor of two than analytical predictions. This discrepancy could be resolved if the wattmeter readings are halved. A rationale for such an approach and strong analytical evidence for its support are given in the report.

(3) Additional tests are required to obtain a broader data base for design application. Particularly desirable is the use of more test specimens and more sophisticated cryogenic test techniques.

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