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THERMAL CONTACT CONDUCTANCE BETWEEN METALS IN A VACUUM ENVIRONMENT

FINAL REPORT

16 August 1965

CLASSIFICATION AND CONTENT APPROVAL

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INTRODUCTION

The Saturn IB/V Instrument Unit utilizes thermal conditioning panels which mount about the IU inner skin structure to provide (1) the physical mounting locations for components and (2) a heat sink for removal of heat generated within components.

Heat transfer between the components and thermal conditioning panel, in the vacuum environment of space, is primarily by conduction. Component mounting thus becomes the major consideration in achieving effective heat transfer from component to mounting structures.

A reduction in the heat transfer capability directly affects reliability, since degradation of solid state components occurs when operating at above ambient temperature levels, and also places a limit on packaging density.

Thermal conductivity values within solids have been sufficiently established, but very little is known about the thermal contact conductance between dissimilar metallic surfaces applicable to Saturn IB/V design. The following program was undertaken to obtain basic heat transfer data for structural materials presently used in Saturn IB/V IU Component Case Structure Design.

DISCUSSION

1. Test Program Outline

A. Basic Considerations - Environmental

The definition of heat transfer involves each of the three modes.

Convection

Radiation

Conduction

How each mode enters into the overall heat transfer function must be considered for the specific operating environment.

The environment to be considered will be a vacuum environment since more than 99% of the Saturn mission will be at orbital altitudes.

1. Convection

Convection is dependent upon a fluid or gaseous substance as a heat transfer medium and subsequently upon air density and gravitational effects.

Both air density and gravity effects reduce drastically as orbital altitudes are reached. Molecular mean free path for air at pressures of 1×10^{-4} torr can be shown to be 5.04×10^{-1} meters. At normal atmosphere (760 torr) the mean path is 6.63×10^{-8} meters. The low number of molecular collisions occurring at 1×10^{-4} torr allow a gaseous conduction of 1.63×10^{-6} watts/cm^{2} ^{o}K. At 760 torr the gaseous conductance increases to 998 watts/cm^{2} ^{o}K. These conductance values were derived across a 2.5 micron spacing of two parallel plates. This spacing was considered to be the equivalent best case convective heat transfer condition between the non-contacting areas of the test sample surfaces. The temperature of one of the plates was assumed at 288^{o} K for these calculations.

Initial testing revealed conductance values at low contact pressures to be on the order of 0.1 watts/cm^{2} ^{o}K. This indicates heat transfer due to convection will amount to less than 0.002 percent of the total contact conductance in a vacuum environment of less than 1 x 10^{-4} torr.

2. Radiation

The effects of radiation heat transfer between adjacent material surfaces with moderate temperature differential between surfaces has been found to be quite low. Radiation to the surrounding environment however would introduce appreciable errors. The effects of radiation heat transfer to the surrounding environment was nullified by the use of separator disks and radiation shields in order to assure effective measurement of thermal conductivity.

3. Conduction - Contact Conductance

Heat transfer between a component structure and the thermal conditioning panel surface is dependent upon the geometry of physical contact with intimate metal to metal contact required to provide a heat transfer path.

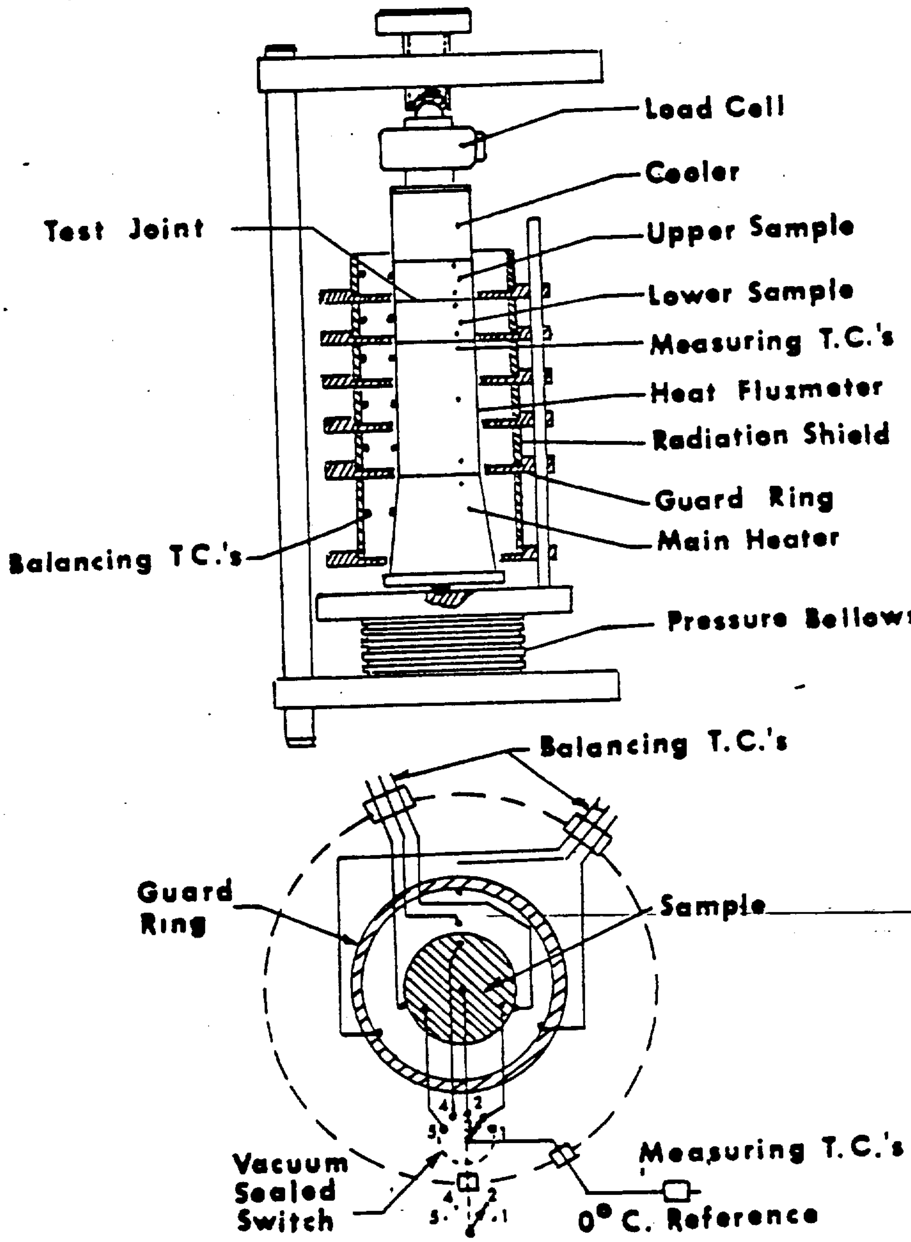
The ability of materials in contact to transfer heat through surface contact is defined as thermal contact conductance. It is this parameter, controlling heat transfer in a vacuum environment, that is to be accurately determined.

B. Basic Considerations - Test Hardware

The test fixture required to determine thermal contact conductance consisted of the following thermocouple instrumented hardware (Figure 1).

1. Heat Source: The main heater consists of two 80 watt cartridge type heaters installed in a gold plated truncated copper cone.

2. Heat Fluxmeter: The fluxmeter is a cylindrical section of high purity armco iron placed in contact with the main heater. The outer surfaces of the fluxmeter were gold plated. Armco iron was selected as the material for heat flow (flux) determination because of well established heat transfer



TEST FIXTURE AND THERMOCOUPLE INSTRUMENTATION

FIGURE 1

characteristics and inherent high temperature drop per unit length. Thermal characteristics of a section of the original armco iron sample were reaffirmed by tests [1] conducted by the National Bureau of Standards.

3. Test Samples: A location for placement of two cylindical test samples was provided above the fluxmeter. Each test sample was 3.81 cm in diameter and 2.03 cm in length.

4. Heat Sink: A cylindrical shaped heat sink in contact with the upper sample provided a path for water coolant flow used to remove heat from the test column.

5. Physical Joints: The number of physical joints between the individual sections of the test column (i.e. heat source to fluxmeter, fluxmeter to lower sample, upper sample to heat sink) alter the temperature gradient through the test column, directly affecting the accuracy of heat flow measurements by concentrating temperature drops primarily in the physical joint areas.

Heat flow can be considered as flowing in a series path from heater to cooler, the path being analageous to a series electrical circuit. See Figure 2.

The symbol indicates thermal contact resistance which is the reciprocal of thermal contact conductance dependent upon test column load pressures, with the joint between the upper and lower sample being the test joint under study. The symbol is the thermal resistivity (which is the reciprocal of thermal conductivity) of the basic materials in the test column configuration and is independent of test column load pressures.

The thermal contact resistance varies with contact pressure producing a Δt as a function of pressure change.
Since the measurement of heat flow is based on the temperature

[1] Watson, T.H. & H.E. Robinson, "Thermal Conductivity and Electrical Restivity of a Specimen of Armco Iron," N.B.S. Report 8389, July, 1964.

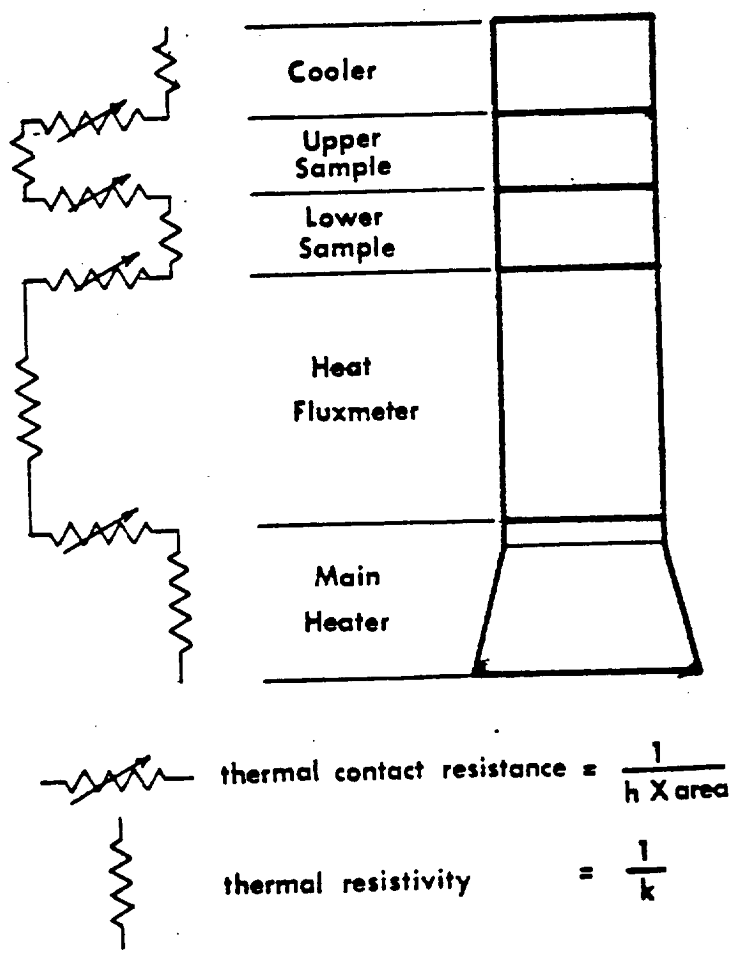


Figure 2 - Thermal Resistance Diagram - Test Column

drop per unit length through the test column it was desirable to reduce temperature drop between (a) the main heater and fluxmeter, (b) fluxmeter and lower sample, and (c) upper sample and cooler.

The contacting surfaces of the test column sections were lapped and coated with a high vacuum silicon grease to achieve a reduction of in the test column configuration.

6. Load Source - Control

To permit the study of contact conductance under a varying load while maintaining vacuum operating conditions, a load source consisting of a pressure regulated bellows assembly was used to apply force to the test column. The resultant pressure was monitored by a load cell placed at the upper (opposite) end of the test column.

As previously noted on Page 3, (Basic Considerations, Environmental) radiation losses were nullified by:

7. Radiation Shields

The test column surface temperature levels were checked at six discrete levels. Six radiation shields surrounding the test column were heated to maintain identical surface temperature levels. Radiation viewing effects between the test column and radiation rings were reduced to a minimum by adding fiberglas rings separating each radiation shield and its adjacent test column surface. The radiation shields and adjacent test column surfaces were gold plated to reduce surface emissivity to a minimum.

C. Test Sample Material Considerations

During the test period heat transfer investigations were performed with the following materials in contact with Aluminum 6061-T6.

(1) Aluminum 6061-T6

(2) Almag 35 (as cast)

(3) AZ91C-T4

(4) Aluminum 356 (as cast)

(5) LA-141

An additional test was performed using Almag 35 (as cast) in contact with AZ91C-T4.

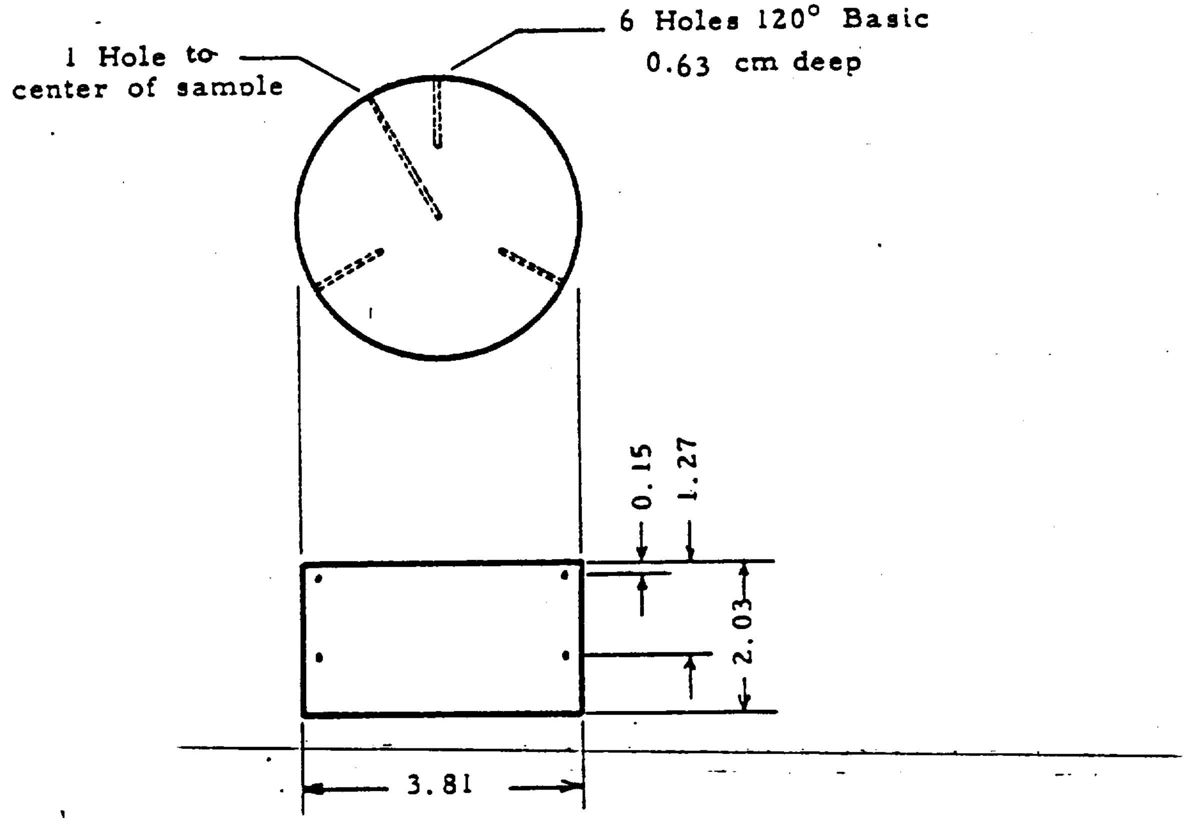
The test samples were prepared from the appropriate cast, or tempered cylindrical bar stock to conform to the physical dimensions shown in Figure 3. Contact surfaces other than the actual test joints were lapped and the outer sample surfaces were polished to obtain a low emissivity.

Test joint surfaces ranged from lapped to flycutter machined, with anodize treatment of two samples (AZ91C and LA-141) and beryllium coating of an LA-141 sample.

Sample surface treatment produced by flycutter machining, and subsequent surface treatments ranged from 0.28 to 2.48 microns. Two samples were lapped to a 0.07 microns surface prior to testing.

Of the two samples required for each test, the sample shown as upper (opposite the applied load) was normally 6061-T6, which at the inception of the test program was the material considered for the thermal conditioning panel mounting surface.

The thermal conditioning panel mounting surface however is presently Aluminum 6951-T6. Characteristic differences between 6061-T6 and 6951-T6 are primarily due to the differences in alloying elements as shown in Table I. The material properties are compared in Table II.



Note: All dimensions in centimeters

Figure 3 - Test Sample Configuration

TABLE I

CHEMICAL COMPOSITION LIMITS
ALUMINUM 6951 - ALUMINUM 6061

Element (%)	Alloy 6951	Alloy 6061
Silicon	0.20-0.50	0.40-0.8
Iron	0.8	0.7
Copper	0.15-0.40	0.15-0.40
Manganese	0.10	0.15
Magnesium	0.40-0.8	0.8-1.2
Chromium		0.15-0.35
Nickel		
Zinc	0.2	0.25
Titanium		0.15
Other	0.15	0.15
Aluminum	Remainder	Remainder

TABLE II

COMPARISON OF MATERIAL PROPERTIES

Property	Units	6951-T6	6061-T6
Brinell Hardness No.	500 KG Load 10 MM Ball	82	95
Thermal Conductivity	w/cm^o c	2.16	1.55
Yield Strength	n/cm^2	23×10^3	28×10^3
Modulus of Elasticity	n/cm^2	6.9×10^6	6.9×10^6

The lower Brinell Hardness rating for 695I-T6 indicates the material surface will yield more readily to an equivalent load permitting a greater contact area to exist between the thermal conditioning panel and case structure.

The thermal conductivity of 6951-T6 is improved compared to 6061-T6 indicating a more effective basic heat sink. A reduction in yield strength will not effectively reduce the structural strength of the thermal conditioning panel since structural strength is primarily provided by the honeycomb structure.

D. Test Sample Surface Considerations

The surface finish of the thermal conditioning panel is specified to be 32 micro inches CLA (0.81 microns) or less. Original surface finishing of the #23 brazing sheet (with 6951-T6 surface) used for the thermal conditioning panel skin is performed by a rolling process which produces a random surface pattern primarily of macroscopic nature. The surface finish of the case structure is to be compatable with thermal conditioning panel surface finish.

1. Surface Treatment and Area of Physical Contact.

Surface conditions for each of the sample test joints were checked for average surface finish and surface flatness prior to contact conductance testing. Test sample positioning (orientation) was controlled during test activity to secure known surface profiles. This was done in order to measure Δt's between adjacent sample areas, and to determine the average type and number of surface contact areas between the test samples.

2. Surface Hardness

Material hardness was measured by two methods - Vickers (diamond point) and Brinell or Rockwell(ball indenter) following conductance testing.

E. Basic Considerations - Instrumentation Accuracy

1. Thermocouples

The basic instrumentation of the test fixture and test samples consisted of #36 copper-constantan thermocouples so placed to measure temperature drops per unit length in the test column. The temperature drop per unit length could be extrapolated to include the temperature from the thermocouple locations to the test sample surfaces.

Thermocouple accuracy was verified to be within 4 microvolts of the N.B.S. calibration curve for copper-constantan thermocouples.

Temperature measurements were recorded as the EMF of individual thermocouples referenced to 273°K (0°C ice bath) using a Leeds and Northrup K-3 potentiometer. Measurement accuracy of the K-3 is 2 microvolts or approximately. .05°K.

It becomes readily apparent that the basic accuracy of measurements is primarily dependent upon the recorded differences in EMF between individual thermocouples. For example, an inaccuracy of 0.1° K (4 microvolts) for a temperature differential ~~of 1.0° K results in a~~ 10% error whereas the same inaccuracy for a temperature differential of 10.0° K results in a 1% error. Thus basic thermocouple instrumentation was considered the most critical factor in test fixture design since calculation of heat flow is based on thermal EMF (temperature) measurements.

Thermocouple placement within the test samples was verified as being correct by the use of x-ray photographic techniques.

Run 1 was performed primarily to estimate the accuracy which could be expected with the test fixture. The test sample surfaces were lapped to a surface finish of 0.07 micron CLA to obtain a smooth flat surface condition. Test data for the run indicates a reverse heat flow (from the water cooler heat sink to the heater) or a minus Δt value. The gross error is primarily due to a Δt in the range of basic instrumentation accuracy of 0.1° K.

At this stage of testing the recorded temperatures were referenced to the laboratory ambient environment. Slight shifts of temperature in the laboratory during data collection added to temperature measuring inaccuracies. An ice bath reference thermocouple system was established early in the test period resulting in the elimination of errors due to shifts in ambient laboratory temperature.

Total test accuracy was estimated to be normally within $\pm$ 2% which includes (1) variations is load pressure (2) thermocouple -- instrumentation inaccuracies, and (3) fluxmeter errors.

This error is primarily based on measured Δt's greater than 2.5° C. Basic error increases to $\pm$10% with Δt's in the 0.5°C range.

At reduced contact pressures the basic limiting factor on measuring accuracy was imposed by a reduction in wattage flowing through the column which lowered the Δt's within the fluxmeter and test samples, allowing a greater percentage error to exist in the temperature measurements of these areas. At high contact pressures the basic limiting factor on measurement accuracy was imposed primarily by the low Δt measured between the test samples with moderate wattage flow.

2. Pressure Measurements

The accuracy of these measurements was considered to be within the repeatability of strain gage techniques since the load cell was of strain gauge type with bridge readout supplied by a Baldwin SR-4 Calibration Indicator. This pressure measurement accuracy was estimated to be the equivalent of $\pm$3 newtons/cm^2. The error was primarily a result of drift in the bridge internal power source.

3. Voltage Measurement

DC measurements of main heater input wattage were found during the test to normally agree within $\pm 5\%$ of calculated wattage derived from fluxmeter Δt data.

4. Radiation Shield Control

Radiation shield heater voltage was manually adjusted to within a ± 10 microvolt emf differential between measuring thermocouple on the surfaces of the radiation shield and the adjacent test column position. This is equivalent to $0.25^{\circ}K$.

An automatic heater control assembly was constructed and placed into operation during the last three test runs. The temperature tracking accuracy of the heater control units was based on the linearity of the sensing elements, which permitted a 0.4° K nonlinearity in the normal operating range of the test fixture. The units could be easily adjusted, to remove this error during unit operation.

Radiation loss was considered negligible even with a 1.0° C temperature differential between test column and radiation shields.

II. Test Data

A. Test Sample Material Characteristics.

Table III is a listing of the test sample material characteristics.

1. Thermal Conductivity.

Published data on Thermal Conductivity and data accrued during the test are shown in Table III. A comparison between published and test data conductivity values indicates:

a. Aluminum 6061-T6 (twelve samples) agreement within -31 to +12%.

b. Aluminum 356 (as cast) one sample, agreement within +4%.

c. Almag 35 (as cast) five samples, agreement within -13 %

d. Magnesium AZ91C-T4 (four samples) agreement within +12%

e. Mag Lithium LA-141 (two samples) agreement within +8%.

2. Material Hardness (Ball Indenter Method)

This method was used to measure base material hardness on the peripheral surface of the test samples. A one-eighth inch diameter ball indenter, applied with a 100 kilogram load, yielded Rockwell E. Scale readings of surface hardness. The resultant readings (average of three per sample) wese converted to equivalent readings on the Brinell, (BHN) Scale. The hardness of LA 141, however, was below the published lower limit on the Brinell scale and is thus reported as measured.

The overall range of hardness for the materials was:

a. Aluminum 6061-T6 (eleven samples) BHN 92-122.

b. Aluminum 356 (as cast) one sample BHN 53-56.

TABLE III
TEST SAMPLE MATERIAL CHARACTERISTICS

Upper Sample

Sample / Property	Units	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Sample		# 49 ALUMINUM 6061-T6	# 40 ALUMINUM 6061-T6	# 55 ALUMINUM 6061-T6	# 57 ALUMINUM 6061-T6	# 43 ALUMINUM 6061-T6	# 58 ALUMINUM 6061-T6	# 41 ALUMINUM 6061-T6	# 42 ALUM. 6061-T6	#44 ALUMINUM 6061-T6	#4 ALMAG 35 (As Cast)	ALUMINUM 6061-T6	ALUMINUM 6061-T6
Surface Finish (Avg.)	micron CLA	.07	1.23	1.71	1.91	1.19	2.00	1.03	0.86	0.91	0.84	0.46	0.69
Brinell Hardness Number	500Kg Ld. 10 mm Ball	---	112	95-96	93-97	106-107	106-108	119-122	102-109	112	70-71	92-97	92-96
Vickers Hardness Number	5 Kg. Ld. 136° Dia. Pt.	---	130	98-105	106-107	117	118	150-153	128-143	143-146	76-83	102-114	100-113
Yield Strength *	N/cm^2	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$28x10^3$	$14x10^3$	$28x10^3$	$28x10^3$
Modulus of Elasticity *	N/cm^2	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$6.9x10^6$	$7.2x10^6$	$6.9x10^6$	$6.9x10^6$
Poisson's Ratio *	---	.33	.33	.33	.33	.33	.33	.33	.33	.33	.33	.33	.33
Thermal Conductivity	W/cm °C	1.37	1.23	1.59	1.64	1.22	1.66	1.29	1.22	1.39	0.96	1.73	1.67
Thermal Conductivity *	W/cm °C	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.04	1.55	1.55

Lower Sample

Sample / Property	Units	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Sample		# 14 ALMAG 35 (As Cast)	# 2 ALUMINUM	# 52 ALMAG 35 (As Cast)	# 53 ALMAG 35 (As Cast)	# 22 MAGNESIUM AZ91C T4	# 54 ALMAG 35 (As Cast)	# 19 MAGNESIUM AZ91C T4	# 34 ALUMINUM 356	#26 MAGNESIUM AZ91C (Anodized)	#21 MAGNESIUM AZ91C T4	MAG-LITHIUM LA-141 (Anodized)	MAG-LITHIUM LA-141 (Beryllium)
Surface Finish	micron CLA (Avg)	.07	1.03	2.48	2.39	1.18	2.46	1.35	1.85	2.34	1.45	0.81	0.28
Brinell Hardness Number	500Kg. Ld. 10mm. Bl.	---	110-112	67-68.5	64-66.5	57-58.5	65.5-68.5	58.5-60	53-56	53-56	58	E 38-E 44	E37.5-E 43
Vickers Hardness Number	5 Kg. Ld. 136° Dia. Pt.	---	138-140	82-88	83-86	64-72	83-87	64-65	67-86	71.6	63-71	---	104-113
Yield Strength *	N/cm^2	$14x10^3$	$28x10^3$	$14x10^3$	$14x10^3$	$8x10^3$	$14x10^3$	$8x10^3$	$14x10^3$	$8x10^3$	$8x10^3$	$13x10^3$	$13x10^3$
Modulus of Elasticity *	N/cm^2	$7.2x10^6$	$6.9x10^6$	$7.2x10^6$	$7.2x10^6$	$4.5x10^6$	$6.5x10^6$	$4.5x10^6$	$7.0x10^6$	$4.5x10^6$	$4.5x10^6$	$4.1x10^6$	$4.1x10^6$
Poisson's Ratio *	---	.33	.33	.33	.33	.35	.33	.35	.33	.35	.35	.33	.33
Thermal Conductivity	W/cm °C	.90	1.07	.96	.93	.56	.92	.53	1.47	.56	.55	.45	.46
Thermal Conductivity *	W/cm °C	1.04	1.55	1.04	1.04	.50	1.04	.50	1.42	.50	.50	.43	.43

* Published Table Data

c. Almag 35 (as cast) four samples BHN 64-71.

d. Magnesium AZ91C-T4 (four samples) BHN 53-60.

e. Mag Lithium LA-141 (two samples) Rockwell E 38-44.

3. Material Hardness (Diamond Pyramid)

This method was used to measure material hardness on the sample test surface. Five readings per sample were taken upon completion of conductance testing. A 136° diamond point applied with a 5 kilogram load to the sample surfaces yielded Vickers hardness readings as shown in Table III.

In two cases (both anodized test samples) difficulty was experienced in obtaining readings.

The Magnesium AZ91C sample with black anodize surface finish (Run #9 lower sample) did not permit clear reflective viewing of the sample surface required to determine the size of indentation. Only one reading was obtained after many attempts to view diamond pyramid indentation on this sample.

The Mag Lithium LA-141 sample with anodize finish (lower sample Run #11) did not yield readings of surface hardness. On application of the diamond pyramid load,the surface anodizing chipped.

The ranges of Vickers surface hardness for the various test samples were:

a. Aluminum 6061-T6 - 92 to 153

b. Aluminum 356 - 67 to 86

c. Almag 35 - 76 to 89

d. Magnesium AZ91C - 63 to 72

e. Mag Lithium LA 141-104 to 113
(Beryllium Coated)

B. Surface Characteristics

Surface conditions were determined by analyzing strip chart data derived from two sources *

Proficorder

Talysurf

The primary difference between the two surface measuring systems was the ability of the Proficorder to scan across an entire test sample surface (approximately 3.8 cm) whereas the Talysurf scan distance was limited to $\approx$ 1.3 cm.

Table III presents the surface finish data for each of the twenty-four test samples. Surface finish is described as the centerline average deviation (CLA) for a total scan. CLA alone, however, is not considered to be an adequate description of surface conditions for the purpose of analysis.

Additional surface data were reduced from Proficorder and Talysurf test charts. These data are presented in Table IV and consist of (a) the average roughness height and width produced by each pass of the flycutter in the milling process, (b) The average waviness produced by variations in flycutter position with respect to the sample surface during the milling operation, and (c) the average flatness deviation of the waviness peaks on the sample surface.

Sample orientation between the upper and lower samples for test runs #2, 5, 7, 8, 9 and 10 was reconstructed to view the overall effects of surface waviness. A carbon film applied to the test sample surfaces accentuated the surface waviness allowing viewing of matching surface patterns. These waviness characteristics were noted as repeating at intervals of 0.84 to 0.99 centimeters along the sample surface. Approximately 4.2 wave cycles appeared on each sample surface exhibiting these

* Trademarks

(1) Micrometrical Proficorder, Micrometrical Manufacturing Co. Ann Arbor, Michigan

(2) Talysurf Model 3, Taylor, Taylor and Hobson Ltd. Liecester, England

TABLE IV

TEST SAMPLE SURFACE DATA

Test Run No.	CLA (microns)	Roughness height (microns)	Roughness width (microns)	Waviness height (microns)	Waviness width (cm)	Flatness height (microns)	Flatness width (cm)
Upper Test Samples							
1	0.07	N.A.	N.A.	N.A.	N.A.	0.75 *	3.81 *
2	1.23	3.84	330	14.4	0.99	3.37	2.81
3	1.71	4.50	113	N.A.	N.A.	2.85	3.71
4	1.91	4.72	116	N.A.	N.A.	3.30	3.65
5	1.19	3.56	300	10.8	0.89	2.54	3.80
6	2.00	6.12	98	N.A.	N.A.	6.35	3.69
7	1.03	3.37	328	14.2	0.91	0.63	3.47
8	0.86	3.81	330	10.2	0.84	1.40	3.80
9	0.91	3.82	338	10.7	0.83	4.03	3.73
10	0.84	3.82	325	7.6	0.91	1.10	3.79
11	0.41	---	---	N.A.	N.A.	0.20	1.30
12	0.69	---	---	N.A.	N.A.	0.30	1.30
Lower Test Samples							
1	0.07	N.A.	N.A.	N.A.	N.A.	0.75 *	3.81 *
2	1.03	3.06	330	14.0	0.94	2.54	3.52
3	2.48	8.32	119	N.A.	N.A.	2.29	3.23
4	2.39	8.46	119	N.A.	N.A.	3.30	3.71
5	1.18	3.82	306	8.1	0.76	18.80	3.80
6	2.46	8.39	108	N.A.	N.A.	4.45	3.73
7	1.35	4.90	329	7.6	0.93	0.26	3.20
8	1.85	9.14	320	19.0	0.89	5.60	3.63
9	2.34	8.90	320	10.9	0.89	1.30	3.74
10	1.45	5.90	327	9.7	0.95	1.40	3.72
11	0.81	---	---	N.A.	N.A.	0.60	1.30
12	0.28	---	---	N.A.	N.A.	0.10	1.30

N.A. Not Applicable
* Estimated

waviness characteristics, with the exception of the lower test sample for Run #5 which exhibited only two distinct surface waves each 0.76 centimeters apart. Further analysis of this sample indicated a concave deviation in surface flatness of 18.8 microns which is approximately three times greater in magnitude than any other test sample.

Figure 4 is a photograph of two typical samples shown with carbon treated surfaces. Note the basic ridge patterns on each sample surface. Placement of the samples (orientation) could allow surface patterns to overlay on ridge patterns, with five major contact areas existing, or with a 90° shift in sample orientation to produce sixteen to seventeen contact areas on the ridge patterns.

The total maximum number of contact areas noted when when reorienting the samples as placed in the test fixture were:

Run #2 - 14
Run #5 - 14
Run #7 - 5
Run #8 - 15
Run #9 - 16
Run #10 - 17

Test samples from the remaining runs did not exhibit this type of waviness or any recurrent ridge pattern, hence could not be analyzed for apparent areas of surface contact.

C. Contact Conductance vs. Contact Pressure

1. Run #1 Aluminum 6061-T6
Almag 35 (as cast)

The surfaces of the two test samples were lapped to a 0.07 micron CLA surface finish prior to conductance testing. Objective of the run was to determine the degree of accuracy obtainable with the test hardware.

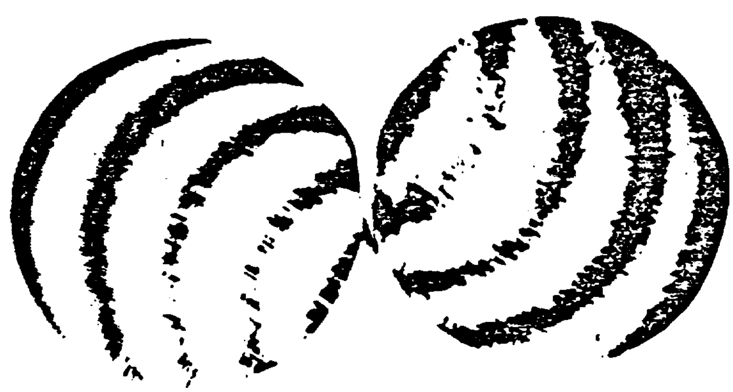
Temperature measurements within each of the measuring planes (same lateral position in fixtures) were found to differ not more than 0.5° C. The difference reflected a change in calculated conductance of approximately 10% at lower contact loads and approximately 5% at higher loads.

Thermocouple instrumentation was referenced to the ambient temperature environment during this run.

As previously noted in Basic Considerations, Instrumentation, Page 12 other inaccuracies introduced gross errors when working with low Δt's (temperature differentials). The average expected contact conductance characteristics for Run #1 are plotted in Figure 5.

Table V lists test conditions and calculated results for Run #1 for thermocouple positions located vertically across the upper and lower samples shown as Short, Long and Average. If heat flow between the test samples were identical at all surface locations the three sets of data would be identical.

Tests seven through ten data, presented in Table V, established conductivity levels upon returning to low applied pressures as being appreciably higher than during initial tests (hysteris effect).



CARBON TREATED TEST SAMPLE SURFACES

FIGURE 4

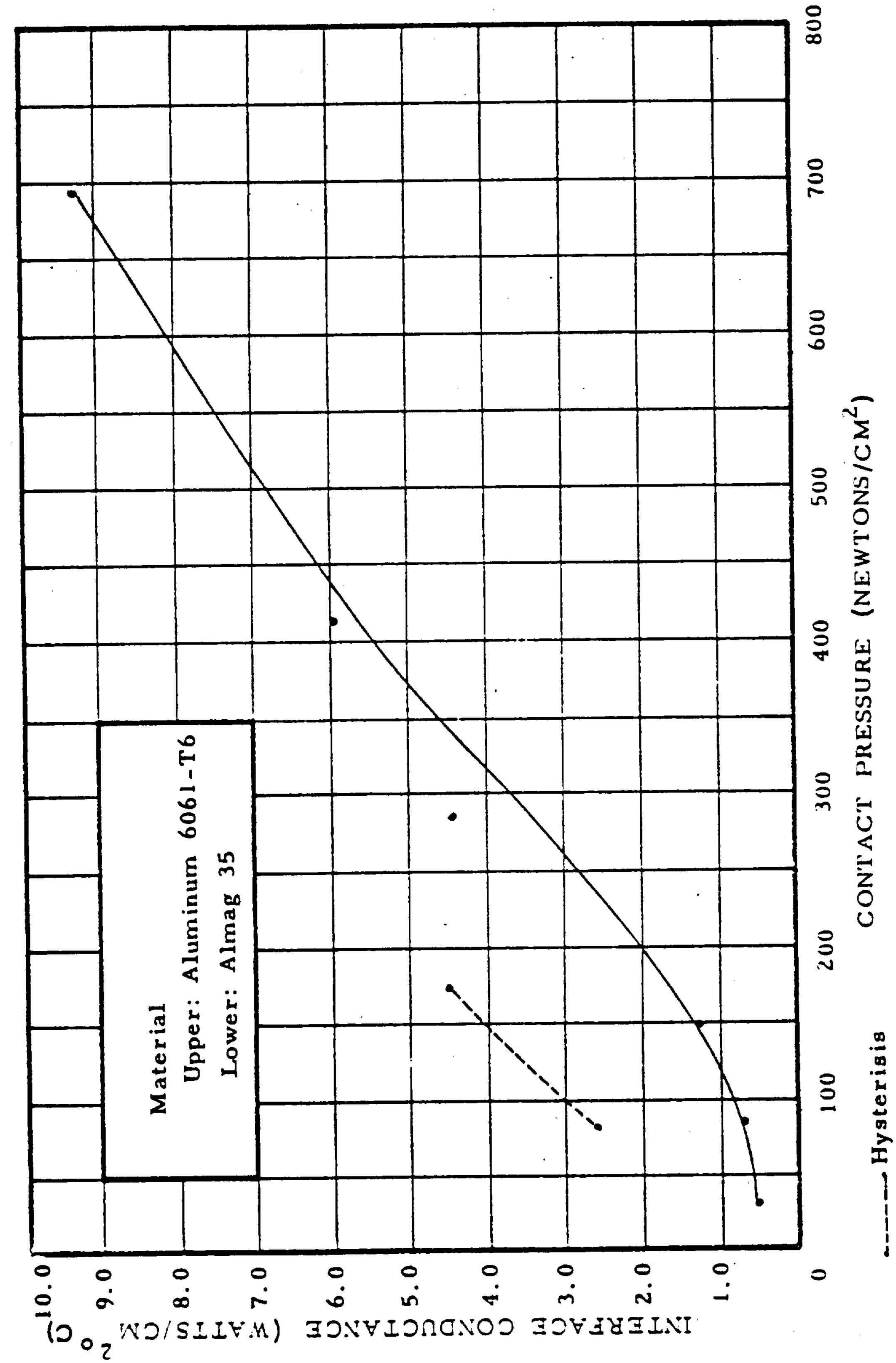


FIGURE 5 - AVERAGE CONTACT CONDUCTANCE - RUN 1

TABLE V CONTACT CONDUCTANCE DATA
RUN 1

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	7.5×10^{-6}	29.0	28.53	3.91	0.640	28.79	5.70	0.443	28.66	4.80	0.523
B	7.5×10^{-6}	29.0	28.54	3.91	0.640	28.79	5.70	0.443	28.66	4.81	0.523
2-A	1.7×10^{-5}	80.8	28.53	2.54	0.987	28.73	3.89	0.647	28.63	3.22	0.781
B	1.7×10^{-5}	80.8	28.50	2.54	0.985	28.73	3.89	0.647	28.61	3.22	0.781
3-A	2.8×10^{-5}	144.9	28.91	1.75	1.453	29.13	2.36	1.083	29.02	2.05	1.240
B	2.8×10^{-5}	144.9	28.96	1.65	1.541	29.14	2.31	1.106	29.05	1.98	1.287
4-A	1.2×10^{-4}	285.4	28.87	0.49	5.185	29.18	0.65	3.948	29.03	0.57	4.479
B	1.2×10^{-4}	285.4	28.73	0.54	4.676	29.01	0.58	4.391	28.87	0.56	4.528
C	1.2×10^{-4}	285.4	29.00	0.60	4.207	29.22	0.67	3.821	29.11	0.64	4.004
5	8.0×10^{-5}	415.8	28.89	0.49	5.136	29.26	0.36	7.063	29.08	0.43	5.953
6	2.0×10^{-4}	693.4	28.83	0.37	6.755	29.21	0.17	14.895	29.02	0.27	9.317
7	2.0×10^{-5}	80.9	29.36	0.84	3.066	29.76	1.12	2.335	29.56	0.98	2.648
8	1.0×10^{-4}	168.3	29.23	0.59	4.351	29.70	0.55	4.709	29.47	0.57	4.525
9	1.1×10^{-4}	317.2	29.17	0.45	5.745	29.54	0.17	15.320	29.35	0.31	8.381
10	6.5×10^{-4}	592.0	28.89	0.35	7.309	29.29	-0.05	-53.324	29.09	0.15	17.095

2. Run #2 Aluminum 6061-T6
Aluminum 6061-T6

Both sample test joints surfaces were flycutter machined to 1.23 and 1.03 microns CLA (upper and lower) respectively. Both samples exhibited noticeable surface waviness characteristics. Orientation of samples in their test atitude revealed contact between samples was distributed through approximately fourteen contact areas.

Upon completion of conductance testing at the max load (700 newtons/cm^2), reduced the load to 145 newtons/cm^2 to check hysteresis effect. Hysteresis shows an approximate 12% increase over initial heat transfer data at 145 newtons/cm^2.

Figure 6 is a plot of Average Contact Conductance vs. Contact Pressure. Table VI presents test data for Run #2 derived from the Δt across the test samples.

TABLE VI - CONTACT CONDUCTANCE DATA

RUN 2

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	6.5×10^{-4}	33.4	29.40	11.28	0.229	29.73	13.96	0.187	29.57	12.62	0.206
B	3.0×10^{-5}	33.4	44.55	14.59	0.268	42.43	41.88	0.089	43.49	28.24	0.135
2	4.0×10^{-5}	82.5	41.88	10.31	0.356	42.48	13.12	0.284	42.18	11.72	0.316
3-A	5.0×10^{-5}	145.5	41.87	8.00	0.459	42.27	10.40	0.356	42.07	9.20	0.401
B	5.0×10^{-5}	145.5	41.88	7.96	0.462	42.18	10.44	0.354	42.03	9.20	0.401
C	5.0×10^{-5}	145.5	41.81	7.83	0.468	42.28	10.33	0.359	42.05	9.08	0.406
4-A	2.5×10^{-4}	289.8	41.75	5.57	0.658	42.18	7.55	0.490	41.96	6.56	0.561
B	2.5×10^{-4}	289.8	41.69	5.52	0.663	42.14	7.47	0.495	41.92	6.50	0.566
5-A	4.5×10^{-4}	415.8	41.54	4.46	0.816	42.01	6.14	0.601	41.78	5.30	0.692
B	4.5×10^{-4}	415.8	41.76	4.41	0.830	42.21	6.11	0.606	41.99	5.26	0.700
6-A	7.0×10^{-4}	552.9	41.70	3.59	1.018	42.16	4.69	0.788	41.93	4.14	0.888
B	7.0×10^{-4}	552.9	41.71	3.60	1.017	42.16	4.95	0.746	41.93	4.27	0.860
C	7.0×10^{-4}	552.9	41.68	3.57	1.024	42.16	5.02	0.737	41.93	4.29	0.857
7	1.0×10^{-3}	700.1	41.68	3.10	1.180	42.16	4.12	0.898	41.92	3.61	1.019
8-A	6.5×10^{-5}	144.9	41.83	7.00	0.524	42.19	9.43	0.393	42.01	8.22	0.447
B	6.5×10^{-5}	144.9	41.89	7.02	0.523	42.38	9.50	0.391	42.13	8.26	0.447

Run #3 Aluminum 6061-T6
Almag 35

Proficorder data of sample surfaces indicated (1) the Aluminum sample contact surface was flycutter machined to a 1.71 micron CLA surface and (2) the Almag sample contact surface was flycutter machined to a 2.48 micron CLA surface. The data also indicated negligible surface waviness with no apparent wave pattern.

Figure 7 is the plot of Average Contact Conductance vs. Load for Run #3. Table VII is a listing of test conditions noted during Run #3 and presents the contact conductance between sample surfaces at locations denoted as Long, Short, and Average.

Run #3, Test 7, shown in Table VII was performed to check hysteresis effect following maximum pressure application. The result indicates no appreciable increase in contact conductance due to hysteresis.

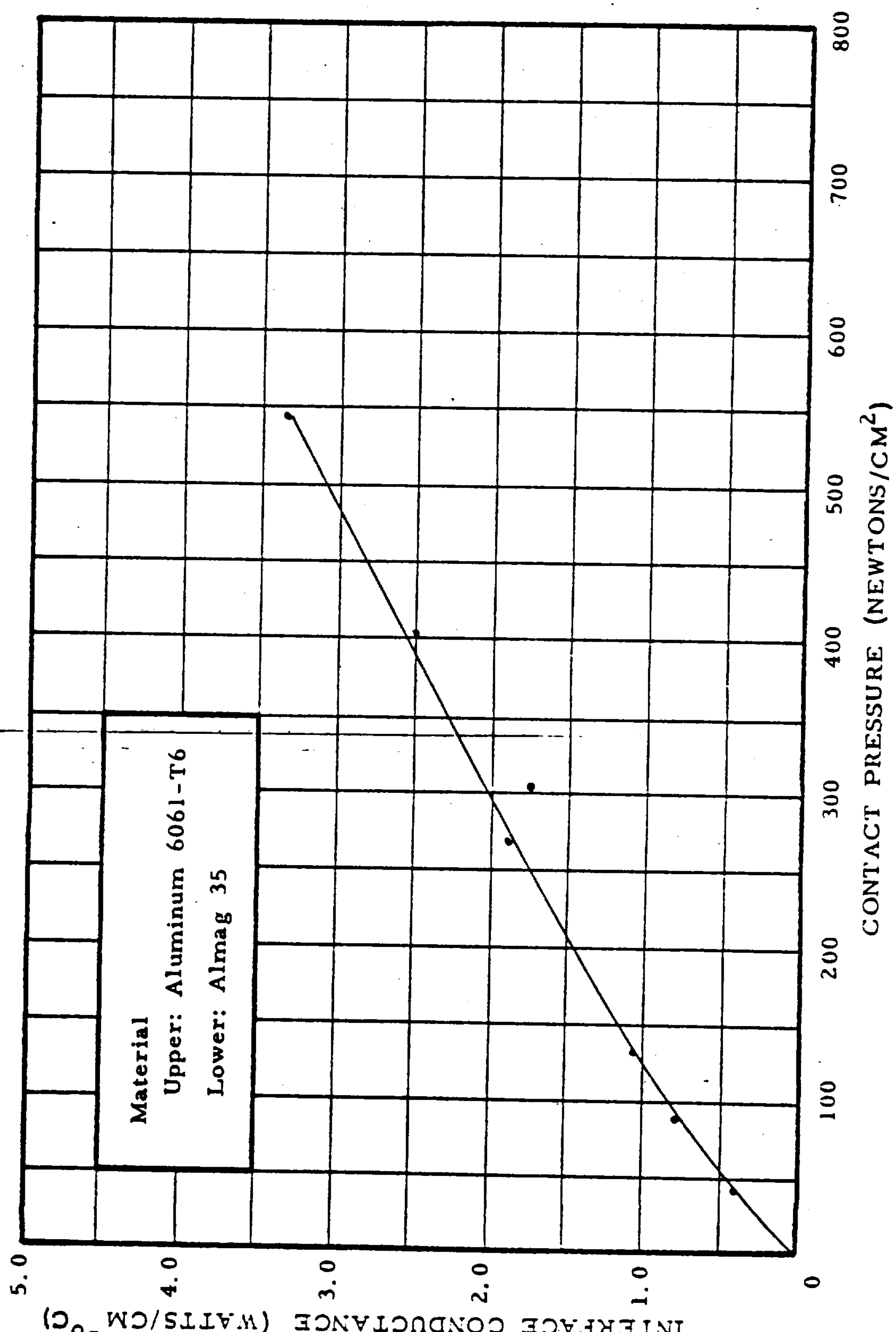


FIGURE 7 - AVERAGE CONTACT CONDUCTANCE - RUN 3

TABLE VII CONTACT CONDUCTANCE DATA

RUN 3

Test	Vacuum Pressure (mm Hg)	Load ([illegible]/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	1.0×10^{-6}	41.2	42.15	9.27	0.399	42.65	8.20	0.456	42.40	8.74	0.426
B	1.0×10^{-6}	41.2	42.22	9.30	0.398	43.55	8.27	0.462	42.88	8.78	0.428
2-A	5.6×10^{-7}	89.2	42.06	5.02	0.735	42.46	4.39	0.849	42.26	4.70	0.788
B	5.6×10^{-7}	89.2	42.01	4.97	0.741	42.48	4.39	0.849	42.24	4.68	0.792
3-A	2.5×10^{-6}	131.5	41.75	3.77	0.972	42.14	3.15	1.172	41.95	3.46	1.063
B	5.7×10^{-7}	133.8	42.58	3.52	1.061	42.42	2.97	1.255	42.50	3.24	1.149
C	5.7×10^{-6}	133.8	42.44	3.60	1.033	42.34	3.04	1.222	42.39	3.32	1.120
4-A	6.2×10^{-7}	269.8	41.78	2.23	1.646	42.26	1.84	2.015	42.02	2.03	1.813
B	4.0×10^{-7}	304.3	42.08	2.40	1.539	42.24	1.83	2.020	42.16	2.12	1.747
5-A	6.0×10^{-7}	403.6	41.59	1.60	2.275	42.27	1.40	2.664	41.93	1.50	2.456
B	6.0×10^{-7}	403.6	41.74	1.61	2.275	42.15	1.30	2.852	41.94	1.45	2.533
6-A	5.1×10^{-7}	541.8	41.70	1.27	2.888	42.02	0.934	3.948	41.86	1.10	3.338
B	5.1×10^{-7}	541.8	41.50	1.21	3.003	42.08	0.958	3.853	41.79	1.09	3.378
7	2.2×10^{-6}	78.0	41.72	6.11	0.599	42.08	5.838	0.632	41.90	5.97	0.615

Run #4 Aluminum 6061-T6
Almag 35

The purpose of this test run was to determine the degree of repeatability which could be expected when testing similar materials. This test was a repeat of Run #3 with comparable samples. Repeatability is shown by plotting Run #3 Contact Conductance Data on Figure 8.

Sample surface conditions were (upper) 1.91 microns CLA and (lower) 2.39 microns CLA. The surfaces however, were quite flat exhibiting no waviness characteristics and only flatness deviations due to surface roughness. Accordingly this constitutes good surface conditions for heat transfer as in the case of Run #3.

Table VIII is a listing of Contact Conductance Data for Run #4.

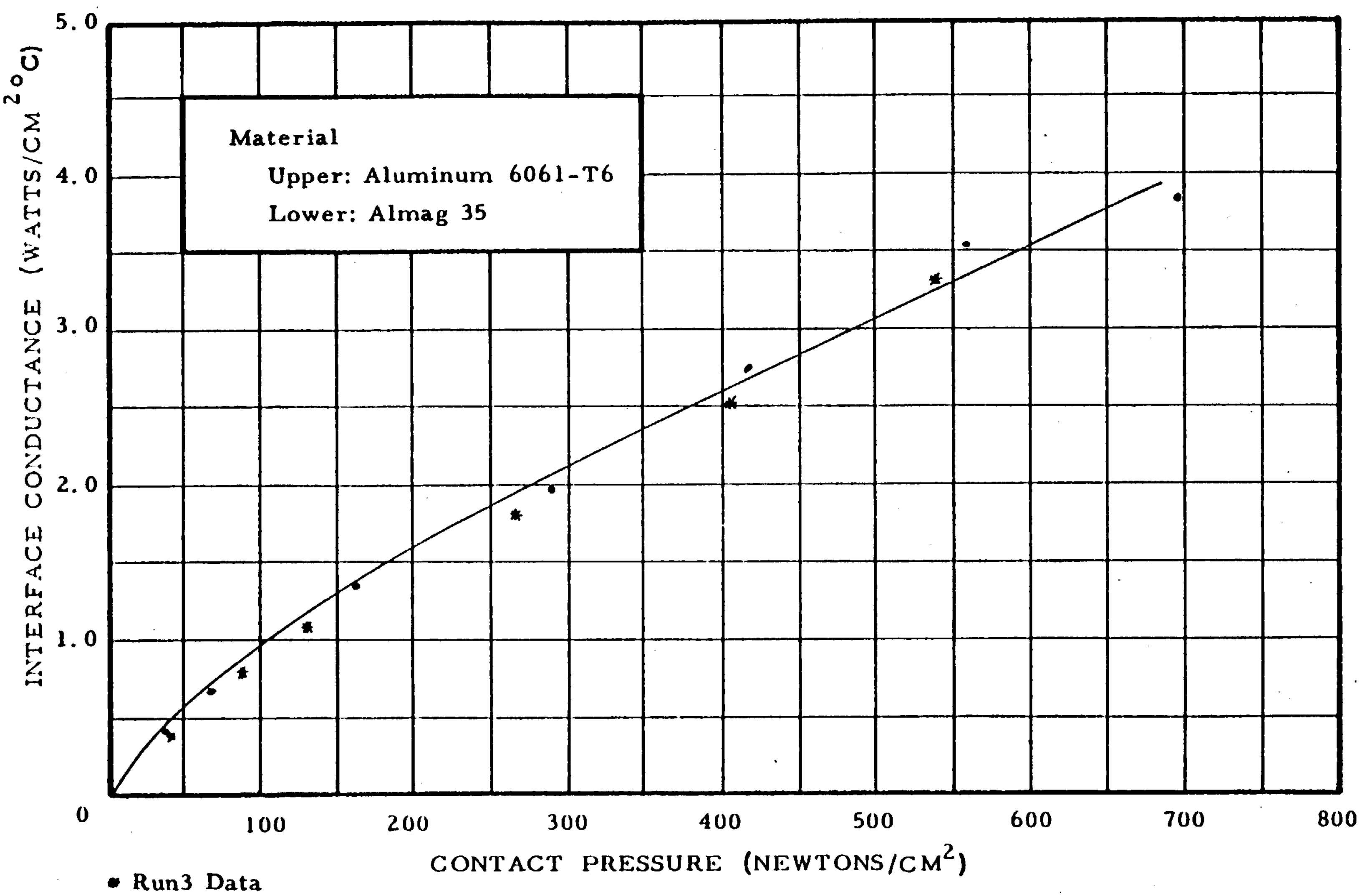


FIGURE 8 - AVERAGE CONTACT CONDUCTANCE RUN 4

TABLE VIII CONTACT CONDUCTANCE DATA

RUN 4

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	3.0×10^{-6}	35.7	42.24	8.27	0.448	42.50	9.49	0.393	42.37	8.88	0.418
B	3.0×10^{-6}	35.7	42.38	8.21	0.453	42.18	9.50	0.390	42.28	8.85	0.419
2-A	2.0×10^{-6}	69.1	42.05	5.32	0.693	42.35	6.07	0.612	42.20	5.70	0.650
B	2.0×10^{-6}	69.1	42.18	5.26	0.704	42.35	6.09	0.610	42.26	5.67	0.654
3-A	6.0×10^{-7}	162.8	41.72	2.66	1.374	42.23	2.89	1.284	41.97	2.77	1.327
B	6.0×10^{-7}	162.8	41.72	2.66	1.378	42.22	2.89	1.280	41.97	2.90	1.270
4-A	6.5×10^{-7}	289.8	41.64	1.80	2.031	41.98	1.98	1.862	41.81	1.89	1.942
B	6.5×10^{-7}	289.8	41.67	1.80	2.034	41.85	1.93	1.898	41.76	1.87	1.964
5-A	7.0×10^{-7}	416.9	41.54	1.28	2.844	42.03	1.36	2.703	41.78	1.32	2.771
B	7.0×10^{-7}	416.9	41.63	1.30	2.803	42.00	1.39	2.653	41.82	1.39	2.634
6-A	7.0×10^{-7}	556.3	41.50	1.00	3.632	41.82	1.07	3.436	41.66	1.04	3.531
B	7.0×10^{-7}	555.2	41.44	0.95	3.837	41.99	1.10	3.364	41.72	1.02	3.583
7-A	7.0×10^{-7}	692.3	41.43	0.90	4.047	41.84	0.96	3.826	41.63	0.93	3.932
B	7.0×10^{-7}	692.3	41.57	0.88	4.148	41.85	1.08	3.390	41.71	0.98	3.730

Run #5 Aluminum 6061-T6
Magnesium AZ91C

Surface finish for the test samples was (upper) 1.19 microns CLA and (lower) 1.18 microns CLA.

The prime objective during this test was to determine the near optimal value of heat transfer. Plots of the initial and final runs with cyclic variation of test pressures are presented in Figure 9. It will be noted that final levels are approximately 0.1 watts/cm^2°C above original levels.

Although surface finish based on CLA data shows a better finish (2X) than previous test runs with Aluminum and Almag 35, the Contact Conductance Values are approximately one third that of the previous data. A characteristic ridge pattern was however noted on both test samples. Reconstruction of test sample mating revealed only limited area of ridge contact between test samples due to concavity of the lower test sample.

Table IX - 1 and IX - 2 lists the Contact Conductance Data which includes measured Δ t's recorded across test sample surfaces during the test.

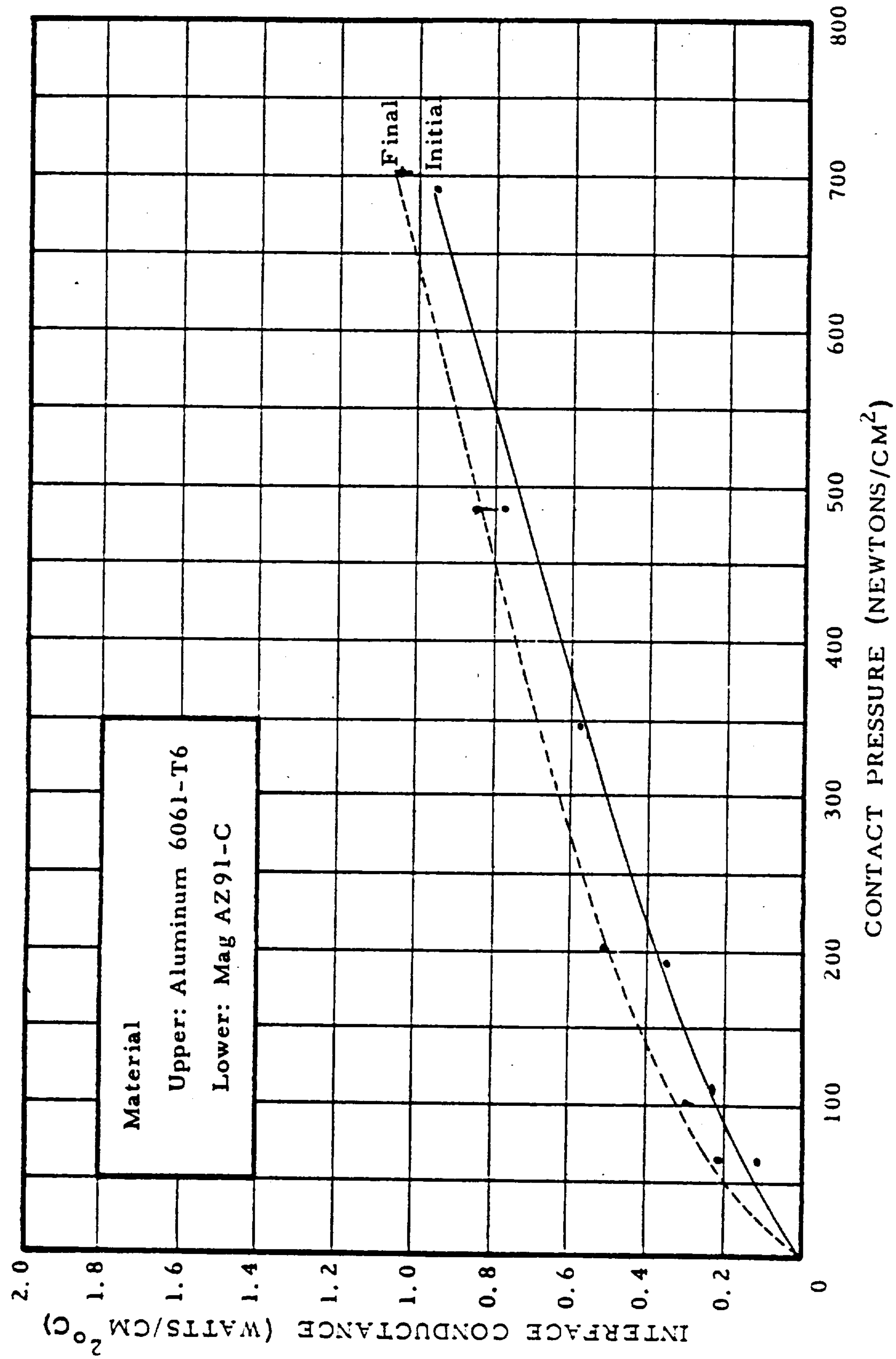


FIGURE 9 - AVERAGE CONTACT CONDUCTANCE - RUN 5

TABLE IX - 1 CONTACT CONDUCTANCE DATA

RUN 5

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	1.2×10^{-6}	62.4	41.43	27.69	0.131	41.69	31.91	0.115	41.56	29.80	0.122
B	1.2×10^{-6}	62.4	41.35	27.46	0.132	41.73	31.71	0.115	41.54	29.58	0.123
2-A	1.0×10^{-6}	101.4	41.65	18.15	0.201	42.04	21.05	0.175	41.84	19.60	0.187
B	1.0×10^{-6}	101.4	41.41	17.56	0.207	41.85	21.01	0.175	41.63	19.29	0.189
C	1.0×10^{-6}	101.4	41.50	17.53	0.208	42.00	21.00	0.175	41.75	19.26	0.190
3-A	2.0×10^{-6}	190.1	41.43	9.65	0.377	41.94	11.08	0.332	41.69	10.36	0.353
B	2.0×10^{-6}	190.1	40.58	9.62	0.370	41.86	10.98	0.334	41.22	10.30	0.351
4-A	4.7×10^{-6}	345.0	41.38	5.84	0.622	41.86	6.64	0.553	41.62	6.24	0.585
B	4.7×10^{-6}	345.0	40.57	5.91	0.602	41.81	6.60	0.556	41.19	6.25	0.578
C	4.7×10^{-6}	345.0	41.35	5.86	0.619	41.81	6.62	0.554	41.58	6.24	0.584
5-A	1.5×10^{-6}	486.0	41.06	4.42	0.814	41.52	4.96	0.734	41.29	4.69	0.772
B	7.0×10^{-7}	486.0	41.08	4.42	0.816	41.50	4.88	0.746	41.29	4.65	0.779
6-A	1.0×10^{-6}	690.1	41.10	3.69	0.976	41.54	3.98	0.917	41.32	3.83	0.946
B	1.0×10^{-6}	690.1	41.02	3.65	0.987	41.55	3.97	0.917	41.29	3.81	0.951
C	5.0×10^{-7}	693.4	41.08	3.62	0.995	41.52	3.96	0.919	41.30	3.79	0.955
D	5.0×10^{-7}	693.4	41.11	3.63	0.993	41.70	3.97	0.922	41.41	3.80	0.956
7-A	4.5×10^{-7}	455.9	40.97	3.78	0.950	41.41	4.02	0.903	41.19	3.90	0.926
B	4.5×10^{-7}	455.9	41.01	3.83	0.940	41.50	4.11	0.886	41.26	3.97	0.912
8-A	4.5×10^{-7}	345.0	41.25	4.89	0.739	41.62	5.40	0.676	41.44	5.15	0.706
B	4.5×10^{-7}	345.0	41.22	4.91	0.737	41.62	5.40	0.676	41.42	5.16	0.705
C	4.5×10^{-7}	345.0	41.17	4.84	0.746	41.54	5.44	0.670	41.36	5.14	0.706
9-A	9.0×10^{-7}	200.7	41.18	6.91	0.523	41.53	7.88	0.462	41.35	7.39	0.491
B	7.5×10^{-7}	200.7	41.28	6.82	0.531	41.75	7.88	0.465	41.51	7.35	0.496
10-A	1.6×10^{-6}	98.1	41.43	12.02	0.302	41.82	15.03	0.244	41.63	13.52	0.270
B	1.6×10^{-6}	99.2	41.45	11.98	0.304	41.78	15.10	0.243	41.62	13.53	0.270
11-A	1.0×10^{-6}	65.8	41.45	17.33	0.210	41.91	21.42	0.172	41.68	19.37	0.189
B	1.0×10^{-6}	66.9	41.30	16.56	0.219	41.78	21.38	0.171	41.54	18.97	0.192

TABLE IX - 2 CONTACT CONDUCTANCE DATA

RUN 5 (cont'd)

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
12-A	8.0×10^{-7}	100.3	41.33	12.31	0.295	41.79	13.79	0.266	41.56	13.05	0.279
B	8.0×10^{-7}	100.3	41.24	12.32	0.294	41.81	13.77	0.266	41.53	13.04	0.279
13-A	5.0×10^{-7}	202.9	41.30	6.66	0.544	41.74	7.70	0.475	41.52	7.18	0.507
B	5.0×10^{-7}	202.9	41.18	7.05	0.512	41.69	8.34	0.439	41.43	7.69	0.472
C	5.0×10^{-7}	202.9	41.17	7.05	0.513	41.40	8.25	0.440	41.29	7.65	0.474
14-A	5.0×10^{-7}	479.4	40.94	4.18	0.859	41.43	4.69	0.775	41.18	4.43	0.815
B	5.0×10^{-7}	479.4	41.07	4.15	0.867	41.54	4.69	0.777	41.30	4.42	0.819
C	7.0×10^{-7}	477.1	41.10	4.57	0.790	41.55	4.57	0.797	41.32	4.57	0.793
15-A	6.0×10^{-7}	693.4	40.98	3.46	1.038	41.48	3.70	0.984	41.23	3.58	1.010
B	6.0×10^{-7}	693.4	40.95	3.46	1.037	41.26	3.71	0.974	41.10	3.59	1.005
16-A	7.0×10^{-7}	705.1	40.79	3.34	1.071	41.21	3.55	1.017	41.00	3.45	1.043
B	7.0×10^{-7}	705.1	40.94	3.34	1.077	41.05	3.52	1.023	41.00	3.43	1.049
17-A	5.0×10^{-7}	482.7	40.97	3.88	0.927	41.37	4.23	0.859	41.17	4.05	0.891
B	5.0×10^{-7}	482.7	40.91	3.90	0.920	41.34	4.21	0.861	41.12	4.06	0.889
18-A	4.0×10^{-7}	201.8	41.01	6.32	0.569	41.35	7.42	0.489	41.18	6.87	0.526
B	4.0×10^{-7}	201.8	41.01	6.30	0.571	41.38	7.37	0.492	41.19	6.83	0.529
19-A	4.5×10^{-7}	100.3	41.11	10.61	0.340	41.42	13.37	0.272	41.26	11.99	0.302
B	4.5×10^{-7}	100.3	41.25	10.65	0.340	41.58	13.33	0.274	41.42	11.99	0.303
20-A	4.5×10^{-7}	65.8	41.33	15.19	0.239	41.80	19.13	0.192	41.57	17.16	0.212
B	4.5×10^{-7}	65.8	41.23	15.33	0.236	41.54	19.10	0.191	41.39	17.21	0.211
21-A	5.5×10^{-7}	101.4	41.04	10.80	0.333	41.66	13.67	0.267	41.35	12.24	0.296
B	5.5×10^{-7}	101.4	41.40	10.76	0.338	41.57	13.69	0.266	41.49	12.23	0.298
22-A	4.0×10^{-7}	202.3	41.00	6.44	0.558	41.51	7.78	0.468	41.25	7.11	0.509
B	3.5×10^{-7}	202.3	40.99	6.49	0.554	41.36	7.78	0.466	41.18	7.13	0.506
23-A	6.0×10^{-7}	486.0	40.86	3.87	0.926	41.14	4.35	0.830	41.00	4.11	0.875
B	6.0×10^{-7}	486.0	40.79	4.15	0.863	41.07	4.39	0.821	40.93	4.27	0.841
24-A	5.0×10^{-7}	702.3	40.72	3.46	1.033	41.16	3.46	1.045	40.94	3.46	1.039
B	5.0×10^{-7}	702.3	40.69	3.23	1.106	41.08	3.47	1.038	40.89	3.35	1.071

Run #6 Aluminum 6061-T6
Silicone Grease (Interstitial Layer)
Almag 35

This test run was performed to determine the effectivness of an interstitial layer of silicone grease applied between the test samples. Surface finish was (upper) 2.00 microns CLA and (lower) 2.46 microns CLA. Profilometer recordings indicated that sample surfaces were flat and consistent with finishes on samples used for test Runs #3 and 4. Thus test data should be comparable if silicone grease were not used as an interstitial material.

Test data indicates a marked improvement in heat transfer at lower contact pressures but only a slight improvement at higher pressures over previous test data at Runs #3 and 4.

Figure 10 is the plot of Contact Conductance vs. Contact Pressure for Run #6. Table X is the listing of Contact Conductance Data for Run #6.

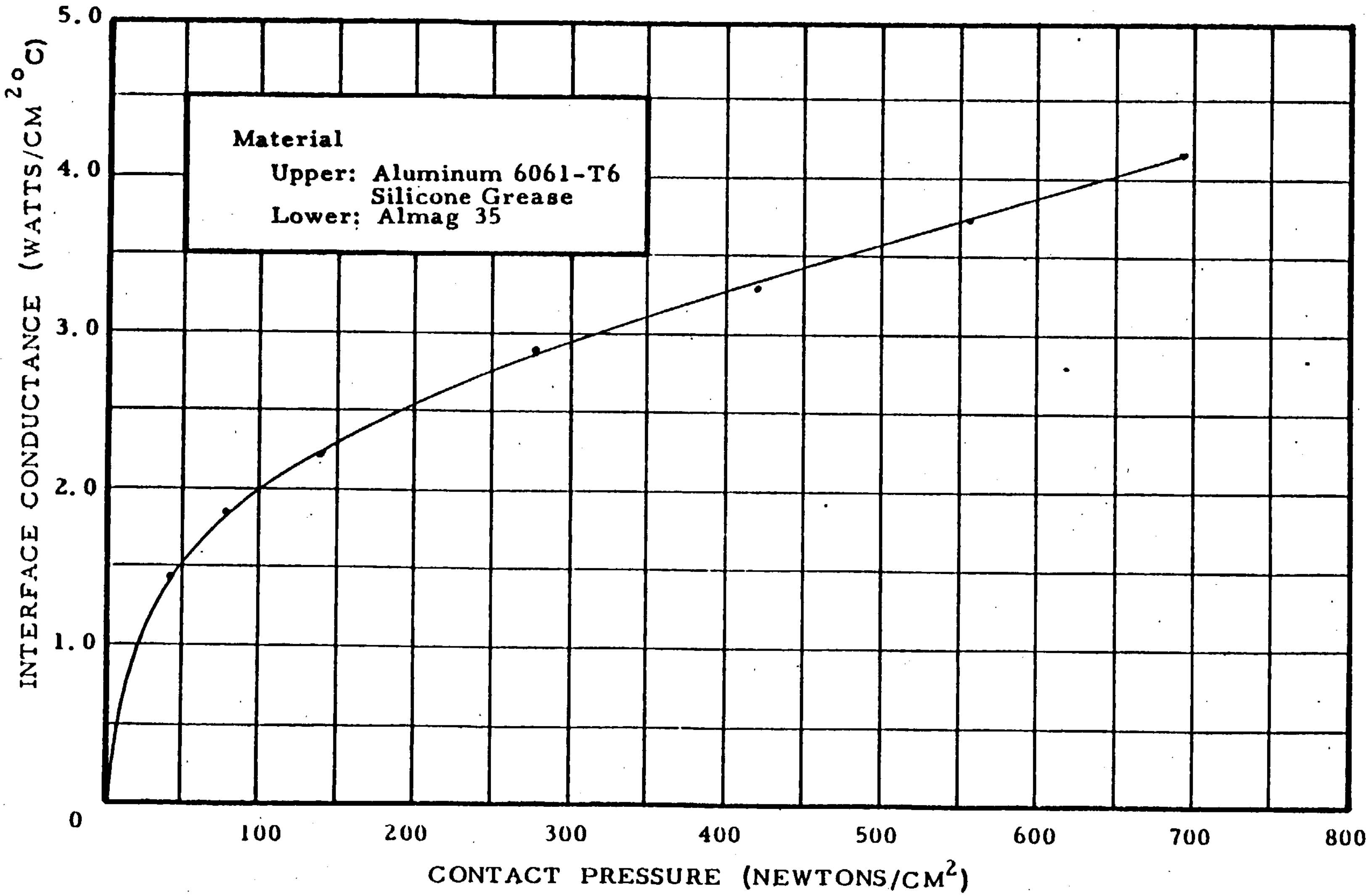


FIGURE 10 - AVERAGE CONTACT CONDUCTANCE - RUN 6

TABLE X - CONTACT CONDUCTANCE DATA

RUN 6

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	5.0×10^{-7}	33.4	41.62	2.29	1.595	42.17	3.44	1.075	41.89	2.87	1.283
B	5.0×10^{-7}	33.4	41.73	1.73	2.118	42.15	2.83	1.308	41.94	2.28	1.615
2-A	6.0×10^{-7}	76.9	41.27	1.70	2.135	41.86	2.28	1.610	41.56	1.99	1.834
B	6.0×10^{-7}	76.9	41.38	1.78	2.035	41.66	2.29	1.598	41.52	2.04	1.790
3-A	3.0×10^{-7}	138.2	41.27	1.49	2.433	41.78	2.00	1.830	41.53	1.75	2.087
B	3.0×10^{-7}	138.2	41.40	1.44	2.524	41.81	1.97	1.860	41.60	1.71	2.140
4-A	3.0×10^{-7}	276.5	41.61	1.04	3.508	41.46	1.48	2.453	41.53	1.26	2.888
B	3.0×10^{-7}	276.5	41.61	0.99	3.676	42.00	1.51	2.447	41.80	1.25	2.935
5-A	3.5×10^{-7}	416.9	41.64	0.87	4.175	41.92	1.35	2.718	41.78	1.11	3.290
B	3.5×10^{-7}	416.9	41.61	0.85	4.283	42.03	1.34	2.754	41.82	1.10	3.349
6-A	1.0×10^{-7}	555.2	41.56	0.78	4.658	41.90	1.17	3.132	41.73	0.98	3.743
B	1.0×10^{-7}	555.2	41.59	0.78	4.665	41.82	1.20	3.066	41.70	0.99	3.698
7-A	1.0×10^{-6}	691.2	40.99	0.71	5.095	41.30	1.05	3.462	41.14	0.88	4.119
B	1.0×10^{-6}	691.2	41.16	0.70	5.136	41.54	1.03	3.549	41.35	0.87	4.194

Run #7 Aluminum 6061-T6
Magnesium AZ91C

Surface conditions of the test samples were (upper) 1.03 microns CLA and (lower) 1.35 microns CLA. Inspection of the sample surfaces revealed a surface ridge condition similar to many samples used in previous runs.
Surface conditions were in fact similar to those of Run #5 with one exception, the lower sample surface concavity which existed in Run #5 did not appear on these samples. The resultant data indicates 40% increase in contact conductance compared to Run #5. Inspection of surface contact areas indicated that the five major ridges on each sample had been in contact, compared to the fourteen ridge contacts noted when mating samples of Run #5. Run #7 data indicates that a "Best Case" mating condition of test samples surfaces existed.

Figure 11 presents the plot of Contact Conductance vs. Contact Pressure for Run #7. Table XI lists Contact Conductance Data for Run #7.

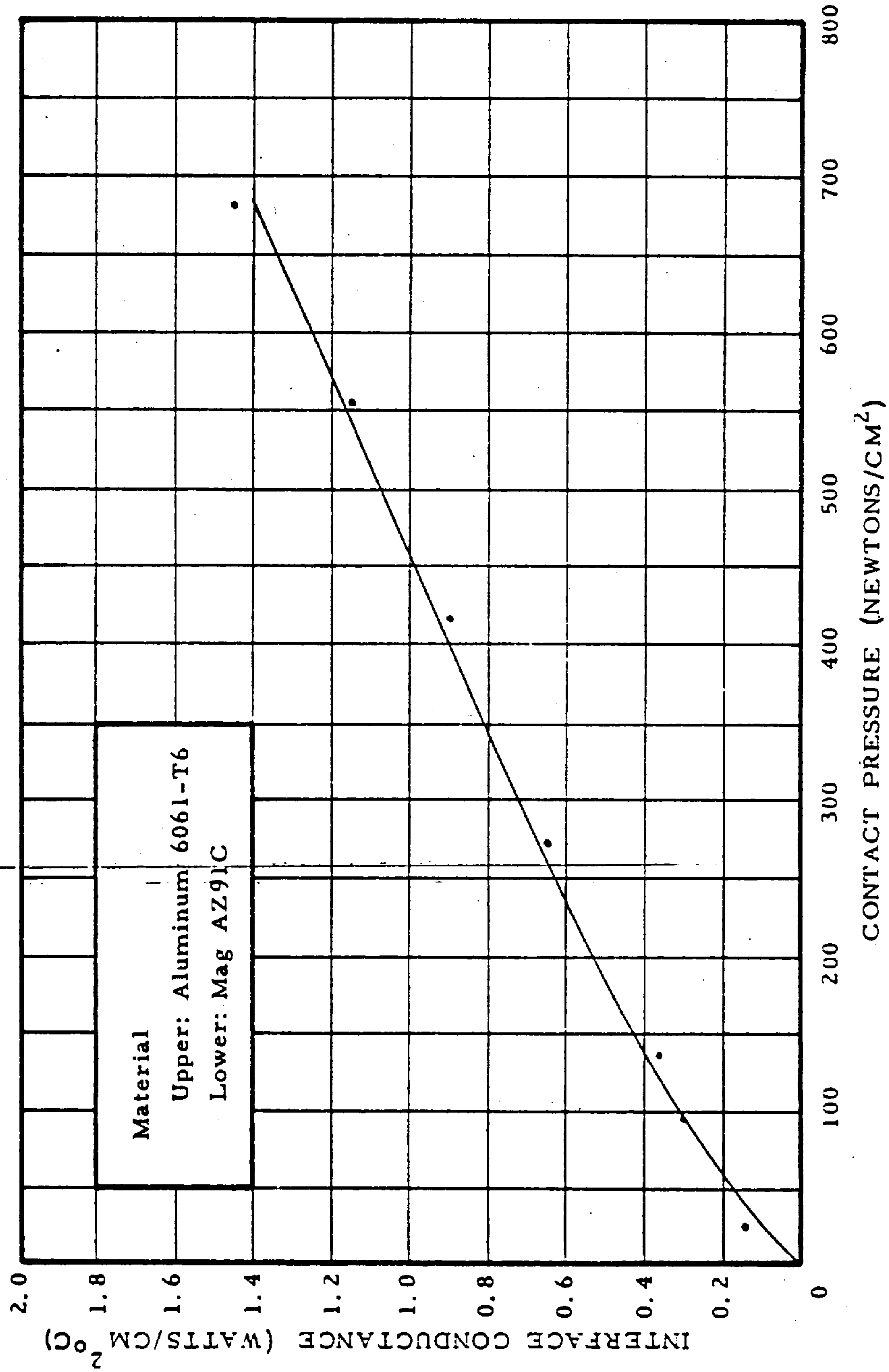


FIGURE 11 - AVERAGE CONTACT CONDUCTANCE - RUN 7

TABLE XI - CONTACT CONDUCTANCE DATA

RUN 7

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. $\left(\frac{w/cm^2}{°C}\right)$
1-A	2.0×10^{-6}	24.5	36.36	23.48	0.136	36.79	23.82	0.135	36.57	23.65	0.136
B	1.0×10^{-6}	24.5	36.34	23.40	0.136	36.67	23.89	0.135	36.51	23.64	0.135
2-A	2.5×10^{-6}	95.9	36.39	10.82	0.295	36.78	11.22	0.288	36.59	11.02	0.291
B	1.5×10^{-6}	95.9	36.45	10.79	0.296	36.76	11.15	0.289	36.60	10.97	0.293
3-A	7.0×10^{-7}	138.2	36.22	8.50	0.374	36.39	8.91	0.358	36.30	8.70	0.366
B	7.0×10^{-7}	138.2	36.25	8.47	0.375	36.37	8.95	0.356	36.31	8.71	0.366
4-A	7.0×10^{-7}	274.2	36.30	4.67	0.682	36.52	5.18	0.618	36.41	4.93	0.648
B	4.0×10^{-7}	274.2	36.42	4.69	0.681	36.59	5.13	0.625	36.51	4.91	0.652
5-A	5.0×10^{-7}	414.7	36.28	3.26	0.978	36.51	3.82	0.839	36.39	3.54	0.903
B	5.0×10^{-7}	414.7	36.17	3.28	0.967	36.34	3.73	0.855	36.25	3.51	0.907
6-A	2.0×10^{-6}	554.1	36.06	2.55	1.239	36.37	2.97	1.073	36.21	2.76	1.150
B	1.0×10^{-6}	555.2	36.00	2.51	1.259	36.40	2.93	1.091	36.20	2.72	1.169
7-A	3.0×10^{-6}	680.0	36.01	1.98	1.599	36.21	2.42	1.310	36.11	2.20	1.440
B	1.5×10^{-6}	680.0	36.00	1.95	1.617	36.28	2.42	1.315	36.14	2.19	1.450

Run #8 Aluminum 6061-T6
Aluminum 356

The test samples used for this run were (upper) 0.86 microns and (lower) 1.85 microns CLA. Surface measurements indicated that five ridge patterns existed on each test sample; and when placed in the test orientation the samples contacted at fifteen ridge intersections. Test data indicates a contact conductance comparable to those noted in Run #5 for Aluminum 6061-T6 and Magnesium AZ91C with similar fly-cutter surface ridge intersects.

Figure 12 is an Average Plot of Contact Conductance vs. Contact Pressure for Run #8. Table XII is the listing of Contact Conductance Data for Run #8.

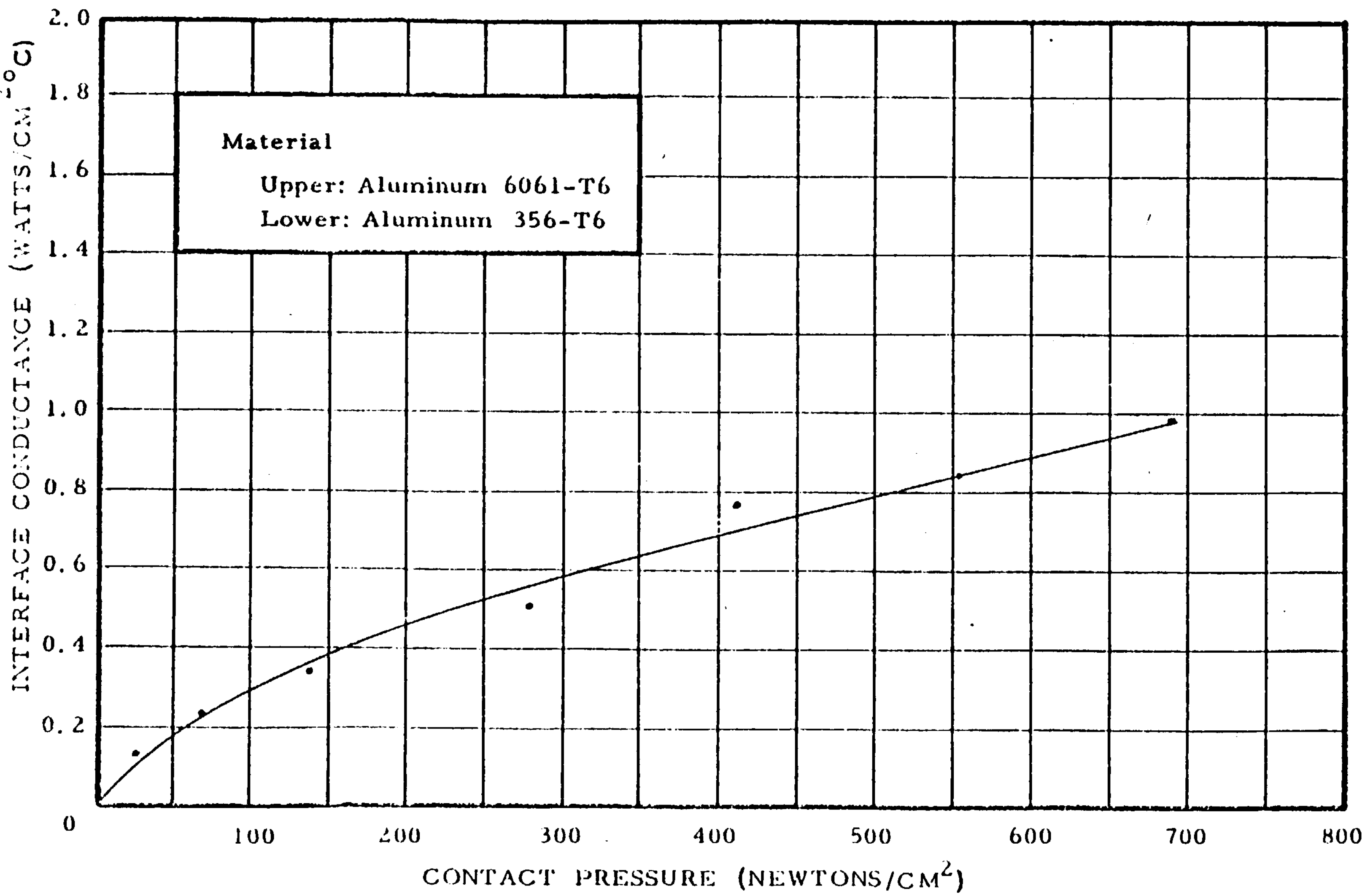


FIGURE 12 - AVERAGE CONTACT CONDUCTANCE - RUN 8

TABLE XII - CONTACT CONDUCTANCE DATA

RUN 8

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. $\left(\frac{w/cm^2}{°C}\right)$
1-A	3.0×10^{-6}	24.5	38.70	22.68	0.150	39.02	25.22	0.136	38.86	23.95	0.142
B	4.5×10^{-6}	24.5	38.58	22.59	0.150	39.03	25.17	0.136	38.81	23.88	0.143
C	1.0×10^{-5}	30.1	38.69	20.90	0.162	39.16	23.86	0.144	38.92	22.38	0.153
D	6.0×10^{-6}	27.9	38.91	20.93	0.163	39.23	23.87	0.144	39.07	22.40	0.153
2-A	1.0×10^{-5}	68.0	38.64	12.70	0.267	39.01	15.44	0.222	38.82	14.07	0.242
B	1.0×10^{-5}	68.0	38.63	12.70	0.267	39.01	15.42	0.222	38.82	14.06	0.242
3-A	3.0×10^{-6}	138.2	39.05	8.90	0.385	39.45	11.41	0.303	39.25	10.15	0.339
B	4.0×10^{-6}	138.2	39.08	8.90	0.385	39.41	11.41	0.303	39.24	10.16	0.339
4-A	5.0×10^{-6}	276.5	38.92	5.75	0.593	39.27	7.97	0.432	39.10	6.86	0.500
B	4.0×10^{-6}	276.5	38.92	5.73	0.596	39.30	7.99	0.431	39.11	6.86	0.500
5-A	4.0×10^{-6}	414.7	38.25	4.17	0.805	38.55	4.56	0.741	38.40	4.37	0.771
B	4.0×10^{-6}	414.7	38.28	4.17	0.806	38.56	4.54	0.745	38.42	4.36	0.774
6-A	3.0×10^{-6}	552.9	38.73	3.33	1.021	39.07	4.82	0.711	38.90	4.07	0.838
B	3.0×10^{-6}	552.9	38.81	3.30	1.031	39.12	4.82	0.712	38.96	4.06	0.842
7-A	4.0×10^{-6}	691.2	38.66	2.83	1.197	38.99	4.05	0.844	38.83	3.44	0.989
B	6.0×10^{-6}	691.2	38.64	2.83	1.196	38.97	4.08	0.838	38.80	3.46	0.985
8-A	1.4×10^{-5}	276.5	38.62	5.31	0.638	38.94	7.71	0.443	38.78	6.51	0.523
B	1.3×10^{-5}	276.5	38.65	5.40	0.627	38.98	7.73	0.442	38.81	6.57	0.518
9-A	5.0×10^{-6}	27.9	38.92	16.19	0.211	39.32	19.28	0.179	39.12	17.73	0.194
B	5.0×10^{-6}	27.9	38.93	16.19	0.211	39.35	19.26	0.179	39.14	17.72	0.194

Run #9 Aluminum 6061-T6.
Anodized Magnesium AZ91C

Sample surface finishes were (upper) 0.91 microns CLA and (lower) 2.34 microns CLA. Both sample test surfaces exhibited the characteristic wave pattern of five ridges on each test surface with an average mating at sixteen intersecting areas. The average heat transfer over the test sample surface is shown in the plot of Contact Conductance vs. Contact Pressure, Figure 13. Average Contact Conductance for Run #9 is approximately one-half the value of contact conductance for Run #7 (similar materials with no anodize surface finishes).

Test data presented in Table XIII starts with test 9. This was due to silicon oil vapor backstreaming from the vacuum diffusion pump into the test area during the original test series. The sample surfaces were cleaned of silicon oil and testing was repeated starting with Test 9.

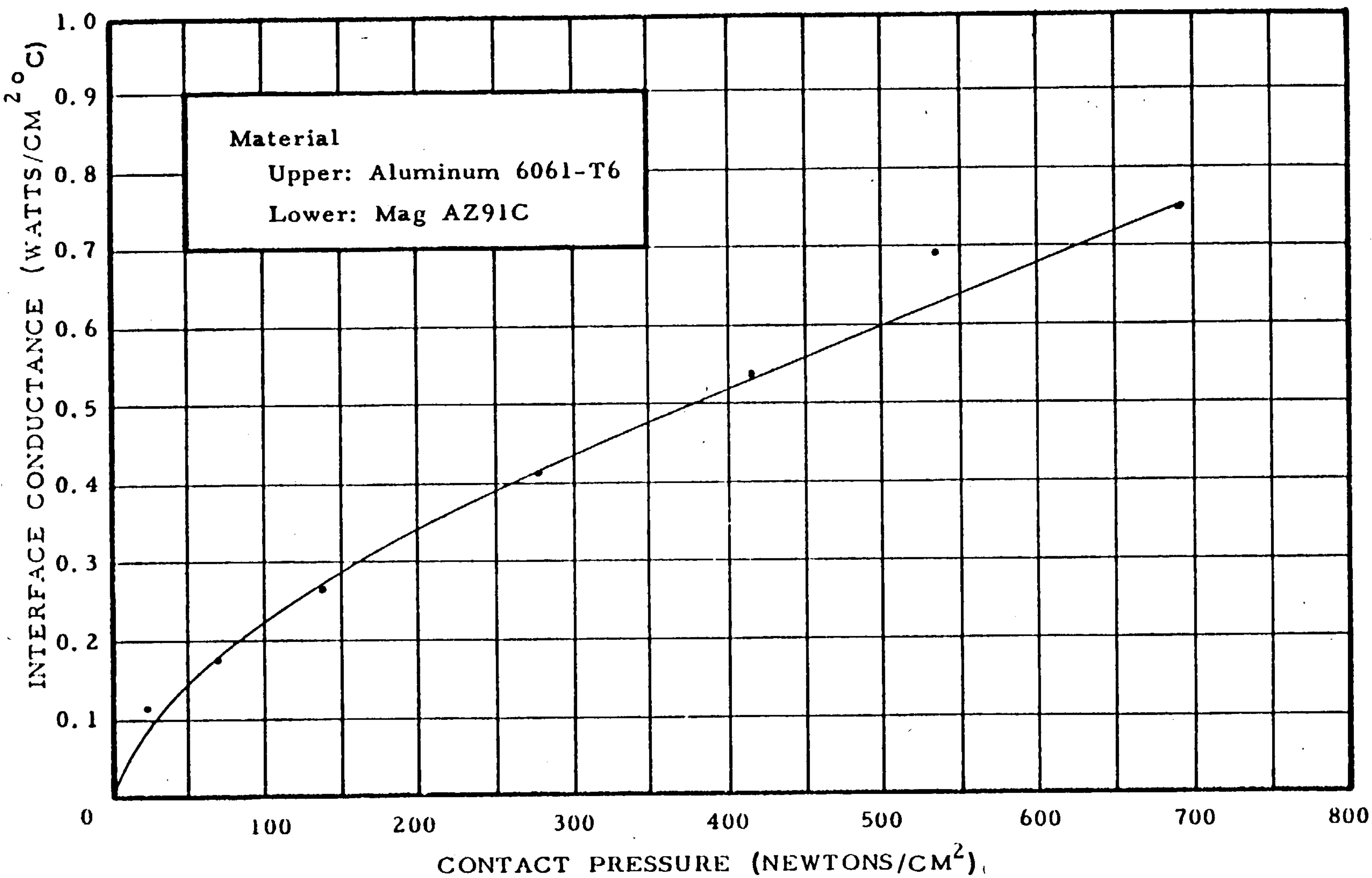


FIGURE 13 - AVERAGE CONTACT CONDUCTANCE RUN 9

TABLE XIII - CONTACT CONDUCTANCE DATA

RUN 9

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. $\left(\frac{w/cm^2}{°C}\right)$
9-A	10^{-6} RANGE	22.3	25.01	18.92	0.116	25.28	20.45	0.108	25.14	19.69	0.112
B			25.06	18.92	0.116	25.30	20.43	0.109	25.18	19.67	0.112
C			25.04	18.92	0.116	25.27	20.41	0.109	25.15	19.66	0.112
10-A		69.1	32.56	15.28	0.187	32.45	17.02	0.167	32.50	16.15	0.177
B			32.48	15.31	0.186	32.61	16.99	0.168	32.55	16.15	0.177
C			32.48	15.31	0.186	32.67	16.99	0.169	32.58	16.15	0.177
11-A		138.2	35.53	11.02	0.283	35.76	12.30	0.255	35.64	11.66	0.268
B			35.55	11.04	0.282	35.70	12.30	0.255	35.63	11.67	0.268
C			35.63	11.04	0.283	35.92	12.30	0.256	35.78	11.67	0.269
12-A		276.5	38.63	7.83	0.433	38.81	8.63	0.394	38.72	8.23	0.413
B			38.60	7.85	0.431	38.83	8.59	0.397	38.72	8.22	0.413
C			38.60	7.83	0.433	38.88	8.61	0.396	38.74	8.22	0.414
13-A		414.7	38.27	6.01	0.558	38.53	6.53	0.518	38.40	6.27	0.537
B			38.27	5.99	0.561	38.48	6.53	0.517	38.37	6.26	0.538
C			38.24	6.03	0.556	38.43	6.51	0.518	38.33	6.27	0.536
14-A		535.1	38.08	4.65	0.718	38.08	5.02	0.666	38.08	4.83	0.691
B			38.11	4.63	0.723	38.16	5.01	0.668	38.13	4.82	0.694
C			38.25	4.62	0.726	38.27	5.01	0.670	38.26	4.81	0.697
15-A		691.2	38.02	4.26	0.783	38.15	4.65	0.720	38.09	4.45	0.750
B			38.00	4.26	0.782	38.13	4.62	0.723	38.06	4.44	0.752
C			37.97	4.26	0.781	38.15	4.62	0.724	38.06	4.44	0.751
16-A		276.5	38.15	5.44	0.615	38.25	5.96	0.563	38.20	5.70	0.588
B			38.07	5.42	0.616	38.31	5.96	0.564	38.19	5.69	0.589
C			38.15	5.42	0.618	38.23	5.94	0.565	38.19	5.68	0.590
17-A		27.9	32.43	9.26	0.307	32.51	10.26	0.278	32.47	9.76	0.292
B			32.42	9.24	0.308	32.51	10.26	0.278	32.47	9.75	0.292
C			32.39	9.24	0.308	32.48	10.24	0.278	32.43	9.74	0.292

Run #10   Almag 35
Magnesium AZ91C

The thermal contact conductance between two "soft alloys" was investigated to determine what effective heat transfer could be expected between such materials compared to the relatively "Hard" alloy Aluminum 6061-T6, in combination with a "Soft" alloy magnesium AZ91C. (Run #7)

A direct comparison, however, is not possible because of the difference of surface contact points (five for Run #7 and seventeen for Run #10). It is noted that the contact conductance values recorded during Run #10 are higher than those recorded during Run #7.

Figure 14 is a plot of the Average Contact Conductance vs. Contact Pressure for Run #10. Table XIV presents Test Data for Run #10.

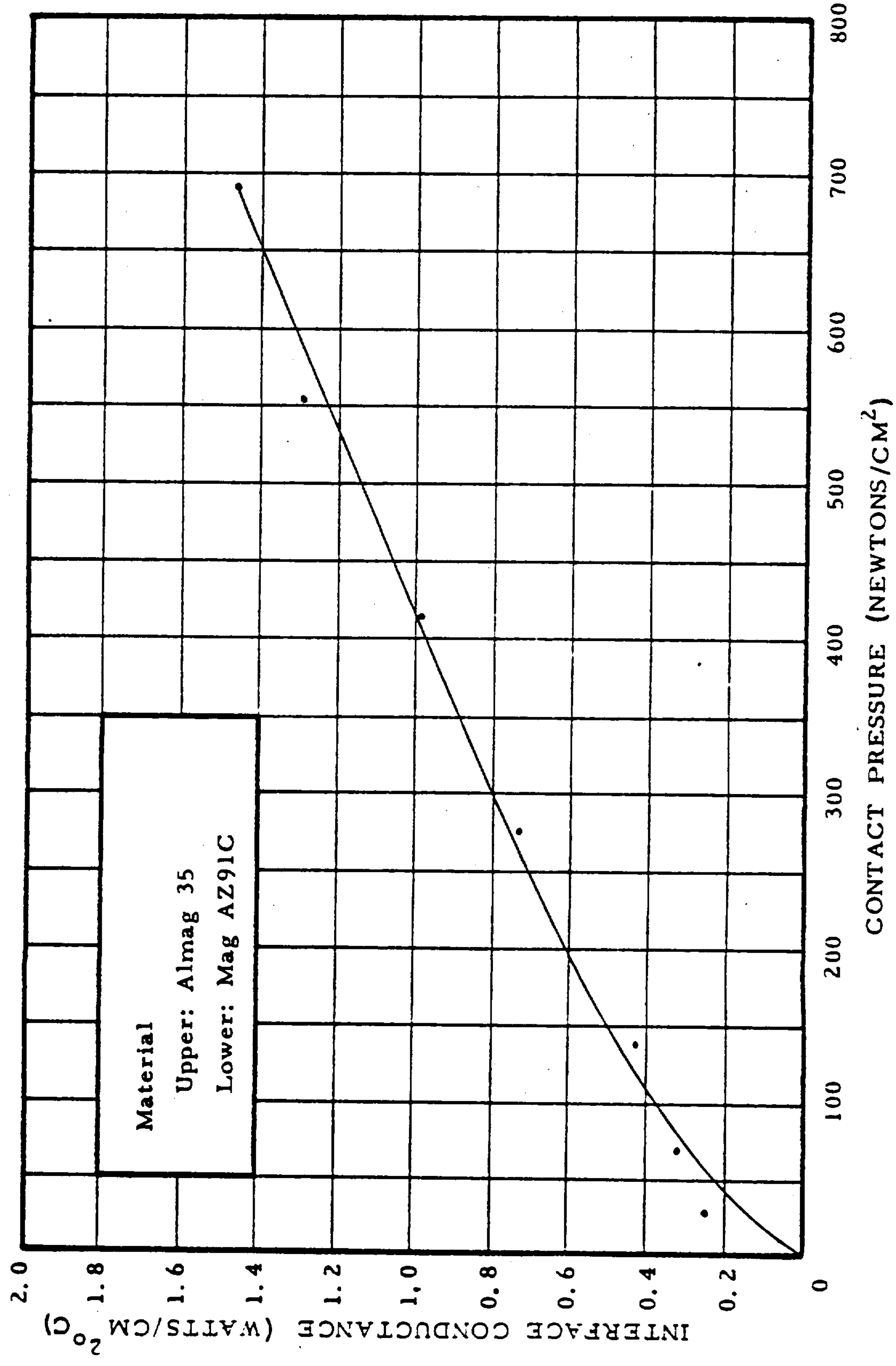


FIGURE 14 - AVERAGE CONTACT CONDUCTANCE- RUN 10

TABLE XIV - CONTACT CONDUCTANCE DATA

RUN 10

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long $\left(\frac{w/cm^2}{°C}\right)$	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. $\left(\frac{w/cm^2}{°C}\right)$
1-A	10^{-6} RANGE	27.9	32.98	11.75	0.246	32.90	12.37	0.233	32.94	12.06	0.240
B			33.01	11.68	0.248	33.06	12.34	0.235	33.04	12.01	0.241
C			33.06	11.73	0.247	33.12	12.34	0.235	33.09	12.03	0.241
2-A		69.1	32.93	8.88	0.325	33.01	9.41	0.308	32.97	9.14	0.316
B			32.96	8.86	0.326	33.03	9.45	0.307	32.99	9.15	0.316
C			32.90	8.88	0.325	32.98	9.38	0.308	32.94	9.13	0.316
3-A		138.2	38.89	7.66	0.445	38.88	8.14	0.419	38.88	7.90	0.432
B			38.96	7.66	0.446	38.88	8.12	0.420	38.92	7.89	0.433
C			38.86	7.67	0.445	38.88	8.14	0.419	38.87	7.90	0.431
4-A		276.5	38.69	4.40	0.772	38.71	4.81	0.706	38.70	4.60	0.737
B			38.74	4.44	0.765	38.76	4.78	0.711	38.75	4.61	0.737
C			38.76	4.44	0.766	38.75	4.81	0.707	38.76	4.62	0.735
5-A		414.7	38.62	3.31	1.024	38.56	3.56	0.950	38.59	3.43	0.986
B			38.48	3.27	1.034	38.53	3.56	0.949	38.50	3.41	0.989
C			38.58	3.26	1.038	38.58	3.56	0.951	38.58	3.41	0.992
6-A		552.9	38.42	2.44	1.384	38.45	2.80	1.203	38.43	2.62	1.287
B			38.45	2.43	1.386	38.42	2.78	1.212	38.43	2.61	1.293
C			38.36	2.46	1.368	38.39	2.76	1.221	38.38	2.61	1.290
7-A		691.2	38.44	2.18	1.544	38.35	2.42	1.391	38.39	2.30	1.464
B			38.41	2.19	1.542	38.41	2.42	1.394	38.41	2.30	1.465
C			38.44	2.16	1.560	38.44	2.42	1.396	38.44	2.29	1.474
8-A		276.5	38.32	4.19	0.802	38.24	4.66	0.720	38.28	4.42	0.759
B			38.38	4.19	0.804	38.32	4.68	0.719	38.35	4.43	0.759
C			38.35	4.19	0.803	38.29	4.70	0.715	38.32	4.45	0.756
9-A		27.9	35.66	14.53	0.215	35.68	15.30	0.205	35.67	14.92	0.210
B			35.71	14.55	0.215	35.63	15.37	0.203	35.67	14.96	0.209
C			35.63	14.51	0.216	35.63	15.30	0.204	35.63	14.90	0.210

Run #11 Aluminum 6061-T6
Anodized Mag Lithium LA-141

Thermal Conductance Characteristics for this run are presented in Figure 15. The sharp upswing in conductance at 700 newtons/cm^2 is a result of migration of silicon grease into the test joint. The expected plot of Contact Conductance vs. Pressure is shown as a dotted line.

Surface finish on the samples was (upper) 0.46 and (lower) 0.81 microns. No surface waviness was noted on Talysurf recordings for both surfaces.

Surface measurements of hardness using the Vickers diamond pyramid method was not possible due to chipping of the anodize surface.

Table XV presents the Contact Conductance Test Data taken during Run #11. The difference in Δ t between lateral thermocouple locations was quite low indicating and even distribution of heat transfer at the surface interface.

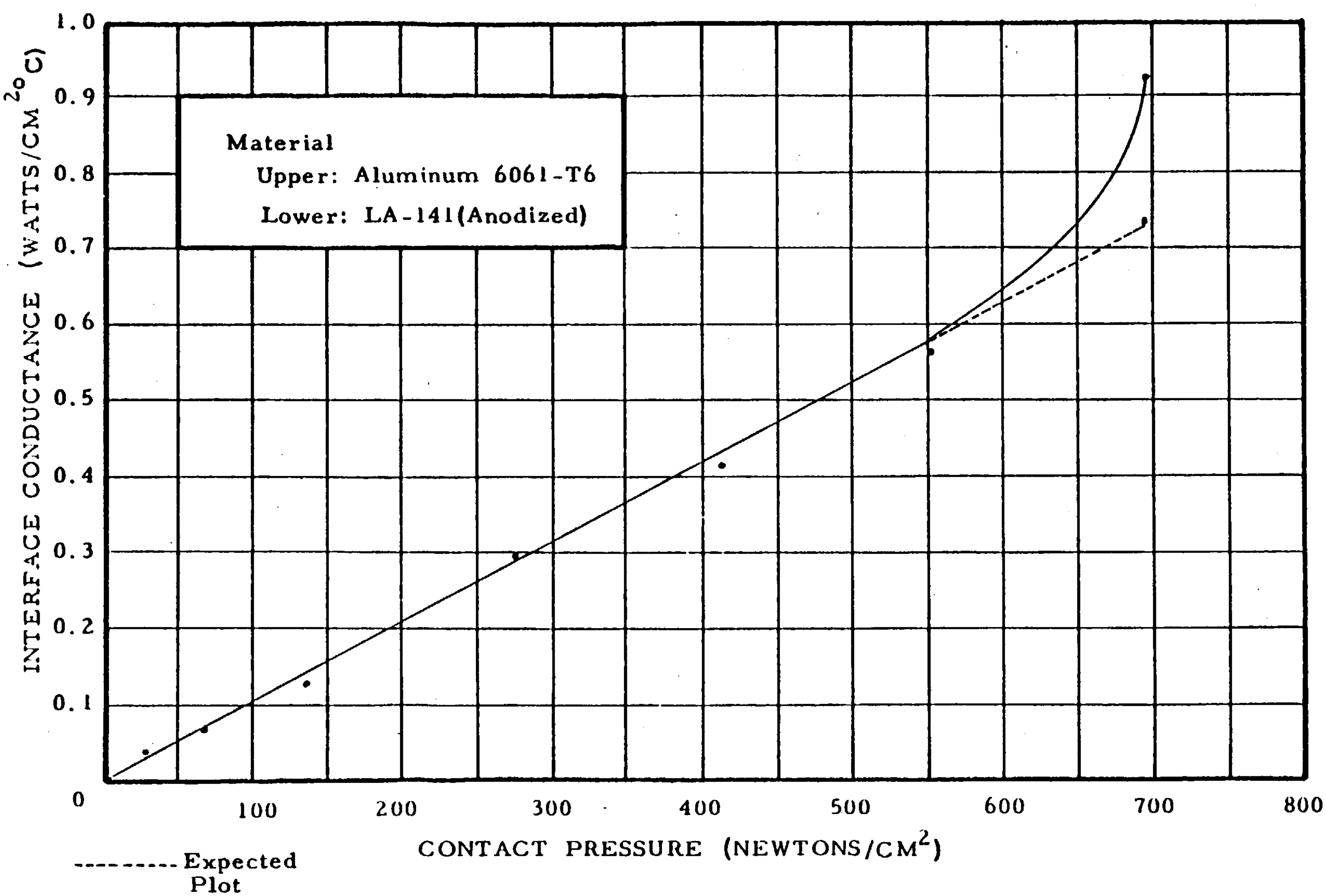


FIGURE 15 - AVERAGE CONTACT CONDUCTANCE - RUN 11

TABLE XV - CONTACT CONDUCTANCE DATA

RUN 11

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	10^{-6} RANGE	27.9	5.08	12.00	0.037	5.11	12.37	0.036	5.10	12.19	0.037
B			5.08	12.00	0.037	5.17	12.35	0.037	5.13	12.17	0.037
C			5.17	11.97	0.038	5.05	12.38	0.036	5.11	12.17	0.037
2-A		69.1	8.14	10.61	0.067	7.87	11.07	0.062	8.01	10.84	0.065
B			7.93	10.67	0.065	8.14	11.04	0.065	8.04	10.85	0.065
C			8.08	10.64	0.067	7.90	11.07	0.063	7.99	10.85	0.065
3-A		138.2	10.90	7.20	0.133	10.64	7.59	0.123	10.77	7.40	0.128
B			11.05	7.22	0.134	10.93	7.61	0.126	10.99	7.41	0.130
C			10.87	7.22	0.132	10.93	7.70	0.125	10.90	7.46	0.128
4-A		278.7	14.87	4.27	0.305	14.78	4.66	0.278	14.82	4.47	0.291
B			14.78	4.31	0.301	14.99	4.58	0.287	14.88	4.45	0.294
C			14.78	4.25	0.305	14.78	4.61	0.281	14.78	4.43	0.293
5-A		414.7	18.10	3.73	0.426	18.21	4.00	0.399	18.16	3.86	0.412
B			18.04	3.75	0.422	18.04	3.96	0.400	18.04	3.86	0.410
C			18.04	3.70	0.427	18.13	3.96	0.402	18.08	3.83	0.414
6-A		552.9	22.08	3.34	0.579	22.11	3.57	0.543	22.10	3.46	0.560
B			22.03	3.32	0.582	22.89	3.56	0.539	21.96	3.44	0.560
C			22.00	3.33	0.581	22.09	3.55	0.545	22.05	3.44	0.562
7-A		696.7	31.37	2.80	0.983	31.40	3.16	0.871	31.38	2.98	0.923
B			31.31	2.83	0.972	31.39	3.19	0.864	31.35	3.01	0.915
C			31.33	2.76	0.998	31.36	3.19	0.863	31.34	2.97	0.925
8-A		276.5	31.51	4.97	0.556	31.67	5.78	0.481	31.59	5.37	0.516
B			31.45	4.90	0.563	31.66	5.83	0.477	31.56	5.36	0.516
C			31.50	4.83	0.572	31.69	5.85	0.475	31.59	5.34	0.519
9-A		105.9	8.35	2.94	0.249	8.01	3.46	0.203	8.17	3.20	0.224
B			8.35	3.16	0.232	8.16	3.40	0.210	8.25	3.28	0.221
C			8.25	3.26	0.222	8.04	3.48	0.203	8.14	3.37	0.212

Run #12 Aluminum 6061-T6
Mag Lithium LA-141 (Beryllium Coated)

Sample preparation for the test samples yielded flat smooth surfaces for the Beryllium Coated Mag Lithium (see Table IV, page 19).

The Aluminum 6061-T6 Sample was also quite flat. As a result the surface finish provided excellent contact conditions.

Contact Conductance vs. Contact Pressure Data for this run is presented inFigure 16. Test data for Run #12 is presented in Table XVI.

Visual observation of surface condition following test revealed a blistering of the beryllium sample surfaces indicating that poor coating adhesion of beryllium existed.

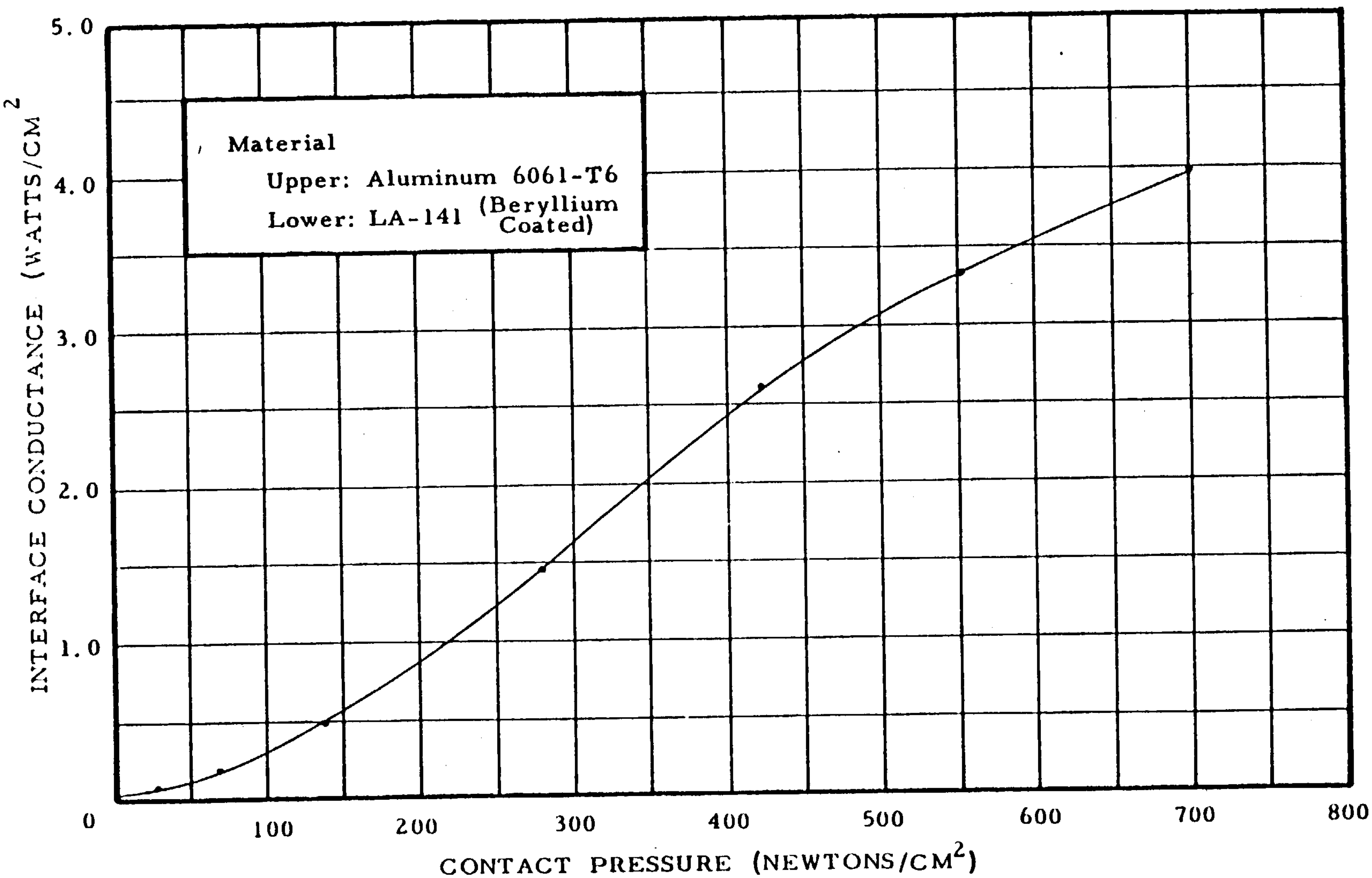


FIGURE 16 - AVERAGE CONTACT CONDUCTANCE - RUN 12

TABLE XVI - CONTACT CONDUCTANCE DATA

RUN 12

Test	Vacuum Pressure (mm Hg)	Load (N/cm^2)	Flux Meter Short (Watts)	ΔT Short (°C)	Cond. Short ($\frac{w/cm^2}{°C}$)	Flux Meter Long (Watts)	ΔT Long (°C)	Cond. Long ($\frac{w/cm^2}{°C}$)	Flux Meter Avg. (Watts)	ΔT Avg. (°C)	Cond. Avg. ($\frac{w/cm^2}{°C}$)
1-A	10^{-6} RANGE	27.9	6.51	7.94	0.072	6.54	8.06	0.071	6.52	8.00	0.072
B			6.51	7.89	0.072	6.41	8.09	0.070	6.46	8.00	0.071
C			6.47	7.84	0.072	6.35	8.04	0.069	6.41	7.94	0.071
2-A		66.9	11.41	5.60	0.179	11.17	6.06	0.162	11.29	5.83	0.170
B			11.38	5.57	0.179	11.32	5.95	0.167	11.35	5.76	0.173
C			11.20	5.53	0.178	11.23	5.91	0.167	11.21	5.72	0.172
3-A		138.2	14.32	2.41	0.520	14.32	2.72	0.461	14.32	2.57	0.489
B			14.35	2.34	0.538	14.20	2.75	0.453	14.27	2.55	0.492
C			14.58	2.36	0.543	14.46	2.74	0.463	14.52	2.55	0.500
4-A		278.7	18.67	1.12	1.461	18.70	1.12	1.465	18.68	1.12	1.463
B			18.61	1.12	1.453	18.58	1.10	1.482	18.59	1.11	1.467
C			18.64	1.12	1.457	18.61	1.27	1.290	18.62	1.19	1.369
5-A		421.4	22.49	0.82	2.390	22.41	0.69	2.863	22.45	0.76	2.605
B			22.41	0.82	2.371	22.32	0.71	2.744	22.36	0.77	2.544
C			22.41	0.80	2.442	22.38	0.69	2.855	22.39	0.75	2.632
6-A		552.9	26.81	0.84	2.797	26.90	0.55	4.256	26.85	0.70	3.377
B			26.78	0.81	2.871	26.95	0.60	3.945	26.86	0.71	3.326
C			26.78	0.81	2.872	26.78	0.63	3.732	26.78	0.72	3.246
7-A		700.1	31.60	0.90	3.058	31.74	0.57	4.897	31.67	0.74	3.752
B			31.65	0.83	3.331	31.76	0.53	5.295	31.71	0.68	4.091
C			31.62	0.81	3.421	31.79	0.52	5.315	31.70	0.67	4.165

D. Raw Test Data

1. Computer Input Information

The basic measurements of thermal EMF, contact pressure, and wattage were transferred from the operator test data sheets to the forms shown in Attachments 1A and 1B pages 59 and 60 .

Attachments are shown completed with operator test data for Run#9,Test 13B. Material Conductivity Data for the test sampleswere derived from test sample and fluxmeter Δt data and is shown on lines 4 and 8 of Attachment 1-A.

2. Computer Program

The Data recorded on the Input Data Sheets were subsequently transferred to punched cards to meet computer input requirements.

Thermal EMF in millivolts was converted to degrees centigrade, by the computer program, using a polynomial approximation method.

Constants were used for conversion of basic test data to the desired scales of measurement. The basic program was in VFAP form for processing in a G.E. 235 Computer.

INPUT DATA SHEET

CONTACT CONDUCTANCE TESTING PROGRAM

	KEY PUNCH INFORMATION										
TEST NUMBER-RUN NUMBER		9			1	3	B				
DATE BEGUN				1	Ø	-	1	5	-	6	4
UPPER SAMPLE NUMBER AND MATERIAL		4	4		6	Ø	6	1	-	T	6
CONDUCTIVITY (WATTS/CM°C)			1	3	6	5	3	4			
SURFACE FINISH (INCH CLA) TOP				L	A	P	P	E	D		
SURFACE FINISH (INCH CLA) INTERFACE		3	6		E	-	6				
LOWER SAMPLE NUMBER AND MATERIAL		2	6	A	Z	9	L	C	-	A	N
CONDUCTIVITY (WATTS/CM°C)				5	5	5	Ø	2			
SURFACE FINISH (INCH CLA) BOTTOM				L	A	P	P	E	D		
SURFACE FINISH (INCH CLA) INTERFACE		9	2		E	-	6				
INTERSTITIAL MATERIAL						N	O	N	E		
MAIN HEATER VOLTAGE (VOLTS)		6	1	3	2						
MAIN HEATER CURRENT (AMPS)				6	5						
GUARD HEATER VOLTAGE (VOLTS) LEVEL 1			8	4							
GUARD HEATER VOLTAGE (VOLTS) LEVEL 2			5	1							
GUARD HEATER VOLTAGE (VOLTS) LEVEL 3			5	6							
GUARD HEATER VOLTAGE (VOLTS) LEVEL 4			3	5							
GUARD HEATER VOLTAGE (VOLTS) LEVEL 5			4	4	5						
GUARD HEATER VOLTAGE (VOLTS) LEVEL 6			2	Ø							
LOAD CELL UNITS	3	7	2	Ø	E	+	1				
VACUUM (mm Hg)			1	Ø	E	-	6				

NOTE: SEE KEY FOR MEANINGS OF ABBREVIATIONS.

	TEST NUMBER-RUN NUMBER	9 13B	22
	TIME BEGUN	3Ø9PM	23
	Thermocouple Inputs (millivolts)		
1.	HEATER LONG	5Ø45	24
2.	HEATER SHORT (AVG)	5Ø44	25
3.	HEAT METER-TOP LONG	3366	26
4.	HEAT METER-TOP SHORT (AVG.)	337Ø	27
5.	HEAT METER-MIDDLE LONG	4Ø55	28
6.	HEAT METER-MIDDLE SHORT (AVG.)	4Ø52	29
7.	HEAT METER-BOTTOM LONG	48Ø7	30
8.	HEAT METER-BOTTOM SHORT (AVG)	48Ø3	31
9.	UPPER SAMPLE-LONG	2322	32
10.	UPPER SAMPLE-SHORT (AVG)	2329	33
11.	LOWER SAMPLE-LONG	2667	34
12.	LOWER SAMPLE-SHORT (AVG)	265Ø	35
13.	UPPER SAMPLE COOLER FACE	22Ø9	36
14.	LOWER SAMPLE METER FACE	295Ø	37
15.	COOLER	1881	38
	TEST OPERATORS INITIALS	GVL	39

ATTACHMENT 1B

3. Magnetic Tape Storage

The Raw Input Data entered into the GE 235 Computer was converted to magnetic tape format for permanent storage. A printout of tape data was checked for errors introduced during the transfer of data from operator test data sheets to magnetic tape. Subsequent corrections to Magnetic Tape Data yielded an accurate permanent record of Contact Conductance Test Data.

A final printout verified the correctness of Test Data.

4. Printer Output

Attachment 2A is a printout of reduced test data for Run 9 Test 13B. This Attachment shows the basic 39 lines of information as shown on the Input Data Sheets, attachment 1A and 1B pages 59 and 60 . Also shown is the conversion of thermocouple EMF to the equivalent temperature (in $^{\circ}$C).

Attachments 2B, 2C and 2D pages 63 thru 65 presents the calculated data for other parameters for Run #9, Test 13B. The underlined data shown on these attachments can also be found in reduced form in Table XIII page 48.

CONTACT CONDUCTANCE TESTING PROGRAM

TEST NUMBER-RUN NUMBER	9	13R
DATE BEGUN....................................		10-15-64
UPPER SAMPLE NUMBER AND MATERIAL	44	6061-T6
CONDUCTIVITY (WATTS/CM C).............		1.36534
SURFACE FINISH (INCH CLA) TOP		LAPPED
INTERFACE	36	E-6
LOWER SAMPLE NUMBER AND MATERIAL	26	AZ-91CAN
CONDUCTIVITY (WATTS/CM C)		.55502
SURFACE FINISH (INCH CLA) TOP		LAPPED
INTERFACE	92	E-6
INTERSTITIAL MATERIAL......................		NONE
MAIN HEATER VOLTAGE (VOLTS)		61.32
MAIN HEATER CURRENT (AMPS)		.65
GUARD HEATER VOLTAGE (VOLTS) LEVEL 1 .		8.4
GUARD HEATER VOLTAGE (VOLTS) LEVEL 2 .		5.1
GUARD HEATER VOLTAGE (VOLTS) LEVEL 3 .		5.6
GUARD HEATER VOLTAGE (VOLTS) LEVEL 4 .		3.5
GUARD HEATER VOLTAGE (VOLTS) LEVEL 5 .		4.45
GUARD HEATER VOLTAGE (VOLTS) LEVEL 6 .		2.0
LOAD CELL READING (UNITS)		372.E+1
VACUUM (MM HG)		1.0E-6

TEST NUMBER-RUN NUMBER........................	9	13R	
TIME BEGUN....................................		3.09PM	
THERMOCOUPLE INPUTS (MILLIVOLTS)			Equivalent Temp (C)
1. HEATER LONG		5.045	116.225170
2. HEATER SHORT (AVG)		5.044	116.204293
3. HEATER METER -TOP LONG		3.366	80.1840174
4. -TOP SHORT (AVG)		3.370	80.2723933
5. -MIDDLE LONG		4.055	95.2230237
6. -MIDDLE SHORT (AVG) ..		4.052	95.1583225
7. -BOTTOM LONG		4.807	111.237791
8. -BOTTOM SHORT (AVG) ..		4.803	111.153647
9. UPPER SAMPLE -LONG		2.322	56.0646683
10. -SHORT (AVG)		2.329	56.8254815
11. LOWER SAMPLE -LONG		2.667	64.5392195
12. -SHORT (AVG)		2.650	64.1536222
13. UPPER SAMPLE COOLER FACE		2.209	54.0626378
14. LOWER SAMPLE METER FACE		2.950	70.9221361
15. COOLER		1.881	46.4015940

TEST OPERATORS INITIALS GVL

ATTACHMENT 2A

Q SHORT
UJ SHORT

LOAD ON SAMPLE PSI	+601.473684
LOAD ON SAMPLE NEWTONS/CM2.........	+414.701500
WATTS IN	+39.8580000
WATTS FLOWING IN FLUX METER.........	+38.2673730
RATIO OF WATTS FLOWING TO WATTS IN	+.960092655
DELTA T FOR LOWER SAMPLE............	+.952567419
DELTA T FOR UPPER SAMPLE............	+.387225138
DELTA T AT JOINT	+5.98834811
DELTA T AT JOINT/WATT AT THE LOAD...	+.156487044
JOINT CONDUCTANCE AT THE LOAD W/C2DC	+.560553102

Q SHORT
UJ LONG

LOAD ON SAMPLE PSI	+601.473684
LOAD ON SAMPLE NEWTONS/CM2.........	+414.701500
WATTS IN	+39.8580000
WATTS FLOWING IN FLUX METER.........	+38.2673730
RATIO OF WATTS FLOWING TO WATTS IN	+.960092655
DELTA T FOR LOWER SAMPLE............	+.952567419
DELTA T FOR UPPER SAMPLE............	+.387225138
DELTA T AT JOINT	+6.53475855
DELTA T AT JOINT/WATT AT THE LOAD...	+.170765799
JOINT CONDUCTANCE AT THE LOAD W/C2DC	+.513681888

Q SHORT
UJ AVERAGE

LOAD ON SAMPLE PSI	+601.473684
LOAD ON SAMPLE NEWTONS/CM2.........	+414.701500
WATTS IN	+39.8580000
WATTS FLOWING IN FLUX METER.........	+38.2673730
RATIO OF WATTS FLOWING TO WATTS IN	+.960092655
DELTA T FOR LOWER SAMPLE............	+.952567419
DELTA T FOR UPPER SAMPLE............	+.387225138
DELTA T AT JOINT	+6.26155334
DELTA T AT JOINT/WATT AT THE LOAD...	+.163626422
JOINT CONDUCTANCE AT THE LOAD W/C2DC	+.536094947

ATTACHMENT 2B

```
Q  LONG
UJ SHORT
LOAD ON SAMPLE  PSI  ................   +601.473684
LOAD ON SAMPLE  NEWTONS/CM2,........    +414.701500
WATTS IN ...........................    +39.8580000
WATTS FLOWING IN FLUX METER,........    +38.4787393
RATIO OF WATTS FLOWING TO WATTS IN      +.965395639
DELTA T FOR LOWER SAMPLE............    +.957828837
DELTA T FOR UPPER SAMPLE............    +.389363940
DELTA T AT JOINT  ..................    +5.98094790
DELTA T AT JOINT/WATT AT THE LOAD...    +.155435131
JOINT CONDUCTANCE AT THE LOAD W/C2DC    +.564346667
```

```
Q  LONG
UJ LONG
LOAD ON SAMPLE  PSI  ................   +601.473684
LOAD ON SAMPLE  NEWTONS/CM2,........    +414.701500
WATTS IN ...........................    +39.8580000
WATTS FLOWING IN FLUX METER,........    +38.4787393
RATIO OF WATTS FLOWING TO WATTS IN      +.965395639
DELTA T FOR LOWER SAMPLE............    +.957828837
DELTA T FOR UPPER SAMPLE............    +.389363940
DELTA T AT JOINT  ..................    +6.52735828
DELTA T AT JOINT/WATT AT THE LOAD...    +.169635450
JOINT CONDUCTANCE AT THE LOAD W/C2DC    +.517104757
```

```
Q  LONG
UJ AVERAGE
LOAD ON SAMPLE  PSI  ................   +601.473684
LOAD ON SAMPLE  NEWTONS/CM2,........    +414.701500
WATTS IN ...........................    +39.8580000
WATTS FLOWING IN FLUX METER,........    +38.4787393
RATIO OF WATTS FLOWING TO WATTS IN      +.965395639
DELTA T FOR LOWER SAMPLE............    +.957828837
DELTA T FOR UPPER SAMPLE............    +.389363940
DELTA T AT JOINT  ..................    +6.25415312
DELTA T AT JOINT/WATT AT THE LOAD...    +.162535291
JOINT CONDUCTANCE AT THE LOAD W/C2DC    +.539693856
```

ATTACHMENT 2C

```
Q  AVERAGE
UJ SHORT
LOAD ON SAMPLE  PSI  ...............         +601.473684
LOAD ON SAMPLE  NEWTONS/CM2.........         +414.701500
WATTS IN ...........................         +39.8580000
WATTS FLOWING IN FLUX METER.........         +38.3730594
RATIO OF WATTS FLOWING TO WATTS IN           +.962744230
DELTA T FOR LOWER SAMPLE............         +.955198209
DELTA T FOR UPPER SAMPLE............         +.388294572
DELTA T AT JOINT  ..................         +5.98464789
DELTA T AT JOINT/WATT AT THE LOAD...         +.155959623
JOINT CONDUCTANCE AT THE LOAD W/C2DC         +.562448770
```

```
Q  AVERAGE
UJ LONG
LOAD ON SAMPLE  PSI  ...............         +601.473684
LOAD ON SAMPLE  NEWTONS/CM2.........         +414.701500
WATTS IN ...........................         +39.8580000
WATTS FLOWING IN FLUX METER.........         +38.3730594
RATIO OF WATTS FLOWING TO WATTS IN           +.962744230
DELTA T FOR LOWER SAMPLE............         +.955198209
DELTA T FOR UPPER SAMPLE............         +.388294572
DELTA T AT JOINT  ..................         +6.53105833
DELTA T AT JOINT/WATT AT THE LOAD...         +.170199052
JOINT CONDUCTANCE AT THE LOAD W/C2DC         +.515392403
```

```
Q  AVERAGE
UJ AVERAGE
LOAD ON SAMPLE  PSI  ...............         +601.473684
LOAD ON SAMPLE  NEWTONS/CM2.........         +414.701500
WATTS IN ...........................         +39.8580000
WATTS FLOWING IN FLUX METER.........         +38.3730594
RATIO OF WATTS FLOWING TO WATTS IN           +.962744230
DELTA T FOR LOWER SAMPLE............         +.955198209
DELTA T FOR UPPER SAMPLE............         +.388294572
DELTA T AT JOINT  ..................         +6.25785311
DELTA T AT JOINT/WATT AT THE LOAD...         +.163079337
JOINT CONDUCTANCE AT THE LOAD W/C2DC         +.537893394
```

ATTACHMENT 2D

APPENDIX I

Test Hardware Description, Test Methods, Operating Procedures, and System Schematic Diagrams are presented in this section as follows:

A. Test Chamber

B. Description of Test Fixture

C. Temperature Instrumentation

D. Test Sample Preparation

E. Assembly of Samples in Test Fixture

F. Preparing for Test

G. Returning Test Chamber to Atmospheric Pressure

Figure 1 - Test Chamber
Figure 2 - Thermocouple Locations, Lower Sample
Figure 3 - Thermocouple Locations, Upper Sample
Figure 4 - Conductance Test System Schematic
Figure 5 - Automatic Heater Control Circuit
Table 1 - Automatic Heater Control Components List.

A. TEST CHAMBER

The vacuum test chamber consists of a glass bell jar sealed against a metal feed through ring and base plate. The feed through is used as a convenient method of providing ports for water, power, and instrumentation. A system schematic is shown in Figure 4, Page 15.

Obtaining initial vacuum in the low 10^{-3} torr range is accomplished with a Welch "Duo Seal" Pump Model 1402B; for ultimate evacuation of 10^{-6} torr an NRC Equipment Corporation type 0171 diffusion pump is used. This vacuum was monitored originally with an ionization gage controller *. A Cenco Discharge Vacuum gage and controller was used during the later phase of the test activity to give indications that chamber pressure in the 10^{-6} torr range as being reached.

Type BA-60-NBK
* Manufactured by Vacuum Products Div.
F. J. Cooke Inc.

B. DESCRIPTION OF TEST FIXTURE

A diagram of the test fixture is shown in Figure 1. The main support structure consists of an upper and a lower plate held by three steel rods. A pressure bellows is mounted to the bottom plate to produce the loading force on the measuring column.

The measuring column consists of the heater, heat flux-meter, lower sample, upper sample and cooler as described below:

Heater

The main heater consists of two standard 80 watt cartridge heaters installed in a truncated copper cone plated with gold. Four thermocouples were installed near the heat meter interface to indicate the effectiveness of the copper to smooth out the heat flux to the flux meter.

Heat Fluxmeter

The fluxmeter has a diameter of 3.81 cm and length of 8.26 cm. Thermocouples are installed in holes drilled in each of three cross sections spaced along the lateral length the fluxmeter. One group of thermocouples is located .95 cm from each contacting end and the third group is centered between the ends.

Four locations for thermocouples were installed in each of the lateral sections of the fluxmeter. Three are spaced 120° apart and 0.64 cm in from the outer surface, the fourth is in the center. All of the thermocouples are aligned axially with the fluxmeter.

Upper and Lower Samples

Test samples are the same diameter as the fluxmeter, 3.81 cm, and have a length of 2.03 cm.

The thermocouple pattern in the sample is similar to that of the fluxmeter. One set of three thermocouples are an average of .635 cm from interface of fluxmeter and cooler (center thermocouples are an average of 0.15 cm from test surface. (see Figures 2 and 3)

Cooler

A water cooled heat sink is used in the test fixture. A water tank approximately 25 cm in diameter by one meter long and an in line heater at thetank inlet are usedto stabilize and control coolant temperature.

Load Cell

A Cox and Stevens, Mfg. Part no. C-41020-1, Load Cell with a force capacity of 4.45×10^4 newtons was used at the top of the test fixture to sense the force exerted on the samples. Output of the load cell was measured with a Baldwin SR-4 Calibration Indicator, Model No. PIC 2ASTCOFF, Range 0 to 60,000 units.

Preload Screw

A preload screw was used at the top of the test fixture to maintain sample alignment during assembly.

Radiation Shields

Six radiation shields of appropriate segment sizes are provided along the lateral length of the test fixture to minimize the radial heat exchange from the measuring column. These shields consist of gold-plated aluminum rings heated electrically with resistive graphite-cloth strips. The graphite-cloth is insulated from the aluminum ring by a layer of glass cloth which is bonded as an assembly with ceramic cement.

Thermal resistance elements are cemented to the inside surface of each radiation shield, opposite each of these elements there is a similar element on the test column. Temperature balance between the column and shields is controlled by regulating the drive voltage to the graphite cloth heaters attached to the shields.

Automatic Heater Control Circuit

A differential amplifier circuit automatically controls the radiation shield heaters, maintaining the same temperature on the radiation shield surface as that of the adjacent portion of the test column.

As the temperature of the shield or column increases or decreases, an unbalance of the differential amplifier drive results. The voltage to the radiation shield heaters change until a state of equilibrium is reached. The circuit schematic is shown in Figure 5.

The accuracy is dependent upon the linearity and response of the Minco resistive elements used to sense the Δ t between the test column and radiation shield surfaces. Linearity between elements has been noted to be within $\pm 1\%$ in the normal temperature operating range. This is equivalent to a Δ t of approximately $\pm 0.4^{\circ}K$ over the normal temperature range. The units can be manually readjusted to remove this source of error while operating.

C. TEMPERATURE INSTRUMENTATION

Temperatures throughout the test fixture were measured from No. 36 gauge copper-constantan thermocouples.

Thermocouples within the fixture are selectable using Thermoelectric, Type 80363 Rotary Switches, combined with a vacuum feed through rotary switch. These measuring thermocouples are referenced to an ice bath junction.

A Leeds and Northrup K-3 Potentiometer Catalog No. 7553-5, an Eppley Laboratories Inc. Standard Cell, Model No. 749633 and a Leeds and Northrup Electronic Null Detector are used for measuring the thermally generated EMF of the individual thermocouples. The capability specification for the K-3 is approximately 2 microvolts, which corresponds to about .05° C.

D. TEST SAMPLE PREPARATION

1. Weld junction of copper - constantan leads (approx. 2 1/2 ft. long) 14 required.

2. Form Bead with Armstrong A2 adhesive over the junction, this will provide centering of junction in hole and strengthen the joint. Bead must be small enough for free insertion into sample.

3. Prepare surface with catalyst from Baldwin Lima Hamilton kit Catalog No. 103158, and attach thermal ribbon (Minco Products Inc. Model S7B) to side of sample with Eastman 910 Adhesive.

4. After initial bead of Armstrong A2 Adhesive has hardened, recoat with Armstrong A2 cement and insert into upper and lower samples per Figures 2 and 3.

E. ASSEMBLY OF SAMPLES IN TEST FIXTURE

1. Coat sample surface thermocouple junctions with Armstrong A2 cement. Attach three thermocouples on each side of upper and lower sample approximately centered and equally spaced, allowing adhesive to set prior to installation.

2. Apply silicone grease to top of fluxmeter and position lower sample centered with fluxmeter.

3. Center upper sample with lower sample and orient test samples keeping the reference position A in line.

4. Apply silicone grease to mating surface of water cooler and center on upper sample.

5. Tighten inlet and outlet water connections to water cooler.

6. Check load cell indicator for zero.

7. Place load cell on cooler.

8. Assemble upper plate to main structure.

9. Apply minimun pressure required to hold column alignment with preload screw.

10. Ascertain that the fluxmeter, lower sample, upper sample and water cooler are concentric and that reference position A on upper and lower samples is maintained in alignment.

11. Connect thermocouple for water cooler.

12. Turn load cell indicator on and check pressure.

(Pressure on load cell must not exceed 100 load cell units).

13. Solder all thermocouples from sample to appropriate leads from connector.

F. PREPARING FOR TEST

1. Clean top surface of feed through ring and rubber seal on bell jar. Coat with high vacuum silicone grease and assemble.

2. Close vent valve to chamber.

3. Open valve to allow water flow through sample cooler.

4. Start mechanical vacuum pump.

5. Open "block off valve" between mechanical pump and diffusion pump.

6. Close water valve to diffusion pump heater area, turn on diffusion pump heater when pressure is less than 50 microns.

7. When diffusion pump is hot (approximately 30 minutes) turn on LN_2.

8. When vacuum is below 20 microns reset safety circuit, as pressure approaches 1 micron, place safety circuit switch to "on" position.

9. Turn on water heater, main heater, radiation shield heaters and radiation shield heater logic.

10. Set air pressure at proper level, 250 load cell units for start of test.

G. RETURN TEST CHAMBER TO ATMOSPHERIC PRESSURE

1. Turn off diffusion pump heater, LN_2 supply, main heater voltage and radiation shield heaters.

2. Turn on water for cooling diffusion pump heater.

3. Disconnect LN_2, connect air line to diffusion pump cold trap, open solenoid valve allowing air to pass through cold trap until all LN_2 has been removed (approximately 1 1/2 hour)

4. After LN_2 has been removed close "block off valve" between mechanical pump and diffusion pump.

5. Open vacuum chamber vent allowing pressure to build up slowly.

6. Turn off mechanical pump when pressure in chamber has equalized.

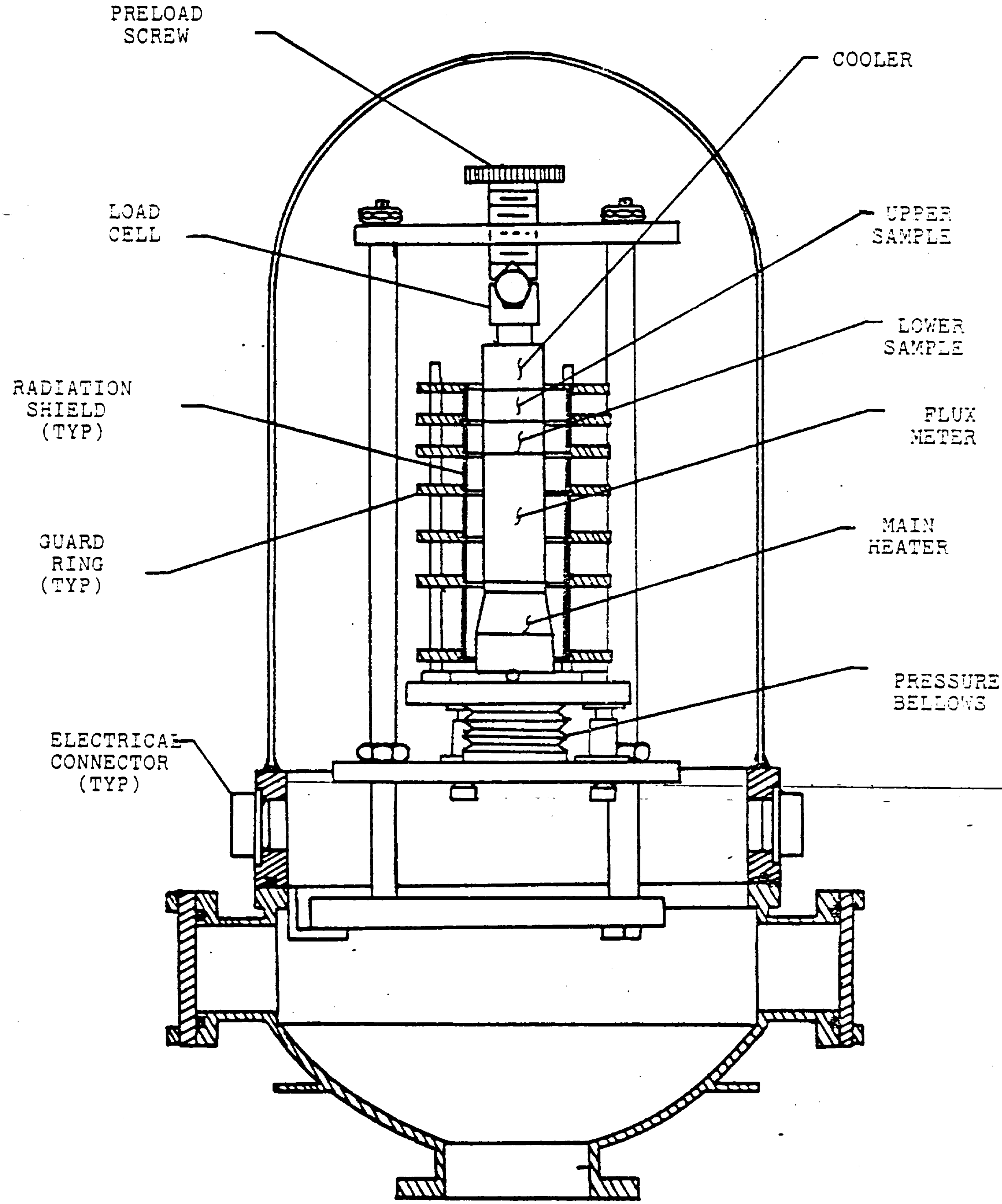
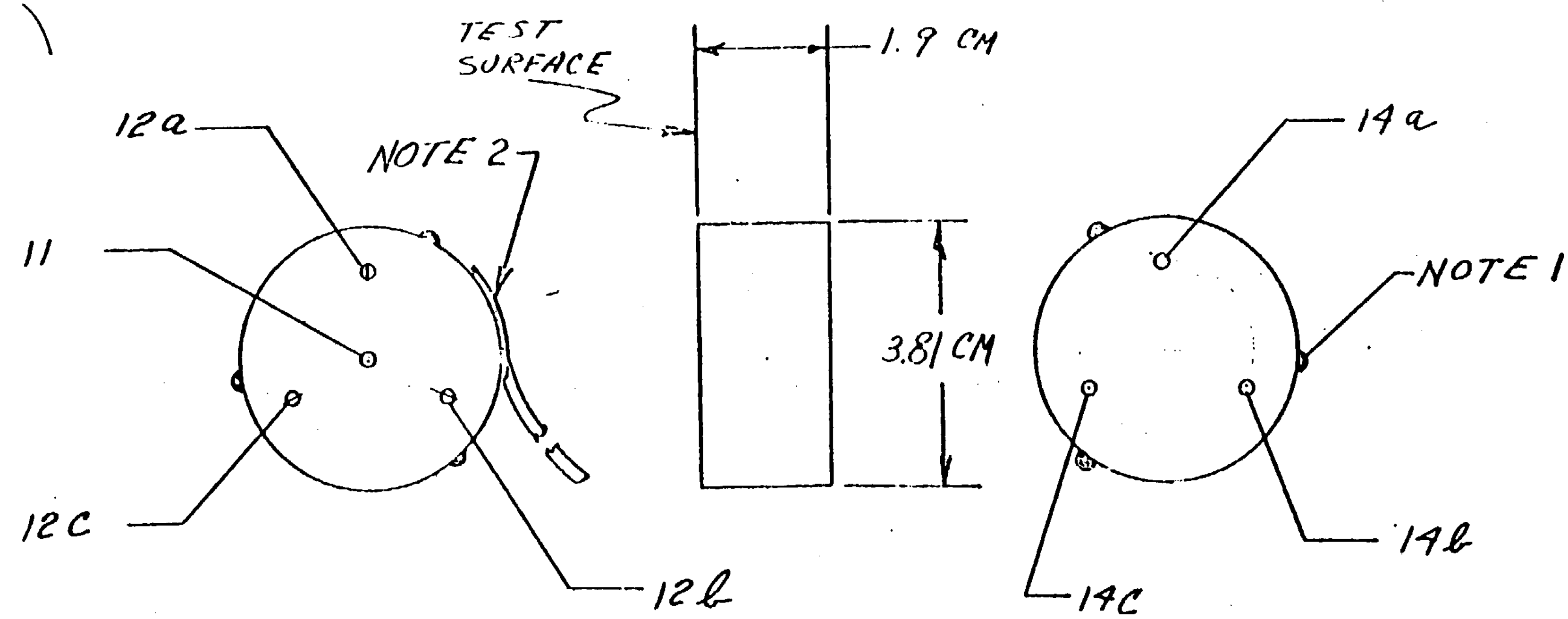


FIGURE 1

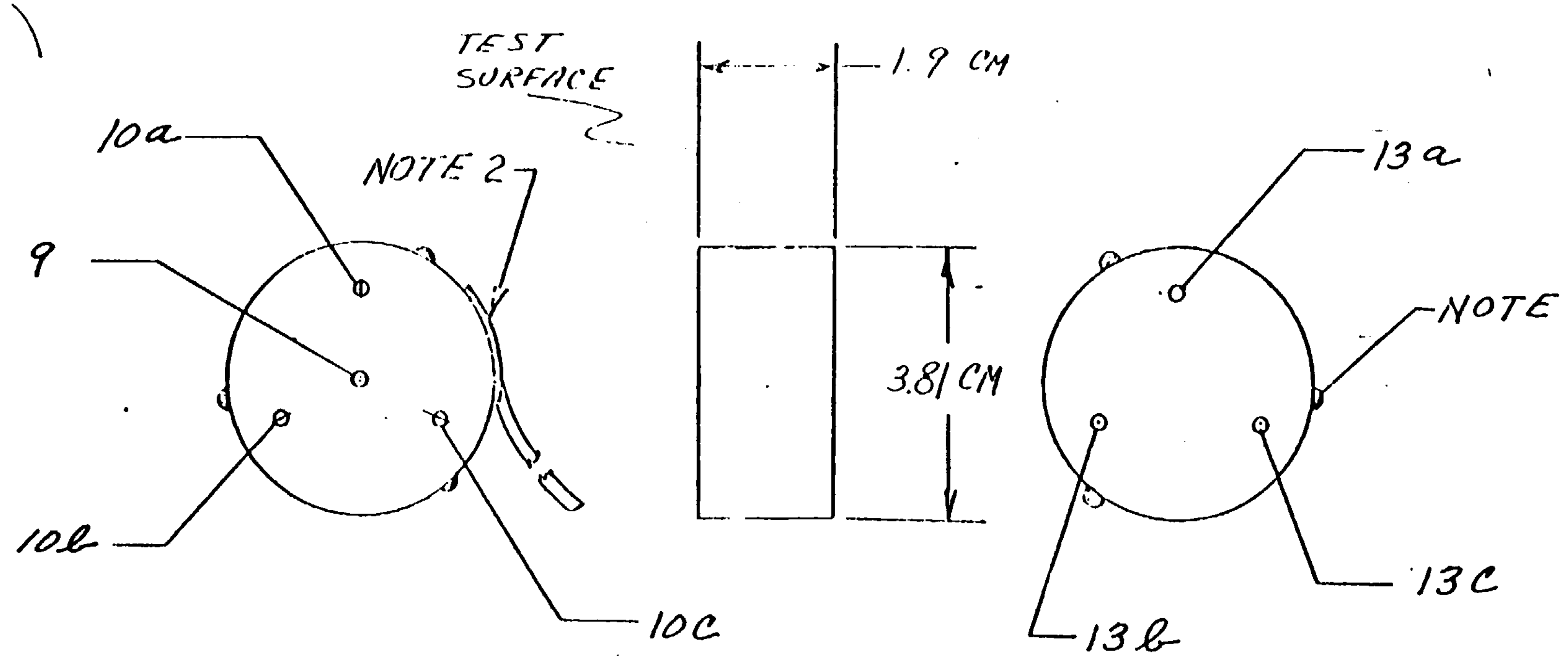
TEST CHAMBER



NOTES:

1. SURFACE THERMOCOUPLES #24 3 REQ'D. EQUALLY SPACED
2. THERMAL RIBBON MODEL S7B MINCO PRODUCTS INC. ATTACH TO SAMPLE WITH EASTMAN 910 ADHESIVE

FIGURE 2
THERMOCOUPLE LOCATIONS
LOWER SAMPLE



NOTES:

1. SURFACE THERMOCOUPLES #26
   3 REQ'D. EQUALLY SPACED
2. THERMAL RIBBON MODEL S7B
   MINCO PRODUCTS INC. ATTACH
   TO SAMPLE WITH EASTMAN 910
   ADHESIVE

FIGURE 3
THERMOCOUPLE
LOCATIONS
UPPER SAMPLE

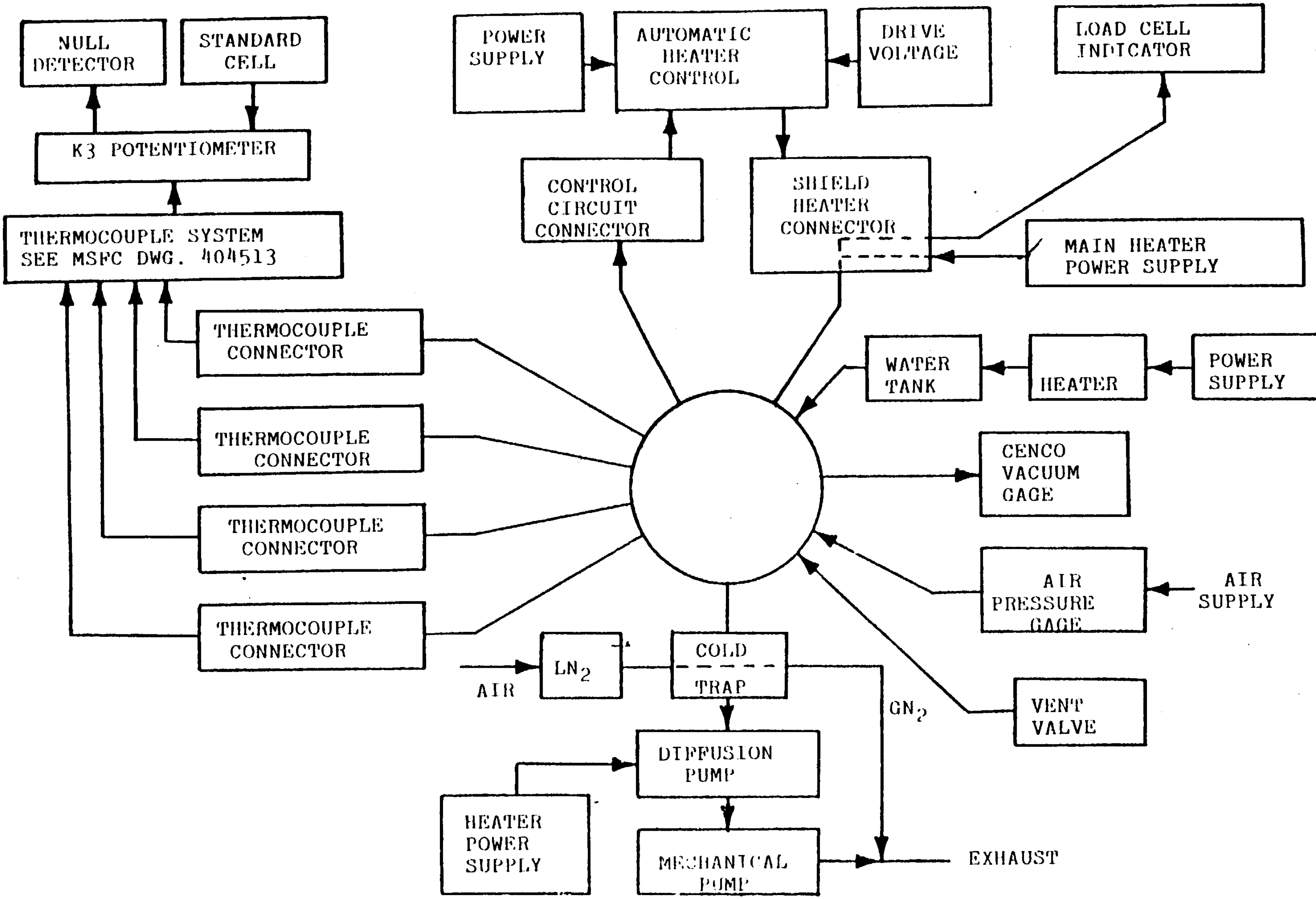
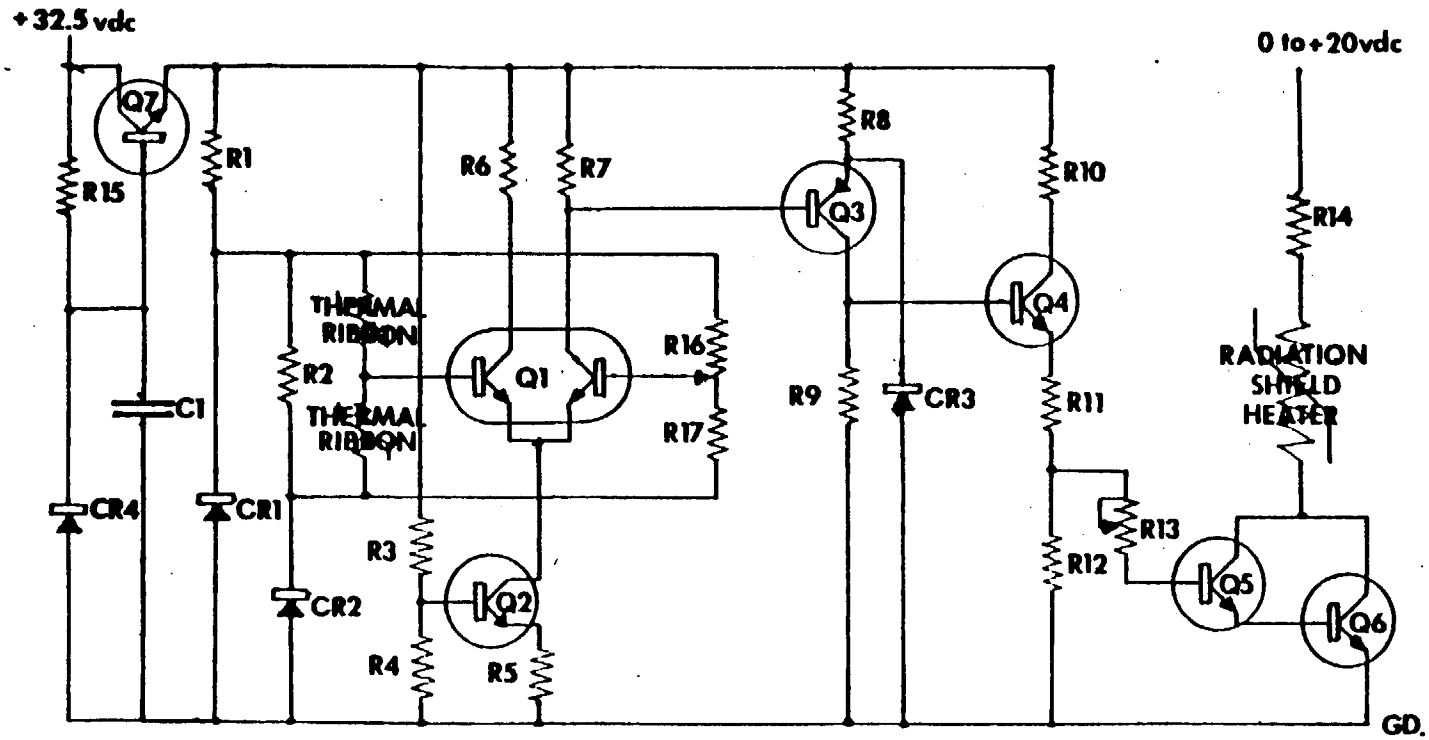


FIGURE 5
CONDUCTANCE TEST SYSTEM SCHEMATIC



AUTOMATIC HEATER CONTROL CIRCUIT

FIGURE 5

TABLE I

COMPONENT LIST

AUTOMATIC HEATER CONTROL CIRCUIT

Reference	Name	Part No. or size
R1	Resistor	560 ohms
R2	Resistor	2. 2 K
R3	Resistor	100 ohms
R4	Resistor	22 K
R5	Resistor	47 K
R6	Resistor	47 K
R7	Resistor	47 K
R8	Resistor	3. 3 K
R9	Resistor	16 K
R10	Resistor	220 ohms 1 W
R11	Resistor	240 ohms 1 W
R12	Resistor	62 ohms 1 W
R13	Bourns Trimpot	2 K
		Unit #1 10 ohms (5+5) 15 W
	Impedance	Unit #2 10 ohms (5+5) "
R14	Match Re-	Unit #3 18 ohms (6+6+6) "
	sistors Series	Unit #4 15 ohms (5+5+5) "
	Connected	Unit #5 10 ohms (5+5) "
		Unit #6 7 ohms (3+4) "
R15	Resistor	510 ohms 1 W
R16	Bourns Trimpot	2 ohms 1 W
R17	Bourns Trimpot	100 ohms

TABLE I (cont'd)

Component List - Automatic Heater Control Circuit Cont'd

Reference	Name	Part No. or size
Q1	Transistor	2N2060
Q2	Transistor	2N930
Q3	Transistor	2N2907
Q4	Transistor	2N2222
Q5	Transistor	2N2034
Q6	Transistor	2N1724
Q7	Transistor	2N2034
CR1	Diode	1N968B
CR2	Diode	1N753
CR3	Diode	1N970A
CR4	Diode	1N971
C1	Capacitor	100 uf 50VDC