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The effect of surface roughness, cure pressure, and temperature level on the thermal resistance of bonds and contacts

David Leo Schwaller

THE EFFECT OF SURFACE ROUGHNESS, CURE PRESSURE, AND TEMPERATURE LEVEL ON THE THERMAL RESISTANCE OF BONDS AND CONTACTS

BY

DAVID LEO SCHWALLER

A

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ABSTRACT

This investigation was conducted to determine the thermal effect of temperature level, surface roughness, and curing pressure on bars and bonded interfaces.

The equipment used in this investigation is shown in Fig. 1 and Fig. 2. The four specimens used, cylindrical aluminum alloy bars, were cut radially at their midpoints and faced on a lathe. Heat was supplied by an electrical resistance heating element and an ice bath was used to conduct heat from the alloy specimen. A heat shield was used to insure one dimensional heat flow. Spacers were placed in the insulation at the top, the interface, and the bottom of the aluminum bar to prevent heat conduction around the interface. These spacers also made a more constant temperature gradient in the insulation around the heat source and heat sink. This setup is shown in Fig. 6. Eighteen thermocouples located at three radial positions at six different levels were used to measure the heat flow through the test cylinder. Radial losses were controlled by six resistance heaters in the heat shield. Losses through the insulation were kept to less than 4.5%.

Partial results from the tests are shown in Tables IV, V, and VI. Figures 9, 10, and 11 show the effect of curing pressure, surface roughness, and temperature level on the thermal resistance of bare and bonded interfaces.

The thermal resistance of the bare interface increased with surface roughness, as did the resistance of the epoxy

filled interface cured at 2 psi. Because of a change in the adhesive layer thickness the thermal resistance of the bond layer decreased with curing pressure. Thermal resistance decreased with an increase in mean interface temperature for all tests conducted.

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NOMENCLATURE

Symbol	Physical Quantity	Units
A	Cross-sectional area of specimen	sq ft
k	Thermal Conductivity	Btu/hr ft ^{o}F
L	Length of specimen	ft
q	Heat flow	Btu/hr
r_i	Inner radius	ft
r_o	Outer radius	ft
R_t	Thermal resistance	hr sq ft ^{o}F/Btu
T_h	Higher temperature	^{o}F
T_c	Lower temperature	^{o}F
$\frac{dT}{dx}$	Temperature gradient	^{o}F/ft

INTRODUCTION

In recent years the resistance to heat transfer offered by metallic joints in contact has become a major problem. By decreasing the thermal resistance caused by two surfaces in contact, the thermal efficiency of energy conversion systems could be increased and operating expenses could be lowered. Heat generated by electrical equipment in space vehicles must be conducted from the equipment and radiated to the surroundings. The thermal resistance of the adhesives and contacts securing the ablation shields to rentry space vehicles is extremely critical. In the past, the resistance to the flow of heat in contacts and bond layers was estimated or neglected. Because of the extremely rapid advances in the fields of space travel, high speed aircraft, and missiles, the information available concerning the resistance of contacts and adhesive layers is very limited. Tests on this subject have led to several conclusions but these are not always in complete agreement. Investigations of interface thermal conductance have been performed with the test specimen in air, in a vacuum, under pressure, and with various materials between the interfaces.

This thesis is concerned with the latter of the above stated tests. The problem is to determine to what extent the surface roughness of the specimen and the curing pressure of the adhesive retard or improve heat transfer through interfaces.

To date, the limited reference material on interface

thermal conductance was concerned with bare interfaces of metals; i.e., the effects of dissimilar metals, the interface pressure and relative temperature drop, effects of shims, surface roughness of the interfaces, and the atmosphere surrounding the test specimen. The test apparatus used in the investigations was of a similar arrangement and the type of test specimens was usually either cylindrical with large diameter to height ratio, or plates with large width to thickness ratios. Common parameters to all tests were the heat flow and the temperature gradient across the interfaces.

Dunkle, Gier, and Bevans (8)* while investigating the thermal conductivity of aluminum honeycomb structure, stated that the total thermal resistance of the shell was the sum of the resistances of the aluminum skin, the homeycomb cell, and the bonding adhesive. The total thermal resistance of the structure was measured with a heat meter. The resistance of the aluminum skin was negligible, and the resistance of the honeycomb cell was determined from the cell geometry. Knowing the above stated resistances, the thermal resistance of the bonding adhesive layer was determined. A liquid and a tape bonding material was tested.

Lewis (21) investigated the thermal effect of different adhesive layers between aluminum interfaces. The adhesives used were epoxy thermoset, polyester thermoset, thermoplas-

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*Underlined numbers in parenthesis indicate references listed in the Bibliography.

tic, and silicone rubber. The effects of temperature and curing pressure were also studied.

In their report on the thermal conductance of aircraft joints, Barzelay, Tong, and Hollo (3) noted the factors influencing the thermal conductance across the interface between 75S-T6 aluminum alloy and AISI Type 416 stainless steel structural joints. The effects of heat flow, temperature drop, temperature level, and surface conditions, were investigated. Results from this report indicated: (1) the thermal conductance of the interface joint increases with the mean interface temperature level, while it remains approximately constant with changes in heat flow, (2) thin foils of good conducting materials inserted between the interfaces improve the heat transfer noticeably, (3) common strength-giving bonding materials produce joints with very poor thermal conductance.

The effect of pressure on thermal conductance of contact joint was also investigated by Barzelay, Tong, and Hollo (4). This investigation showed the following trends: (1) the interface conductance increases with pressure, (2) the increase in conductance for a given pressure increment is far more pronounced for the soft material (aluminum) than it is for the hard material (stainless steel), (3) for a given pressure increment the percentage increase of conductance is about the same for all mean interface temperatures, (4) for a given pressure increment and interface temperature the absolute increase of conductance is higher for smoother surfaces.

Fried and Costello (11) report that thermal conductance should improve for a joint material with: (1) increasing contact pressure, (2) reduced surface roughness, (3) improved flatness of surface, and (4) lower yield strength of one of the mating materials. Tests on thin foils placed between the interfaces showed an increase in the thermal conductance. The lead foil exceeded aluminum at low contact pressures (3 to 35 psi).

Fried (12) conducted tests using silicone grease and silicone rubber between the interfaces of an aluminum joint. The silicone rubber did not improve the thermal conductance of the joint, while the silicone grease seemed to be effective in increasing the thermal resistance of the aluminum joint.

In reporting on the thermal conductance of space vehicle interfaces, Fried (10) states: (1) the most promising methods found in these experiments for improving the thermal contact conductance of joints were the use of silicone grease at all contact pressure and lead foil at contact pressures in excess of 10 psi, (2) the results obtained using "soft" metal shims appear to verify the dependence of the contact conductance on the resistance to indentation of the softer of the metallic joint materials, (3) sample flatness, as it affects the actual contact area between the joint surfaces is perhaps the most important variable for bare metal thermal contacts in space vehicles at low contact pressures.

Jansson (17) investigated the effects of various filler materials on the interfaces of aluminum and beryllium blocks. The filler material included epoxy cement, 0.002-inch indium foil, aluminum and gold leaf, and 0.0015-inch lead foil. The indium foil, being a soft material, produced considerably lower thermal resistances than the bare interface. The lead foil decreased the thermal resistance as did the epoxy cement. The other filler materials made no significant differences. By analyzing a joint contact points and the average size of the points, as nearly constant, Jansson states that for any given load, regardless of the surface roughness, there would be a nearly constant thermal resistance. Varying surface roughness should yield different thermal resistances when a fluid is present at the interface. However in the absence of fluid the conduction is dependent upon the contact points alone.

Rodgers (26) found that the direction of heat flow has a marked effect upon the thermal conductance at the interface of some dissimilar metals. Powell, Tye, and Jolliffe (25) disagree with Rodgers' theory of the differences in the mechanism of heat conduction at the points of contact, and attribute the effects on heat flow to thermal warping caused by local temperature differences. Based on their conclusion from tests with a thermal comparator, they report that the direction of heat flow has no effect on thermal conductance.

From the preceding discussion it can be seen that most

of the emphasis has been placed on the bare interface. This paper concentrates upon the effects of having an adhesive between the interfaces which essentially eliminates convection and radiation effects, leaving only conduction heat transfer to consider.

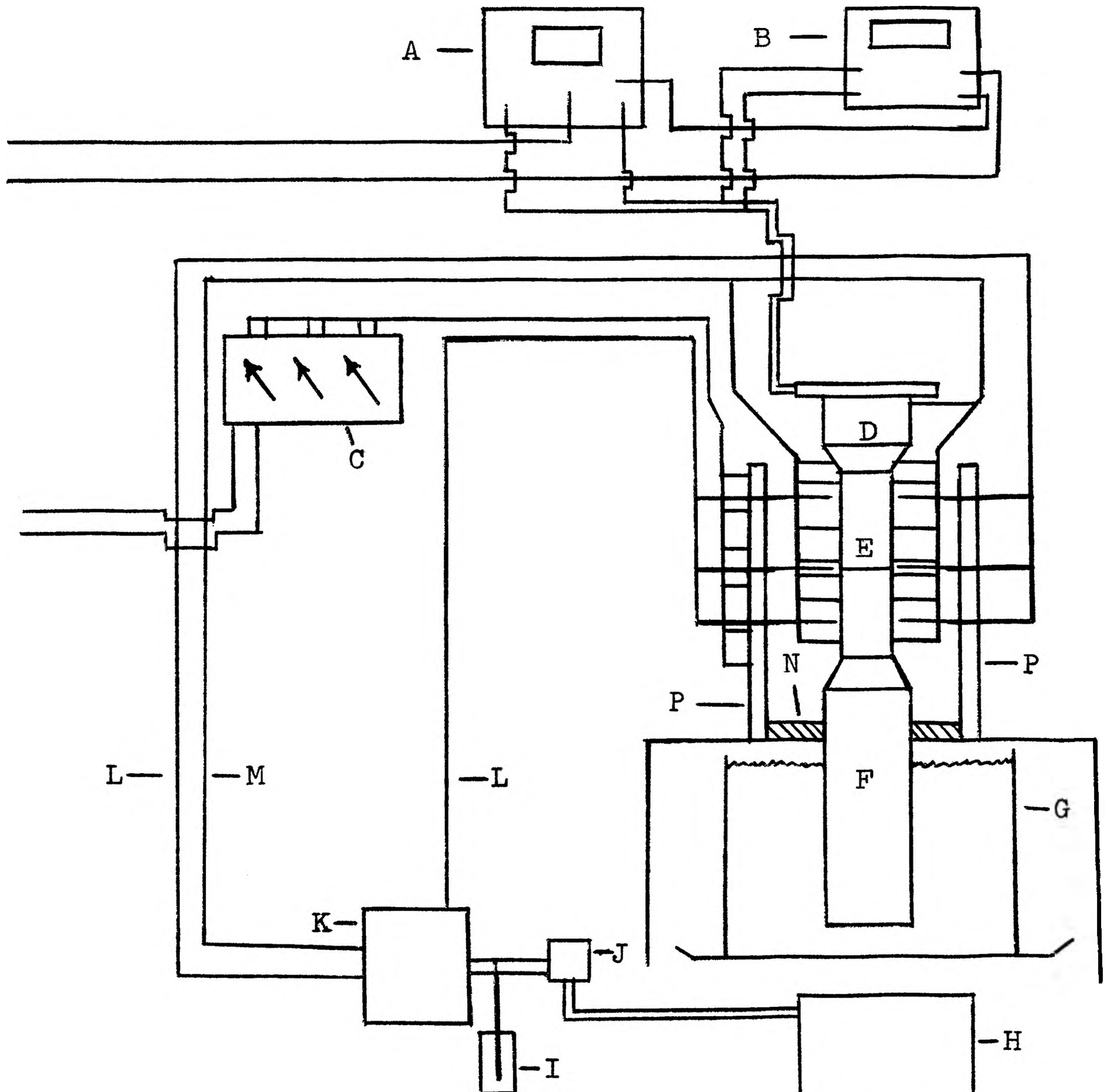
EXPERIMENTAL METHOD AND EQUIPMENT

Description of Apparatus

The general setup of the test equipment is shown in Fig. 1, and a schematic diagram of the equipment is shown in Fig. 2. The equipment was designed to determine the thermal effect of an adhesive at the interface of a cylindrical aluminum specimen. This was accomplished by cutting the specimen radially at its' midpoint, and bonding it together with an adhesive. Heat was supplied at the top end of the specimen by an electrical resistance heater. An ice bath was used to transfer the heat from the bottom of the specimen. The aluminum cylinder was placed in a heat shield and packed in glass wool insulation to minimize the radial heat loss. Once the specimen had reached steady state, the axial temperature distribution along the specimen was recorded, and the thermal resistance of the bond layer was calculated. Tests were conducted varying the interface surface roughness for bonded and bare interfaces, and varying the curing pressure of the adhesive.

Specimen - The four specimens consisted of a cylindrical aluminum alloy (7075-T6) bars which had been cut and faced, then rejoined with a thixotropic epoxy adhesive. The aluminum alloy had a nominal composition of 1.6% copper, 2.5% magnesium, 5.6% zinic, and 0.3% chromium. The eighteen thermocouple holes, six axial holes at three different depths (0.500, 0.250, and 0.125 of the diameter) were arranged as shown in Fig. 3 and Fig. 4. The upper and lower

Fig. 1 Equipment setup for investigation.



A - Variable Voltage Transformer
B - Wattmeter
C - Variable Voltage Transformer
D - Heat Source
E - Specimen
F - Heat Sink
G - Heat Sink Ice Bath
H - Recorder
I - Reference Junction Ice Bath
K - Main Switch Box
L - Heat Shield Thermocouples
M - Specimen Thermocouples
N - Aluminum Disk
P - Heat Shield

Fig. 2 Schematic of Experimental Setup

halves of the specimen are dimensionally the same. The three air gaps, as shown in Fig. 6, were constructed of sheet aluminum 5.50 inches outside diameter and 2.00 inches inside diameter. Because of the low thermal conductivity of still air, as compared to glass wool, the air space at the interface of the specimen reduced the flow of heat around the interface. To prevent a radial temperature gradient around the heat source and heat sink interfaces, air gaps were used. Sheets of aluminum foil were placed between the heat source and heat sink interfaces to decrease the thermal resistance of these joints.

Heat Source - The heat source consisted of an electrical resistance heating element mounted on a tee-shaped block of aluminum. In order to obtain a uniform radial temperature distribution, the heater head was designed in a tee shape, 3.25 inches in diameter at the top and 2.00 inches in diameter at the base. Three thermocouples were mounted in the heat source, 0.125 inches from the base at different radii to check the radial temperature distribution. A fourth thermocouple was located 0.250 inches from the top of the heat source to maintain a check on the heating element temperature. The aluminum tee-block helped to eliminate small variations in the heating element's temperature. A 3.20-pound weight was placed on top of the plate covering the heating element to insure good contact between heat source, specimen, and heat sink. The heat source setup is shown in Fig. 6.

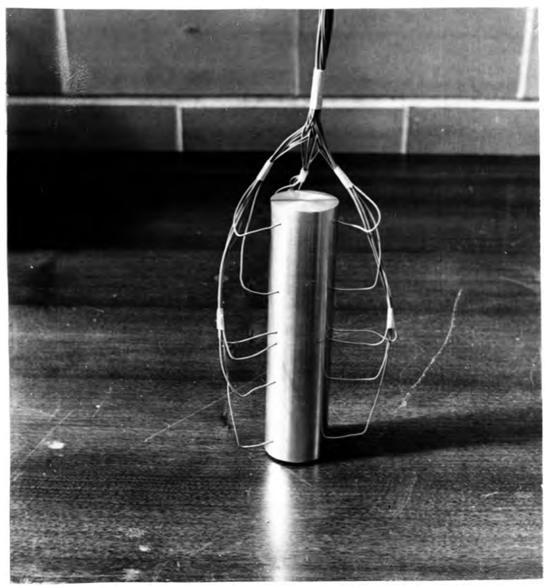


Fig. 3 Test specimen.

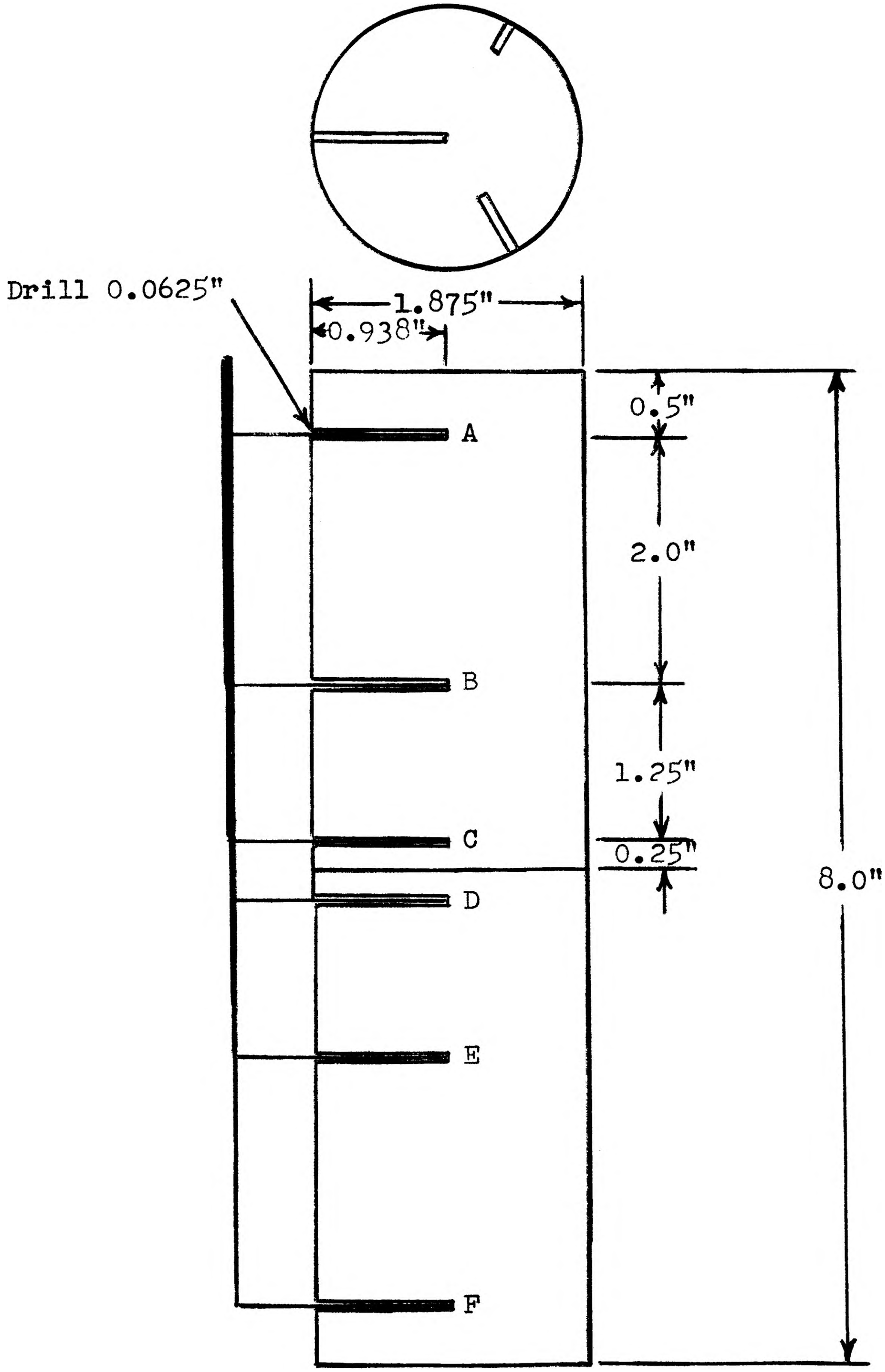


Fig. 4 Test Specimen Details and Thermocouple Numbering System

Heat Sink - The heat sink consisted of an aluminum cylinder 3.25 inches in diameter and 8.00 inches long. The top 2.00 inches was beveled at a 45° angle as shown in Fig. 6. The top of the heat sink was 2.00 inches in diameter. Tapering the top of the sink helped to eliminate radial temperature distributions in the aluminum and in the glass wool insulation. A 2.25-inch inside diameter and 3.00-inch outside diameter cylindrical aluminum tube 6.00 inches long was pressed on the bottom of the 3.25-inch aluminum bar to increase the heat rate through the heat sink. Six holes, 0.500 inches in diameter were drilled at a 45°-angle in the aluminum tube to allow the water in the ice bath to flow through the heat sink. The bottom of the 3.25-inch aluminum cylinder was finned to increase the heat transfer rate. A thermocouple was mounted in the center of the heat sink. Three thermocouples were placed 0.125 inches from the top of the heat sink at different radii to check the radial temperature distribution. The heat sink was maintained at a low temperature by submerging the lower half of the 3.25 inch aluminum cylinder in an ice bath as shown in Fig. 1. The ice bath was continuously agitated by an electric motor driven eccentric and maintained at a temperature of 32°F.

Heat Shield - The heat shield, as shown in Fig. 5, consisted of a "Transite" pressure pipe 13.25 inches long, 7.00 inches outside diameter, and 5.75 inches inside diameter. Nichrome heating wires were placed in grooves, 0.125 inches wide and 0.4375 inches deep, cut radially in the heat shield.

Fig. 5. Heat Shield

An aluminum disk, 0.750 inches thick, 5.750 inches outside diameter and 3.250 inches inside diameter, was placed in the bottom of the heat shield to insure an even temperature distribution in the shield. Because the bottom section of the heat shield was below ambient temperature, a layer of glass wool insulation, 4.50 inches deep, was placed around this section of the shield. Three variable voltage transformers were used to maintain the current in the nichrome heating elements. Eighteen thermocouples were mounted in the heat shield at three levels and six radial positions to determine, thus minimize the radial loss of heat. The heat shield was mounted on a 1/2-inch plywood board, 16 inches square, and secured with four machine screws. This was supported by two 1 inch boards, 12 inches high and 14 inches wide. A hole was cut in the center of the plywood board so the heat sink could extend down into the ice bath. The heat sink was held in position by three angle clips, with lock screws, equally spaced around the hole.

Thermocouples - Forty-four iron-constantan thermocouples were used to measure the temperatures. The thermocouple potentials were measured by a Brown Electronik Continuous Balance Unit, to the nearest hundredth of a millivolt. A 32°F ice bath reference junction was used. The thermocouple numbering system is shown in Fig. 4.

Additional Equipment - The surface roughness of the specimen was measured by a Profilometer. The range of the

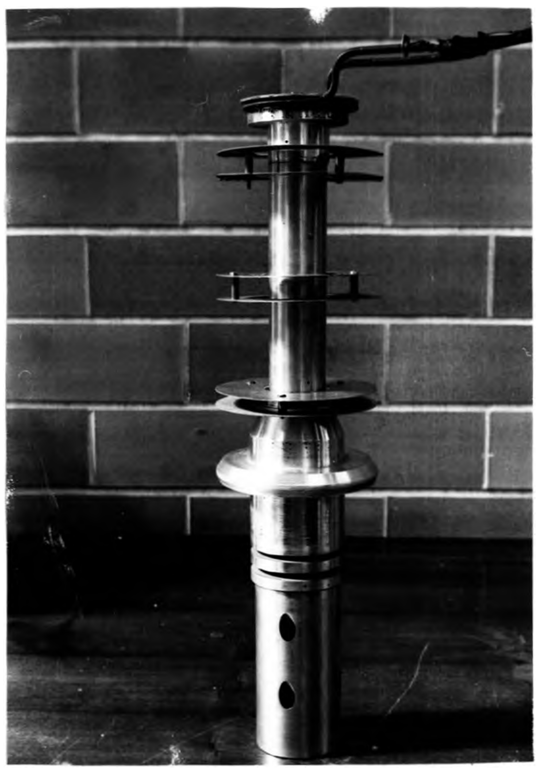


Fig. 6 Complete test specimen as setup in heat shield.

surface roughness (root mean square) was observed. A wattmeter was used to monitor the input power from the powerstat to the heat source. Glass wool was used as the insulating material. Various switch boxes were used in conjunction with the recorder to measure the thermocouple potentials. A voltmeter was used in conjunction with a temperature versus voltage curve for each pair of nichrome heating elements in order to obtain the proper temperature distribution down the heat shield.

Test Procedure

The reference junction and heat sink ice baths were prepared. The thermocouples, wattmeter, electrical sources, and heaters were connected and the power turned on. Power to the heat source was controlled by a variable voltage transformer and monitored by a wattmeter. The power was set until a specific temperature was reached in the upper part of the cylinder and then adjustments were made to retain this temperature. After steady state conditions were reached at this predetermined temperature, and the desired data taken, the input power was readjusted and another predetermined temperature was obtained under steady state conditions. This procedure was continued until the data necessary to complete a particular test had been gathered.

Heat shield voltage, wattmeter readings and temperatures of the heat shield, heat source, heat sink ice bath, and test specimens were initially recorded every 20 minutes and eventually every 10 minutes until readings remained constant for approximately 30 minutes. About 3 hours were required to reach steady state for a given set of conditions. The reference junction ice bath was checked each time data was taken, and the heat sink ice bath was continuously agitated to insure a uniform temperature during the test.

The four aluminum specimens were cut radially at their midpoints, and the interface tooled smooth on a lathe. Placing the bare interfaces in contact, the eighteen thermocouples were fixed in position. The weight of the heat

source, the upper half of the specimen, and a 3.20-pound weight were used on the bare interface run to maintain interface contact. All bond and contact tests were run with the same weight arrangement and identical procedures were used.

Test Data

The test data from the bare interface investigation are shown in Table I. The runs were conducted at two different surface roughness values and an interface contact pressure of 2 psi. The average temperatures of the three thermocouples at the six positions down the specimen are tabulated with the average temperature drop through the insulation. The temperature drop through the insulation was calculated from the readings obtained from the eighteen thermocouples in the heat shield wall. The specimen thermocouple numbering system is shown in Fig. 4. Eight runs were made varying the mean interface temperature.

The results of the epoxy surface roughness test are shown in Table II. The three average rms surface roughness values used were 25, 90, and 145 microinches. The curing pressure for the epoxy adhesive was 2 psi for all three runs. The mean interface temperature was varied for five different runs.

Table III shows the data from the epoxy pressure test. The specimens were cured at three pressures, 2 psi, 35 psi, and 75 psi. The average surface roughness value for this set of runs was 25 microinches (rms). Six runs were made varying the mean interface temperature.

TABLE I

Experimental Data

Bare Interface Test

Surface Roughness microinches rms		85 - 95	140 - 150
Mean Interface Temperature °F		186.4	182.2
Specimen Thermocouple		Temperature °F	Temperature °F
Heat Meter No. 1	A	232.3	220.7
	B	212.3	205.3
Heat Meter No. 2	C	199.7	195.7
Heat Meter No. 3	D	173.0	167.0
	E	160.0	157.3
Heat Meter No. 4	F	139.3	141.7
Temperature Drop through the Insulation °F		6.4	3.4

TABLE II

Experimental Data

Epoxy Surface Roughness Test

Surface Roughness microinches rms		20 - 30	85 - 95	140 - 150
Mean Interface Temperature °F		146.4	144.2	125.5
Specimen Thermocouple		Temperature °F	Temperature °F	Temperature °F
Heat Meter No. 1	A	190.0	167.7	179.7
	B	171.7	158.0	162.7
Heat Meter No. 2	C	160.3	153.7	152.0
Heat Meter No. 3	D	132.0	134.7	99.0
	E	120.3	129.3	88.0
Heat Meter No. 4	F	101.3	120.7	70.3
Temperature Drop through the Insulation °F		6.0	1.70	5.00

TABLE III

Experimental Data

Epoxy Cure Pressure Test

Cure Pressure psi		2	35	75
Mean Interface Temperature °F		205.6	201.0	196.0
Specimen Thermocouple		Temperature °F	Temperature °F	Temperature °F
Heat Meter No. 1	A	253.3	245.3	245.3
	B	229.0	221.3	219.0
Heat Meter No. 2	C	213.3	206.0	202.0
Heat Meter No. 3	D	175.0	196.0	191.0
	E	158.7	180.3	173.7
Heat Meter No. 4	F	132.4	155.3	146.0
Temperature Drop through the Insulation °F		10.0	12.3	8.4

METHOD OF ANALYSIS

Thermal resistance is defined by the equation

$$R_t = \frac{A(T_h - T_c)}{q}, \qquad \text{(I)}$$

where A is the cross-sectional area, q is the rate of heat transfer through the resistance, T_h is the temperature on the hot side of the resistance, and T_c is the temperature on the cold side of the resistance.

The equipment used in this investigation permitted only one dimensional heat flow, thus satifying the Fourier conduction equation,

$$q = -kA \frac{dT}{dx} \, . \qquad \text{(II)}$$

Radial heal losses were minimized by the heat shield and glass wool insulation. The heat rate was calculated at four different areas along the sample. The heat flow through the No. 1 heat meter was calculated from the difference in the temperature of thermocouples A and B. The thermal conductivity (k) was taken from Fig. 7 at the average temperature of thermocouples A and B, and distance (dx) between the thermocouples A and B, and the cross-sectional area of the specimen. The heat flow through heat meters No. 2, No. 3, and No. 4 was calculated using the same procedure. The difference between readings on heat meters No. 1 and No. 4 was taken as the radial side losses. Radial heat losses were also calculated using the following conduction equation for heat flow through a cylindrical wall, assuming the insulation between the heat shield and specimen was a

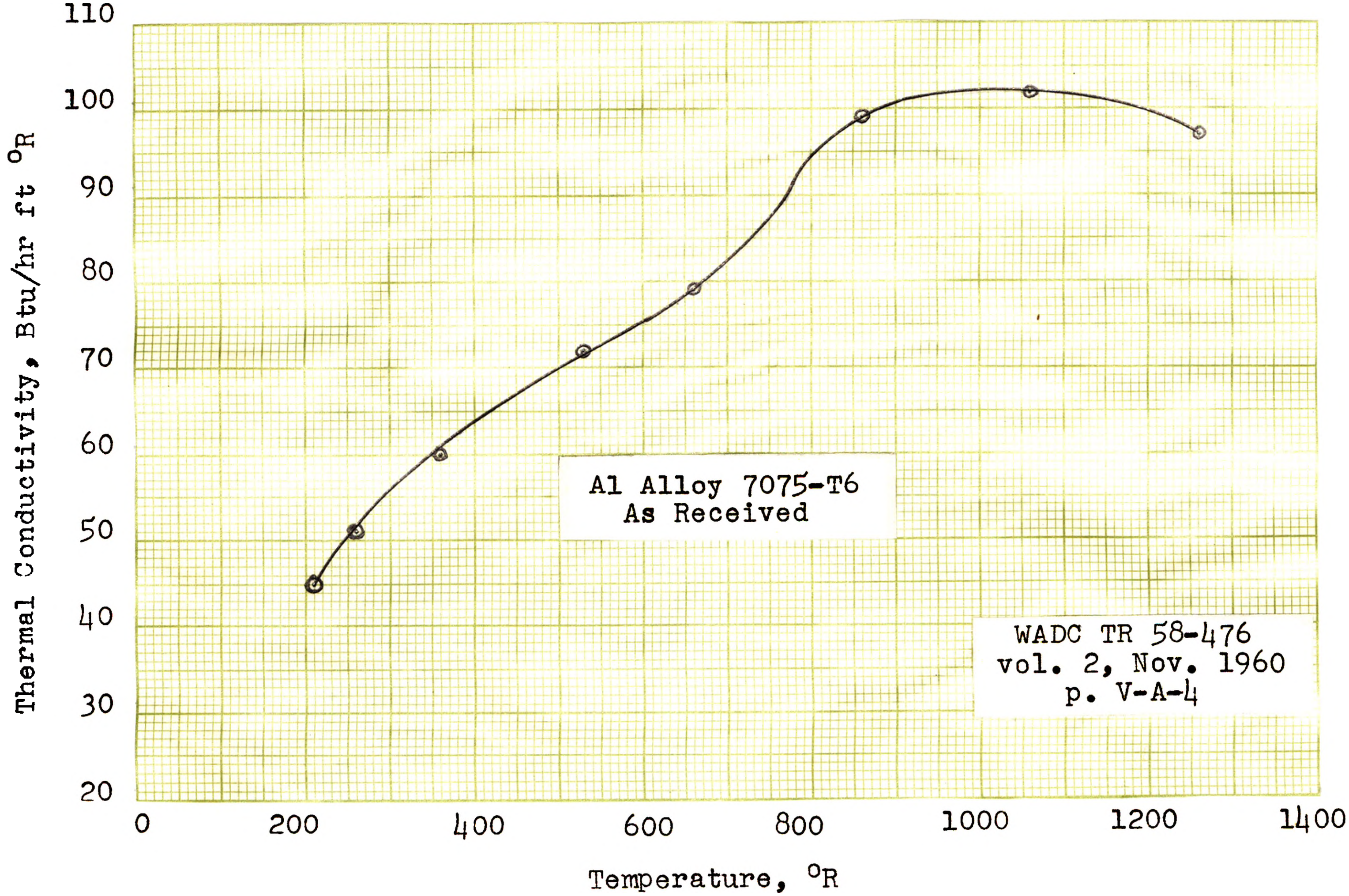

110
100
90
80
70
60
50
40
30
20
Thermal Conductivity, Btu/hr ft °R
0
200
400
600
800
1000
1200
1400
Temperature, °R
Al Alloy 7075-T6
As Received
WADC TR 58-476
vol. 2, Nov. 1960
p. V-A-4

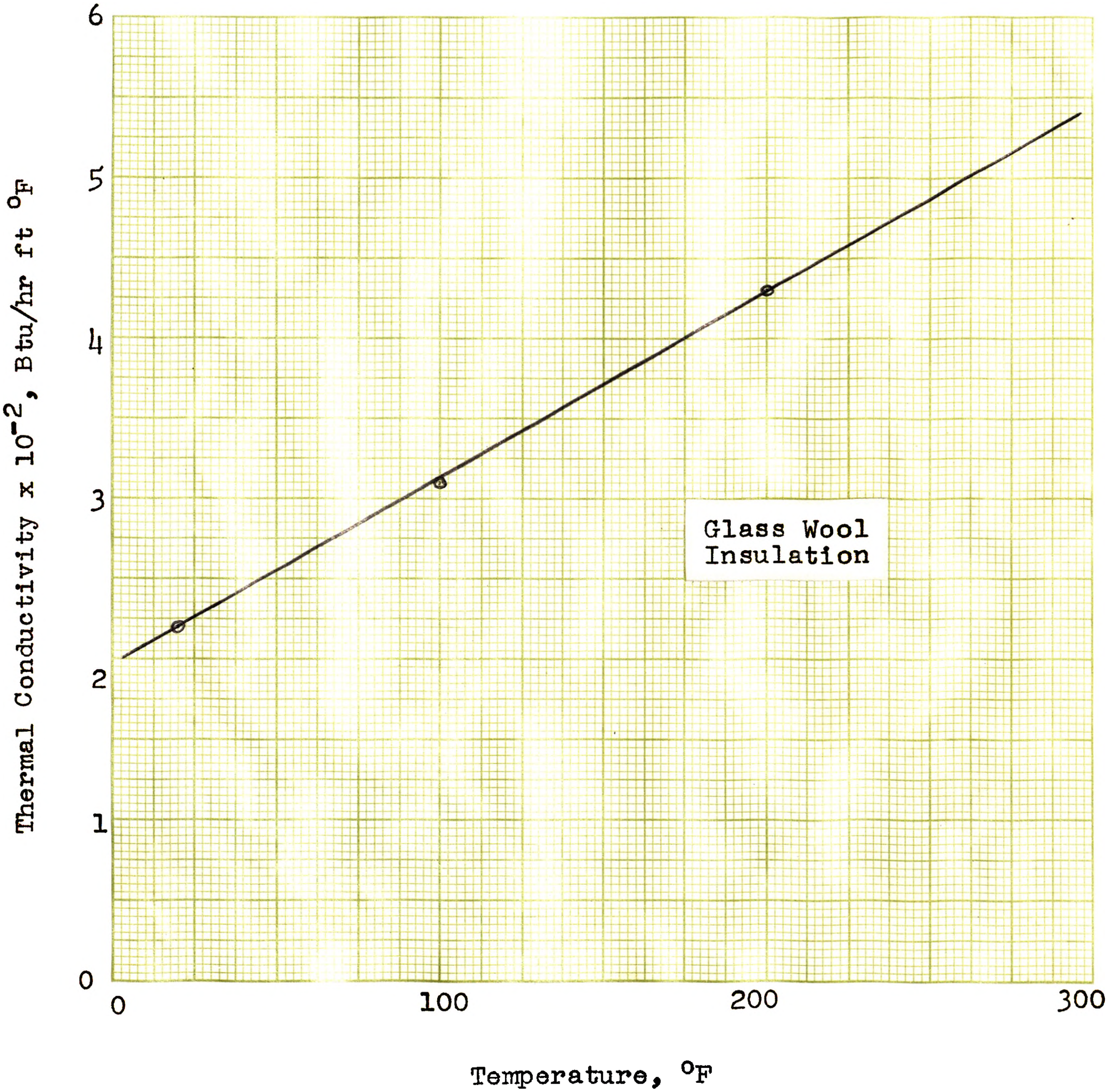
Figure 7

cylindrical wall of length (L):

$$q = 2\pi \frac{kL(T_h - T_c)}{\ln r_o/r_i} . \qquad \text{(III)}$$

The thermal conductivity was taken from Fig. 8 at the mean temperature of the insulation. The temperatures were taken from the average readings of the eighteen thermocouples mounted in the heat shield. Outer and inner radii (r_o and r_i) were measured from the center of the specimen to the thermocouples measuring the temperature drop through the insulation.

Using equation No.II, the temperatures of the upper and lower interfaces were calculated. Heat flow through the interface was assumed to be the same as measured from heat meter No. 2. From the temperature recorded by thermocouple C the thermal conductivity was determined for the upper interface, and the temperature from thermocouple D was used for the lower interface. Using the cross-sectional area of the sample, and equation No. I, the thermal resistance of the interface was calculated.



6
5
4
3
2
1
0
0
100
200
300
Thermal Conductivity x 10^{-2}, Btu/hr ft ^{o}F
Glass Wool
Insulation
Temperature, ^{o}F

Figure 8

DISCUSSION OF RESULTS

The effects of surface roughness and mean interface temperature on the thermal resistance of bonded and dry interfaces are shown in Fig. 9. The joints bonded with epoxy had a greater resistance to the flow of heat than did the bare interfaces. The thermal resistance of the joint decreased with an increase in the mean interface temperature as shown by Barzelay, Tong, and Hollo (3), and Lewis (21). Fig. 11 shows a comparison between the test results of Barzelay, Tong, and Hollo and the results of this test. The curve for the 90 microinch bare interface joint indicates the validity of the test results. Since the chemical classification of the epoxies used in the tests conducted by Jansson (17) and Lewis (21) were not stated, a comparison of the results could not be made.

The results of the epoxy cure pressure test, Fig. 10, show a large decrease in the thermal resistance with an increase in cure pressure. A slight decrease in the thermal resistance was apparent with an increase in the mean interface temperature. The lower value of thermal resistance with cure pressure can be attributed to the decrease in the bond thickness and possibly to the deformation of some of the asperities on the interface surface. The average surface roughness value for the cure pressure test was 25 microinches rms.

A general comparison of all test results shows a decrease in the range of the results with a decrease in the

TABLE IV

Tabulated Results

Epoxy Surface Roughness Test

Surface Roughness microinches rms	20 - 30	85 - 95	140 - 150
Mean Interface Temperature °F	146.4	144.2	125.5
Heat Meter No. 1 (Btu/hr)	163.5	76.7	151.0
Heat Meter No. 2 (Btu/hr)	161.0	74.3	149.8
Heat Meter No. 3 (Btu/hr)	160.8	74.5	148.0
Heat Meter No. 4 (Btu/hr)	161.8	74.2	146.0
% Actual Heat Loss	1.04	3.26	3.31
% Heat Loss Calculated	0.73	.47	.69
Thermal Resistance hr sq ft °F/Btu	.00298	.00435	.00629

TABLE V

Tabulated Results

Epoxy Cure Pressure Test

Cure Pressure psi	2	35	75
Mean Interface Temperature °F	205.6	201.0	196.0
Heat Meter No. 1 (Btu/hr)	230.0	226.0	247.0
Heat Meter No. 2 (Btu/hr)	232.0	224.0	249.0
Heat Meter No. 3 (Btu/hr)	230.0	225.0	247.0
Heat Meter No. 4 (Btu/hr)	229.0	222.0	244.0
% Actual Heat Loss	.436	1.77	1.21
% Heat Loss Calculated	1.05	1.29	.805
Thermal Resistance hr sq ft °F/Btu	.00277	.000494	.000302

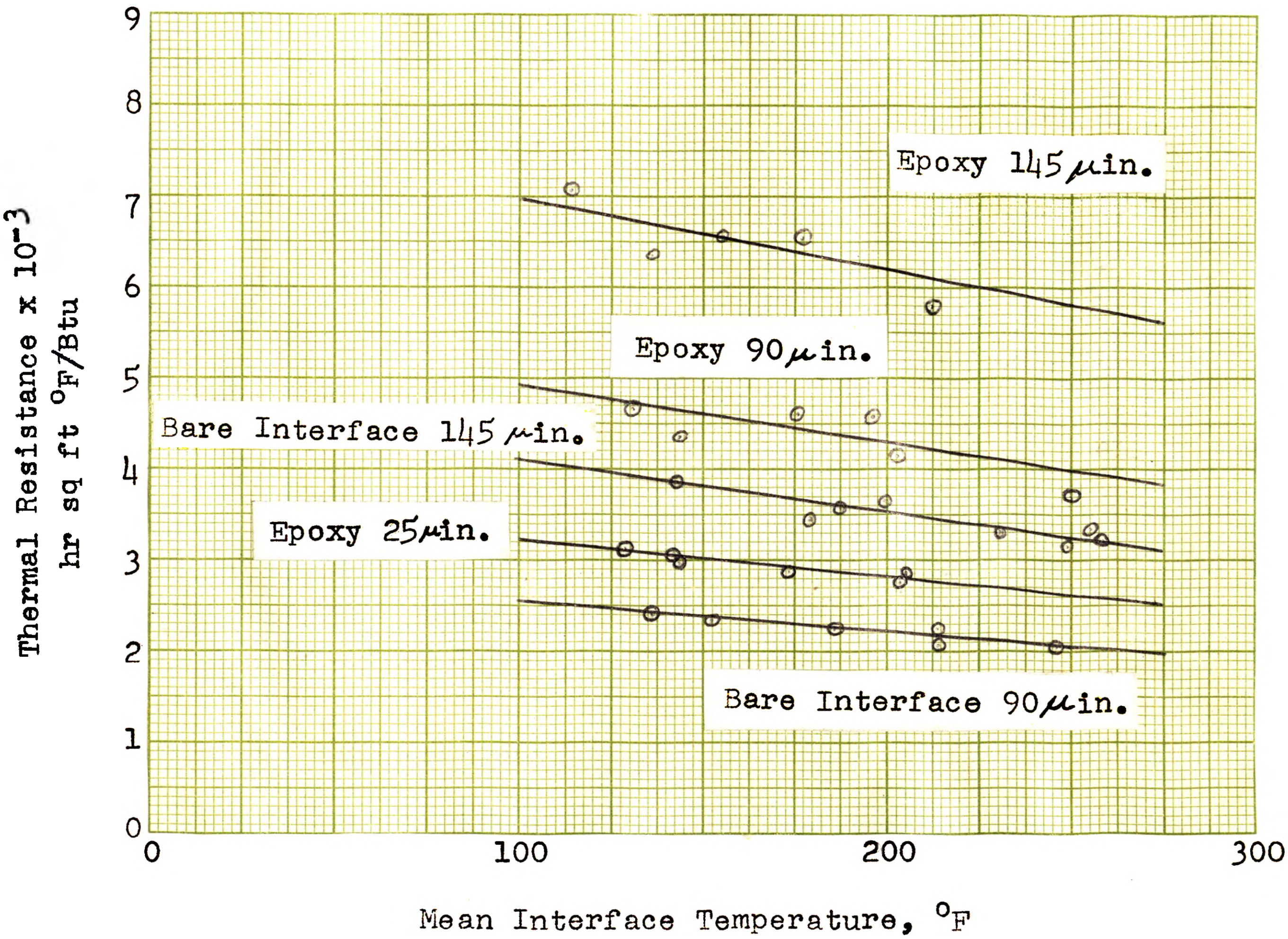

Epoxy 145μin.
Epoxy 90μin.
Bare Interface 145 μin.
Epoxy 25μin.
Bare Interface 90μin.
Thermal Resistance x 10^-3
hr sq ft °F/Btu
Mean Interface Temperature, °F
0
1
2
3
4
5
6
7
8
9
0
100
200
300

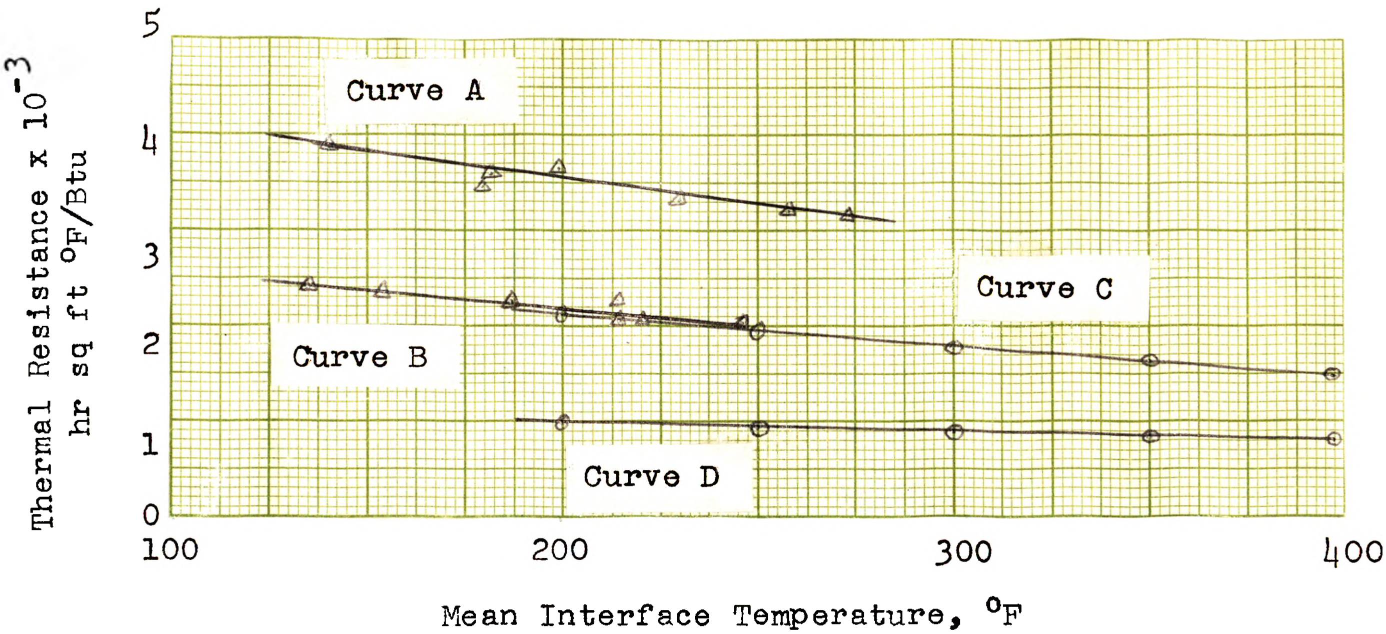
Figure 9

TABLE VI

Tabulated Results

Bare Interface Test

Surface Roughness microinches rms	85 - 95	140 - 150
Mean Interface Temperature °F	186.4	182.2
Heat Meter No. 1 (Btu/hr)	185.5	141.5
Heat Meter No. 2 (Btu/hr)	183.5	139.0
Heat Meter No. 3 (Btu/hr)	184.5	137.0
Heat Meter No. 4 (Btu/hr)	181.0	136.8
% Actual Heat Loss	2.42	3.32
% Heat Loss Calculated	0.80	0.55
Thermal Resistance $X10^{-3}$ hr sq ft °F/Btu	2.25	3.60



Curve A - Results from this investigation at 2 psi and 140 - 150 microinches root mean square surface roughness.

Curve B - Results from this investigation at 2 psi and 85 - 90 microinches root mean square surface roughness.

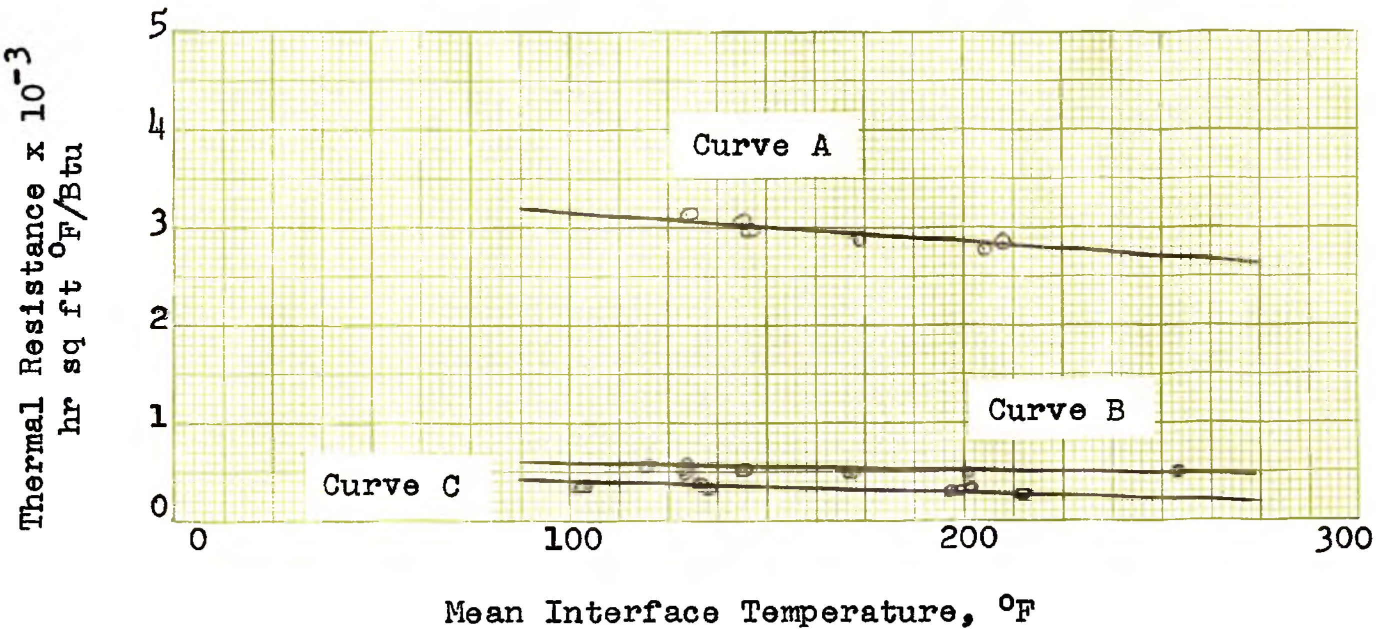
Curve C - Results from Barzelay, Tong, and Hollo's investigation at 5 psi and 90 microinches root mean square surface roughness.

Curve D - Results from Barzelay, Tong, and Hollo's investigation at 5 psi and 10 microinches root mean square surface roughness.

Figure 10

temperature drop across the interface. This can be seen from the curves in Fig. 10. A high heat rate through the sample will also give a more accurate value of thermal resistance, because of the limited means of temperature measurement.

The maximum heat loss during the test was 4.1% with the average being much lower.



Curve A - Curing pressure 2 psi, 25 microinches rms surface roughness.

Curve B - Curing pressure 35 psi, 25 microinches rms surface roughness.

Curve C - Curing pressure 75 psi, 25 microinches rms surface roughness.

Figure 11

CONCLUSION AND RECOMMENDATIONS

The experimental results gave evidence for the following conclusions:

1. The thermal resistance of the bare interface increased with an increase in surface roughness.
2. Cure pressure decreases the thermal resistance of bonded joints.
3. Compared with the bare interface, the thermal resistance of a joint increases when bonded with thixotropic epoxy adhesive.
4. The thermal resistance of a bare interface and an epoxy bonded joint decreases with an increase in the mean interface temperature.

This investigation has produced results which can be used with reasonable assurance that the values of thermal resistance found here would be valid for similar conditions and applications. The adhesives tested were commercial products available for retail purchase. They were cured and tested within the range specified by the manufacturer.

The following recommendations are made:

1. An extensive surface roughness and cure pressure study with more adhesives using various metals and non-metal specimens. Investigating the effects of pressure on shims placed between the interfaces.
2. Determining the thermal resistance of bonds and contacts in a vacuum with a variable temperature heat sink.

3. Modification of the present equipment in regard to the accuracy and arrangement of the thermocouples, efficiency of the heat shield, type of insulation used, and decreasing the thermal resistance at the interfaces of the heat source and heat sink.

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VITA

Born on December 27, 1941, the author received his primary education at St. Peter Grade School in Jefferson City, Missouri. After graduating from Helias High School in May, 1959, he attended the Missouri School of Mines and Metallurgy for four years and graduated with a Bachelor of Science Degree in Mechanical Engineering in May of 1963. The following summer was spent in East Texas working for Socony Mobil Oil Company. In the fall of 1963, the author was accepted into the graduate school at the Missouri School of Mines and Metallurgy and was given a graduate assistantship for the academic year of 1963-64.