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RESULTS OF CONTRACT NAS 8-5207 "THERMAL CONTACT CONDUCTANCE IN A VACUUM" AND RELATED PARAMETER STUDY

by

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INTRODUCTION

This paper shows the results of an in-house and contractual effort to better define the parameters associated with thermal contact conductance. Data for contact conductance vs. applied pressure, and the corresponding graphs are shown for samples of 304 Stainless Steel, AZ31 Magnesium, 6061-T6 Aluminum and Copper.

For a more thorough discussion of the contractual work, the reader is referred to the final report of this contract (NAS8-5207). A paper covering the results of this contract will also be presented at the AIAA 1st Annual Meeting and Technical Display June 29-July 1964, at the Sheraton Park Hotel, Washington, D. C.

In addition to the contractual interface data, an attempt is made to define the observed change of slope of 6061-T6 and 2024-T4 Aluminum when the data are plotted on log-log graph paper. It is shown that by deforming cones, hemispheres, and ellipses, a similar change of slope occurs. It is concluded that these models might possibly represent "scale-up" replicas of the macroscopic points of contact of two mating aluminum surfaces.

A reference list is included which is a revision and extension of the bibliography the author handed out at the February meeting. It contains many previously unknown Russian references.

EXPERIMENTAL PROGRAM

A study of the problems in the early stages of the thermal contact conductance work, has indicated a need for experiments designed to (1) aid in the understanding of the heat transfer mechanism, (2) provide data to verify existing analyses, (3) provide data to aid in the development of new analytical methods.

Subsequently, a thermal contact conductance apparatus suitable for use in vacuum was developed which would permit accurate measurement of thermal conductance as a function of contact pressure. As opposed to the flat plate apparatus used in the investigations reported by Fried, the principal investigator of this study, this apparatus utilized cylindrical columns to minimize flatness deviations under load.

Thermal Test Apparatus

A schematic of the test apparatus is shown in Fig. 1. Figure 2 shows the heat flow section of the apparatus, with a specimen in place, without the radiation shield.

The samples consisted of two metallic cylinders having a diameter of 5.08 cm (2 in.), and a length of 7.62 cm (3 in.) each. Each sample was instrumented with four copper constantan thermocouples to determine the axial temperature gradient due to the uniform heat flux passing between the electric heater and the liquid-cooled sink.

Contact pressure could be varied by means of a stainless steel bellows, pressurized in accordance with the desired load. The load was measured using a strain gage load washer on the heat sink side (Fig. 1).

The entire assembly was installed in a bell jar vacuum system with a right angle cold trap, utilizing a 4-inch oil diffusion pump preceded by a roughing pump to achieve a vacuum of 10^{-4} mm Hg (1.33×10^{-2} newton/m^2) or better.

The heat source utilized in this test was a 100-watt electric resistance element embedded in the main heater assembly which is gaurded by a ring heater and a rear guard heater, as shown in Fig. 1. This system is arranged such that there exists no temperature difference between the main heater and the guards. Each is separately controlled, so that all thermal energy from the main heater has only one direction to go — into the test sample. In order to monitor this system, thermocouples were fastened to the several surfaces seeing each other.

Minimum cross-sectional area supports, made of tubes (Fig. 1), were used between the rear guard and the main heater, in order to minimize heat leak errors, even though the facing surfaces were kept at the same temperature. The desired range of temperature differences between potential heat lead points were kept at ΔT's of 1 °C or less in order not to exceed 1/2 of 1% heat flow errors. Initially, these temperature differences were controlled by use of a deviation amplifier, but experience indicated that manual control, with proper judgment, resulted in less time delay between steady-state points.

The allowable temperature differences were dictated by the amount of heat passing through the test sample, since high heat fluxes through the sample permitted higher heat losses from the heater while permitting the percentage losses to remain the same.

The heat flux was determined by measuring the regulated d-c power input (i.e., voltage and current), using precision instruments. In addition to this, the hot heater resistance was obtained by momentarily turning off the power. In order to eliminate leadline losses in the calculation, the ratio of heater winding resistance to total system resistance was measured and a correction applied to all readings. An ESI bridge having an accuracy of ± 0.05% was used.

A check was performed on the adequacy of the heat flow measurement by determining the thermal conductivity of a piece of ARMCO iron. The measured value came within 2% of the nominal value which, considering all possible variables, is quite good. If we were to perform only thermal conductivity measurements, this accuracy could probably be improved. However, for conductance measurements, with their many sources of error, the cost of improving this system is not quite worth the effort at present.

Temperature Measurement

Considerable attention was paid to accurate temperature measurement techniques in order to minimize possible measurement errors, since the quality of the temperature measurement directly affected the quality of the interface thermal contact conductance obtained. Thermocouple junctions were made of 40-gauge copper-constantan precision grade thermocouple wire. This grade of wire has a nominal tolerance of ± 0.3 °C over the range of interest, but has been found by experience to be considerably better. Junctions were made by mercury pool arc welding techniques.

The thermocouples were installed in the test samples in 2.54-cm deep holes, to place the junction at the cylinder axis. The junction was embedded with Eccobond 56C, an epoxy base cement having a thermal conductivity equal to that of stainless steel. In order to assure that the thermocouple bead actually contacted the sample at the cylinder centerline, a 0.33-cm diameter hole was drilled at the desired axial thermocouple location and a tube of the same material as the sample was inserted with the thermocouple installed. This method had the advantage that there was less likelihood of drill runout when the hole was drilled. It also permitted more positive installation and location of the thermocouple junction. The only exception to the matching of material was that an aluminum tube was used with the magnesium sample. This was not expected to result in an error because: (1) the thermocouple junction was in contact with the sample magnesium, and (2) the thermal effect of different material was not adverse because of the higher thermal conductivity of the aluminum. This would not result in a delay to reach thermal equilibrium.

The choice of 40-gauge thermocouple wire was dictated by the desire to minimize conduction losses. Experience with several hundred thermocouples from such wire (purchased from Thermo-Electric Co.) with no adverse emf characteristics led to the selection of this diameter. The question as to the proper response of the thermocouples when embedded in the samples in a vacuum was circumvented by use of the Eccobond 56C, a fairly free-flowing epoxy cement inserted and packed around the thermocouple bead and wire. Thus, the bead was hermetically isolated from the surrounding atmosphere.

To assure proper response of these thermocouples, they were placed in a constant temperature oven after being installed in the sample and the consistency of the temperature readings was checked. Out of over 60 thermocouples tested, only 4 were found to require corrections in the computation of conductances for the range of temperatures of interest (25-50°C). Particular attention was paid to the precision with which the axial distances between thermocouples were controlled, since the axial distance vs. temperature plots were used to project the temperature gradients to the interface and thus obtain the interface temperature difference.

The constriction resistance effects at and near the interface require that thermocouples be located in the undisturbed region in order to correctly project the temperature gradient. Since only the sample half interfaces are of interest, the heat source and heat sink interfaces with the samples had high vacuum silicone grease applied as a heat transfer promoting device. Thus, no significant constriction effects resulted at these interfaces.

The temperature difference, ΔT, is based on the temperature obtained experimentally, which are then extrapolated to the interface. The accuracy with which this ΔT can be obtained is a function of the accuracy with which the temperature gradient in the sample can be obtained. For high values of contact conductances the ΔT usually was quite low. Conversely, for low values of conductance the ΔT was high. Since a high ΔT resulted in a higher percent accuracy, the relative percent accuracy of contact conductance obtained was constant. A representative temperature gradient curve is shown in

Fig. 3. Of the thermocouples used in the samples, each had its own cold junction. Their emf was read on a Leeds and Northrop K-3 potentiometer, with individual couples switched by means of a transfer switch. Figure 4 shows the vacuum system, thermocouple recorder, power supply, and instrument panel.

Surface Finish Measurements

One significant area of interest, which strongly affects the thermal contact resistance is the surface finish of the interface. Surface finish, by definition, can include surface roughness as well as waviness, which is described by Clausing and "microscopic and macroscopic effects," and by Fenech as "primary and secondary waviness."

In addition to the small asperities which constitute the roughness, a machines surface can have larger peaks and valleys which constitute the waviness. The direction parallel to the ridges and valleys of the waviness is called the lay direction.

A Taylor-Hobson "Talysurf" stylus type profilometer was used to obtain single-line profiles of the various surface finishes prepared to this program. Due to difficulties of operating an in-house "Talysurf" instrument, all but one pair of samples (Nos. 15 and 16) were inspected after thermal contact conductance tests were completed. Thus, any deformation of asperities, which may have taken place during tests would, therefore, be observable. However, it is not very likely that any such effects could be observed, because the "Talysurf" trace is merely the record of a stylus motion following the contours of the surface in a straight line.

Any asperity, deformed or otherwise, on either side of this straight line would, therefore, not be recorded. Although there is no certainty that a trace parallel to or in continuation to an existing trace will resemble the existing trace, there will be a similarity of characteristics, provided the character of the surface is taken into consideration. For example, in the case of machined surfaces, traces should be taken in the direction of tool motion as well as in the perpendicular direction. Particular attention should be paid to lathe-turned finishes at the profile through the center of the surface, because of the non-flatness of the surface at that point. Figure 5 shows typical "Talysurf" traces through the center of a machined surface for a copper sample.

The traces as shown, do not represent a true pictorial representation of the surface, because of the scale differences. These asperities appear to be much more severe than they are in reality. Nevertheless, the traces do provide a significant amount of useful information and provide an excellent means for comparison of surface finishes.

As a result of the length of the stylus travel (1.27-cm max.) which is adjustable, and the use of the optical flat attachment, flatness deviations can also be observed. This is due to the fact that the stylus motion, relative to an optical flat, is recorded.

An additional feature of the "Talysurf" profilometer is its ability to provide a centerline average (CLA) roughness reading, by means of an electronic integrator circuit, for any surface of certain minimum length. Centerline average (CLA) is also known as arithmetic average (AA) and runs somewhat lower than the corresponding root-mean-square (RMS) reading. The latter gives more weight to the larger deviations from the centerline.

Flatness measurements were made using a surface plate and a dial indicator reading 2.5 micrometers, (0.001 inches) which permitted estimation of half divisions (1.3 micrometers). The dial indicator point was set at the sample center and the dial was set at zero. With the dial indicator fixed, the sample was moved so that the point traveled to the interface edge, reading the vertical deviation at the center, one-fourth diameter and at the edge.

This was done at mutually perpendicular diameters. A secondary check was made initially by holding the sample fixed and moving the dial indicator support stand. No significant differences were observed between the two methods. Plus readings indicated high spots, whereas minus readings indicated low spots. Results are shown in Table I in which the maximum values are presented. It should be noted that these values are the maximum from a fictitious plane, i.e., the datum plane as described in the next major section, "Deformation Experiments." Thus, there may occur some matching of interfaces having deviations, which could result in a test assembly of better mating than would be expected on the basis of individual reading. For example, samples 3 and 4 could have a cumulative flatness deviation of only $+1.2 \times 10^{-6}$ meters if they fitted into each other.

Thermal Test Results

The material and the important surface properties of the test samples are shown in Table I. These include roughness, Rockwell hardness, flatness deviation and type of surface preparation. Actual data for these surfaces are shown in Table II.

Stainless Steel 304

Figure 6 shows the results of the stainless steel interface tests. Of interest is the large difference in conductance at the maximum contact pressure. The flatness deviation of the 0.30 micrometer (RMS) roughness samples was 1.3 micrometer, whereas the 1.2 micrometer (RMS) roughness sample had a flatness deviation of approximately 1.5 micrometer, at best, and 3.8, at worst, depending on surface matching.

Of interest is the curvature of the fine finish contact conductance curve whose behavior was confirmed by the descending load curve. Hysteresis could be observed for this specimen for the loading-unloading cycle.

In contract, the coarse finish sample curve shows no hysteresis and is almost linear.

It is of particular interest to note and compare these two curves in Fig. 6 with the corresponding results of Clausing. The resemblance of the Clausing results with Stainless Steel 303, for approximately the same degree of flatness deviation, to our results is remarkable. The importance of the approximate similarity of flatness deviation, as opposed to a marked difference in roughness (Clausing, 3 micro-in for both versus our 12 and 50 micro-in) is demonstrated well in this experiment.

Magnesium

Figure 7 shows the results for Magnesium AZ31B, a widely used magnesium alloy. These samples, which had lathe-turned interfaces exhibited a rather unusual reversal of expected performance. The coarse finished surfaces exhibited higher thermal contact conductances than did the fine finished interfaces. One possible explanation would be the greater effect of a surface film on a fine-finished surface versus that on a coarse-finished surface. Oxide films and tarnish were visible on both sets of samples, since two months had elapsed between machining and use. The reason for conjecture that a film will have a lesser effect on a coarse surface finish, is that the fewer sharper ridges of this finish will result in higher loads per unit area and cause the film to break. Another, and perhaps more plausible, reason is the relatively large flatness deviation for both sample pair, but that the sample assembly may have resulted in a greater mismatch for the poorer performance.

It is of interest to note that Clausing obtained higher conductances for similar material having lower values of flatness deviation and much lower surface roughness.

Aluminum

The resultant conductance versus pressure curves are shown in Fig. 8. It is of interest to note that there was no significant difference in the values of contact conductance for the two surface finishes considered. The results for the finer (0.3-micrometer RMS) finish 6061-T6 Aluminum should have been higher than for the coarse (1.4-micrometer RMS) finish, since the former had lower values of flatness deviation. At present, no explanation can be found for this behavior. The general shape of this curve conforms to that shown by Clausing for 2024 Aluminum, with the conductance somewhat lower at maximum pressure.

Copper

A test for electrical grade copper (OFHC oxygen-free, high-conductivity copper) was performed, because the only available data (Jacobs and Starr) indicated linear variation of conductance with load at moderate loads, whereas, most other materials change in a non-linear manner in that pressure region. As can be seen in Fig. 9, the curve is not linear at low pressures, but does appear to be linear at higher contact pressures. It is also of interest to note that no hysteresis could be observed for this copper joint.

General Remarks

The results for specific metal joints are discussed under their respective headings. This section discusses common-ground observations.

When conductance versus pressure is plotted on log-log paper, a curve (as shown in Figs. 11-13) results, which is somewhat different from earlier observed and expected results. Initially, a slope of one-half to two-thirds was expected for elastic behavior as discussed in another section of this paper. However, plots of data obtained in this study indicate a definite two-regime behavior with a pronounced point of change in slope. The exact reason for this change in slope has not yet been defined, except to show that it possibly represents the change from purely elastic to elastic-plastic deformation behavior. This is discussed in the next section dealing with an experimental study of this phenomenon.

DEFORMATION EXPERIMENTS

The three models (2024-T4 Aluminum) described in this paper are shown in Fig. 10. The cone and hemisphere models were 2.54 cm (1 in.) in diameter and 1.27 cm (0.5 in.) in height. The ellipse semi-major axis was 1.27 cm with its semi-minor axis being .950 cm (.375 in.).

The models in Fig. 10 (column 1) were placed between two flat plates of a steel press with a piece of pressure-sensitive paper placed on their tops and bottoms and a load P_i was applied. A typical piece of the pressure-sensitive paper appears below the models. The blackened area is the deformed area for that particular load. After each specified loading, another paper was placed on the model. Over the entire range of loading from 0-250,000 Newtons (0-60,000 pounds), the deformed area remained circular, as indicated by the blackened area on the paper, and the deformed model. The diameter of this blackened area was measured several times and an average taken, thus leading to the recorded deformed area data in Table III. The tests were performed at room temperature (293° K).

The height of the model was measured by a dial micrometer placed between the two steel plates. The models in columns 2, 3, 4, and 5 of Fig. 10 were subjected to specific loads, and the areas and heights were compared to those of the previously described models in which the load was cycled. No appreciable difference was noticed and, thus, the cycling of loads had produced little work hardening of the models.

As soon as the data were plotted, it was observed that an interesting resemblance existed between the published thermal interface data and the deformation of the model. Of particular interest is that of the area/height deformation versus loading when compared to the thermal interface conductance as a function of its mechanical loading. Figure 11 shows data of the models compared on a log-log plot with that of Fried and of Clausing. In an attempt to bring the data into the same order of magnitude, the following expression was used:

$$\left[K_m\right]_{P=P_i} = k \left[\frac{A}{Y}\right]_{P=P_i} \tag{1}$$

where

k = conductivity of the models

A_{P_i} = deformed area of the model at load (P_i)

Y_{P_i} = height of the model at load (P_i)

$\left[K_m\right]_{P=P_i}$ = computed conductance of the models

to compute a representative thermal conductance. It must be strongly emphasized that the plotted data in Figs. 11-13 taken from the Fried and Clausing reports should not be used in computation. This data has been shifted in magnitude for better visual observation.

It is particularly interesting that both the interface data and the model data experience a change of slope at certain loading values.

The factor that appears to cause this change of slope in the model data is the dependence of the deformed area on the loading. This became evident when the area versus the loading was plotted. The contribution of the model height versus loading did not undergo this sudden change. This critical point of loading at which the slope changes shall, hereafter, be designated P_{cI} for the interface data and P_{cM} for the model data.

As can be seen from Fig. 11, the values of P_{cI} and P_{cM} do not coincide. This might be partly explained by a temperature dependence. In comparing P_{cM} with P_{cI} of Clausing, it is to be noted that the models were at 293°K (70°F) while Clausing reported mean interface temperatures of approximately 386°K (234°F) for eight interfaces. Figure 12 is a plot of the data reported in this paper for 6061 aluminum and the computed model data. This mean interface temperature (T_M) was approximately 301° K (82°F), this value being the average of all the T_1 and T_2 values of interface. Since for this sample T_m was near that of the model temperature, it appears that the slope change at P_{cI} is nearer the value of that of the models P_{cM} than the corresponding Clausing data. However, this comparison is not totally valid since the metals are different. This leads to the question of whether P_{cI} is dependent on the mean interface temperature. If P_{cI} is attributed to the changes of the physical properties of the metal, it would appear reasonable that its value should be lower for higher mean interface temperatures. Thus, it would appear that

$$K_{cI} \ \alpha f (P_{cI}) \ \alpha f \left(\frac{1}{T_m} \right) \qquad (2)$$

If all the load values of the deformation models are divided by the corresponding deformed area, pressure values are recorded which are consistently near the yield strength of the metal, as can be expected for permanent deformation.

It seems that there are other factors which influence P_{cI} for the Clausing data. If the eight data groups are plotted, then P_{cI} appears at different load values for each specimen. This is partly shown by two curves of Fig. 11.

When all the eight samples of 2024-T4 Aluminum values are averaged and plotted, Fig. 13 shows that the two-slope regime is again evident. As can be seen, this corresponds to the included data for the models.

In order to study the functional relationship of the curves a computer program for best fitting the data to an equation was formed. This equation corresponds to the form presented earlier and is $h = A + B P^c$. The data from Clausing, data reported in this paper, and the deformation model data show similar values of the exponent c both before and after the change of slope. The values of A/Y, h, A, B, do not coincide because the data used for the best fit curve were of different units as reported in the respective reports. On Figs. 12 and 13, only the functional notation has been shown for comparison.

The best fit curves are:

1. Model data

$$\frac{A}{Y} = -32.90 + 0.57\, P^{0.72}$$

from $P = 0$ to 10,000 pounds.

$$\frac{A}{Y} = -37.47 + 3.03 \times 10^{-4} P^{1.54}$$

from P = 10,000 to 60,000 pounds,

where

A = deformed area in inches^2
Y = deformed height in inches
P = load in pounds

2. 6061-T6 Aluminum (Fig. 12)

$$h = 9.73 \times 10^{+2} + 1.17 \times 10^{+3} P^{0.09}$$

from P = 10.2 to 419 p.s.i.

$$h = 1.14 \times 10^{+2} + 7.00 \times 10^{-2} P^{1.61}$$

from P = 419 to 1,117.0 p.s.i.

where h is given in BTU/hr ft^2 °F .

3. Average data of Clausing for eight samples of 2024-T4 Aluminum

$$h = 35.41 + 7.59 p^{0.91}$$

from P = 10.4 to 67.0 p.s.i.

$$h = 168.1 + 2.14 p^{1.16}$$

from P = 67.0 to 986.0 p.s.i.

where h is given in BTU/hr ft^2 °F.

CONCLUSIONS

1. The importance of the flatness deviation effects on thermal joint conductance has been demonstrated.

2. The proposed models, based on the elastic deformation relations of Hertz appear to provide an approach to understanding the heat transfer mechanism. This is represented by the approaches of Clausing and this paper.
3. Better surface definition methods are required.
4. More experimental data of suitable accuracy is needed to arrive at (a) semi-relations and (b) statistical correlation.

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TABLE I

Sample Number	Material	Surface Finish				Hardness Rockwell B	Maximum Flatness Deviation		Remarks
		(RMS)		CLA					
		micro-meter	micro-inch	micro-meter	micro-inch		micro-meter	10^{-3} Inches	
1	Stainless Steel 304	0.38	15-15	0.38	16-18	B-80	-1.3	-0.05	Ground Finish
2	Stainless Steel 304	0.25	10-10	0.25	6-14	B-80	----	-----	Ground Finish
3	Stainless Steel 304	1.3	42-60	1.0	21-60	B-80	-1.3	-0.05	Ground Finish
4	Stainless Steel 304	1.1	43-48	0.63	13-37	B-81	+2.5	+ 0.1	Ground Finish
5&6	Not Tested.								
7	AZ-31B Magnesium	0.30	8-16	0.38	12-17	E-63	-1.3	-0.05	Lathe Cut Finish
8	AZ-31B Magnesium	0.30	8-16	0.48	18-20	E-61	-7.6	-0.3	Lathe Cut Finish
9	AZ-31B Magnesium	1.4	50-60	1.4	50-60	E-62	-5.1	-0.2	Lathe Cut Finish
10	AZ-31B Magnesium	1.4	50-60	1.6	58-68	E-62	-3.8	-0.15	Lathe Cut Finish
11&12	Not Tested.								
13	6061-T6 Aluminum	0.30	8-16	0.29	11-12	F-88	----	-----	Lathe cut finish Center, 2 mm dia, depressed
14	6061-T6 Aluminum	0.30	8-16	0.51	20-20	F-87	-1.3	-0.05	Lathe Cut Finish
15	6061-T6 Aluminim	1.4	50-60	0.91	33-38	F-93	+6.4	+0.25	Lathe Cut Finish
16	6061-T6 Aluminum	1.4	50-60	1.4	50-58	F-93	+2.5	+0.1	Lathe Cut Finish
17-24	Not Tested.								
25	Oxygen Free High Cond. Copper	0.20	7-9	0.30	12-12	B-48	+6.4	+0.25	Lathe Cut Finish
26	Oxygen Free High Cond. Copper	0.20	7-9	0.42	16-17	B-48	+1.3	+0.05	Lathe Cut Finish
27	ARMCO Iron		No Test Interface						

TABLE II

Test Run (No.)	Sample Numbers	Material	Interface Temperatures		Pressure (Kilo-Newton/m^2)	Pressure (PSI)	h_c (Watts/m^2-°C)	h_c (BTU/Hr-Ft^2-°F)
			T_1(°C)	T_2(°C)				
1	3 & 4	304-SS	19.3	29.3	66	9	210	37
2	3 & 4	304-SS	19.5	27.2	220	32	284	50
3	3 & 4	304-SS	21.2	26.6	1164	169	471	83
4	3 & 4	304-SS	22.0	25.9	2225	323	698	123
5	3 & 4	304-SS	22.9	24.6	5973	867	1704	300
6	3 & 4	304-SS	23.0	24.4	7696	1117	2118	373
7	3 & 4	304-SS	22.8	24.9	4795	696	1369	241
8	3 & 4	304-SS	23.2	25.2	4699	682	1448	255
9	3 & 4	304-SS	22.0	25.4	2611	379	829	146
10	3 & 4	304-SS	20.2	27.5	778	113	312	55
11	3 & 4	304-SS	20.2	29.2	220	32	244	43
12	1 & 2	304-SS	26.4	31.4	55	8	318	56
13	1 & 2	304-SS	22.8	25.9	220	32	523	92
14	1 & 2	304-SS	25.6	27.5	1096	159	1312	231
15	1 & 2	304-SS	25.4	26.1	2192	318	3652	643
16	1 & 2	304-SS	—	—	4960	720	8174	1439
17	1 & 2	304-SS	—	—	7517	1091	11416	2010
18	1 & 2	304-SS	—	—	3259	473	6526	1149
19	1 & 2	304-SS	25.9	27.3	1184	172	1755	309
20	1 & 2	304-SS	29.0	33.3	219	32	545	96
21	1 & 2	304-SS	32.8	33.3	4112	597	7474	1316
22	1 & 2	304-SS	32.8	33.2	6304	915	9497	1672
23	13 & 14	6061-T6 Al.	25.7	32.0	70	10	1556	274
24	13 & 14	6061-T6 Al.	16.2	20.0	313	45	3164	557
25	13 & 14	6061-T6 Al.	24.4	27.1	1123	163	4408	776
26	13 & 14	6061-T6 Al.	24.8	27.1	2191	318	5419	954
27	13 & 14	6061-T6 Al.	24.0	25.2	5208	756	15773	2777
28	13 & 14	6061-T6 Al.	32.0	32.7	7696	1117	32314	5689
29	13 & 14	6061-T6 Al.	31.7	32.9	5649	820	20408	3593
30	13 & 14	6061-T6 Al.	31.4	33.7	3761	546	10235	1802
31	13 & 14	6061-T6 Al.	31.6	35.5	2886	419	6055	1066
32	9 & 10	AZ-31B Mag	28.3	37.5	110	16	3868	681
33	9 & 10	AZ-31B Mag	29.4	32.5	220	32	5061	891
34	9 & 10	AZ-31B Mag	28.6	29.9	1195	173	10979	1933
35	9 & 10	AZ-31B Mag	35.2	36.1	2280	331	20607	3628
36	9 & 10	AZ-31B Mag	38.7	39.3	5133	745	34171	6016
37	9 & 10	AZ-31B Mag	43.0	43.7	7696	1117	38596	6795
38	9 & 10	AZ-31B Mag	43.4	44.1	5801	842	35375	6228
39	9 & 10	AZ-31B Mag	42.8	43.5	3582	520	32535	5728
40	9 & 10	AZ-31B Mag	43.3	45.9	627	91	9014	1587
41	25 & 26	Copper	45.7	52.4	65	9	6708	1181
42	25 & 26	Copper	45.5	51.5	220	32	7446	1311
43	25 & 26	Copper	45.2	50.1	1095	159	9270	1632
44	25 & 26	Copper	45.2	50.7	2280	331	10099	1778
45	25 & 26	Copper	44.1	47.7	5560	807	12507	2202
46	25 & 26	Copper	44.3	47.4	7696	1117	14171	2495
47	25 & 26	Copper	44.5	48.3	4285	622	11700	2060
48	25 & 26	Copper	44.2	48.2	3424	497	10990	1935
49	25 & 26	Copper	44.2	49.6	658	95	8270	1456
50	25 & 26	Copper	44.2	49.6	394	57	8201	1444
51	7 & 8	AZ-31 Mag	30.6	44.3	65	9	1073	189
52	7 & 8	AZ-31 Mag	31.7	39.2	219	31	1988	350
53	7 & 8	AZ-31 Mag	30.1	33.8	1096	159	4066	716
54	7 & 8	AZ-31 Mag	41.3	44.3	2116	307	7304	1286
55	7 & 8	AZ-31 Mag	41.5	42.9	5461	792	15069	2653
56	7 & 8	AZ-31 Mag	41.8	42.7	7785	1130	27451	4833
57	7 & 8	AZ-31 Mag	45.5	47.3	4112	596	13722	2416
58	7 & 8	AZ-31 Mag	41.8	45.8	1095	159	5492	967
59	7 & 8	AZ-31 Mag	41.7	42.7	7696	1117	21987	3871
60	—	Armco Iron	—	—	—	—	—	—
61	15 & 16	Al. 6061-T6	32.3	45.1	131	19	1999	352
62	15 & 16	Al. 6061-T6	32.5	39.9	219	31	3431	605
63	15 & 16	Al. 6061-T6	39.5	45.6	1095	159	5282	930
64	15 & 16	Al. 6061-T6	39.9	43.9	2193	318	8071	1421
65	15 & 16	Al. 6061-T6	47.6	49.8	5465	793	17244	3036
66	15 & 16	Al. 6061-T6	47.7	49.0	7873	1142	28712	5055
67	15 & 16	Al. 6061-T6	47.9	50.4	4375	635	15040	2649
68	15 & 16	Al. 6061-T6	48.2	51.2	3340	484	12575	2215
69	15 & 16	Al. 6061-T6	41.1	49.4	658	95	3680	648

TABLE III

DEFORMED AREA AND HEIGHT OF MODELS AS A FUNCTION OF APPLIED LOAD

Model	Load		Area		Height	
	kilonewtons	kilopounds	meters^2 $\times 10^{-5}$	Inches	millimeters	inches
All Models	0	0	0	0	12.700	.500
Cone	.445	.100	.107	.002	12.421	.489
Cone	1.335	.300	.324	.005	12.294	.484
Cone	2.224	.500	.636	.010	12.065	.475
Ellipse	2.224	.500	1.140	.018	12.598	.496
Hemisphere	2.224	.500	1.265	.020	12.624	.497
Cone	3.559	.800	1.140	.018	11.938	.470
Cone	5.338	1.200	1.534	.024	11.735	.462
Cone	6.672	1.500	2.027	.031	11.582	.456
Ellipse	6.672	1.500	2.634	.041	12.497	.492
Cone	8.896	2.000	2.588	.040	11.481	452
Hemisphere	8.896	2.00	3.426	.053	12.497	.492
Ellipse	11.121	2.500	3.973	.062	12.370	.487
Cone	13.345	3.00	3.694	.057	11.024	.434
Ellipse	15.569	3.500	5.451	.084	12.319	.485
Cone	17.793	4.000	4.560	.071	10.693	.421
Hemisphere	17.793	4.000	6.936	.108	12.319	.485
Ellipse	22.241	5.000	7.946	.123	12.090	.476
Hemisphere	26.689	6.000	9.813	.152	12.167	.479
Cone	31.138	7.000	7.240	.112	10.033	.395
Ellipse	33.362	7.500	12.067	.187	11.862	.467

TABLE III
(cont.)

Model	Load		Area		Height	
	kilonewtons	kilopounds	meters^2 x 10^{-5}	inches	millimeters	inches
Cone	44.482	10.000	9.810	.152	9.601	.378
Ellipse	44.482	10.000	14.234	.221	11.557	.455
Hemisphere	44.482	10.000	15.329	.238	11.887	.468
Ellipse	55.603	12.500	18.241	.283	11.252	.443
Cone	66.723	15.000	15.328	.238	8.560	.337
Ellipse	66.723	15.000	23.430	.363	10.922	.430
Cone	88.964	20.000	23.155	.369	7.595	.299
Elipse	88.964	20.000	28.199	.437	10.135	.399
Hemishere	88.964	20.000	31.142	.483	11.125	.438
Cone	111.206	25.000	34.071	.528	6.731	.265
Ellipse	111.206	25.000	37.826	.586	9.347	.368
Hemisphere	111.206	25.000	40.677	.631	10.643	.419
Cone	133.447	30.000	42.888	.665	6.020	.237
Ellipse	133.447	30.000	47.480	.736	8.458	.333
Hemisphere	133.447	30.000	48.071	.745	10.109	.398
Cone	155.688	35.000	54.806	.849	5.385	.212
Ellipse	155.688	35.000	59.981	.930	7.595	.299
Hemisphere	155.688	35.000	58.013	.899	9.550	.376
Ellipse	177.928	40.000	70.077	1.086	6.756	.266
Hemisphere	177.928	40.000	67.477	1.046	8.992	.354
Hemisphere	200.170	45.000	78.413	1.215	8.433	.332
Hemisphere	222.411	50.000	90.174	1.400	7.976	.314
Hemisphere	266.893	60.000	123.948	1.921	7.163	.282

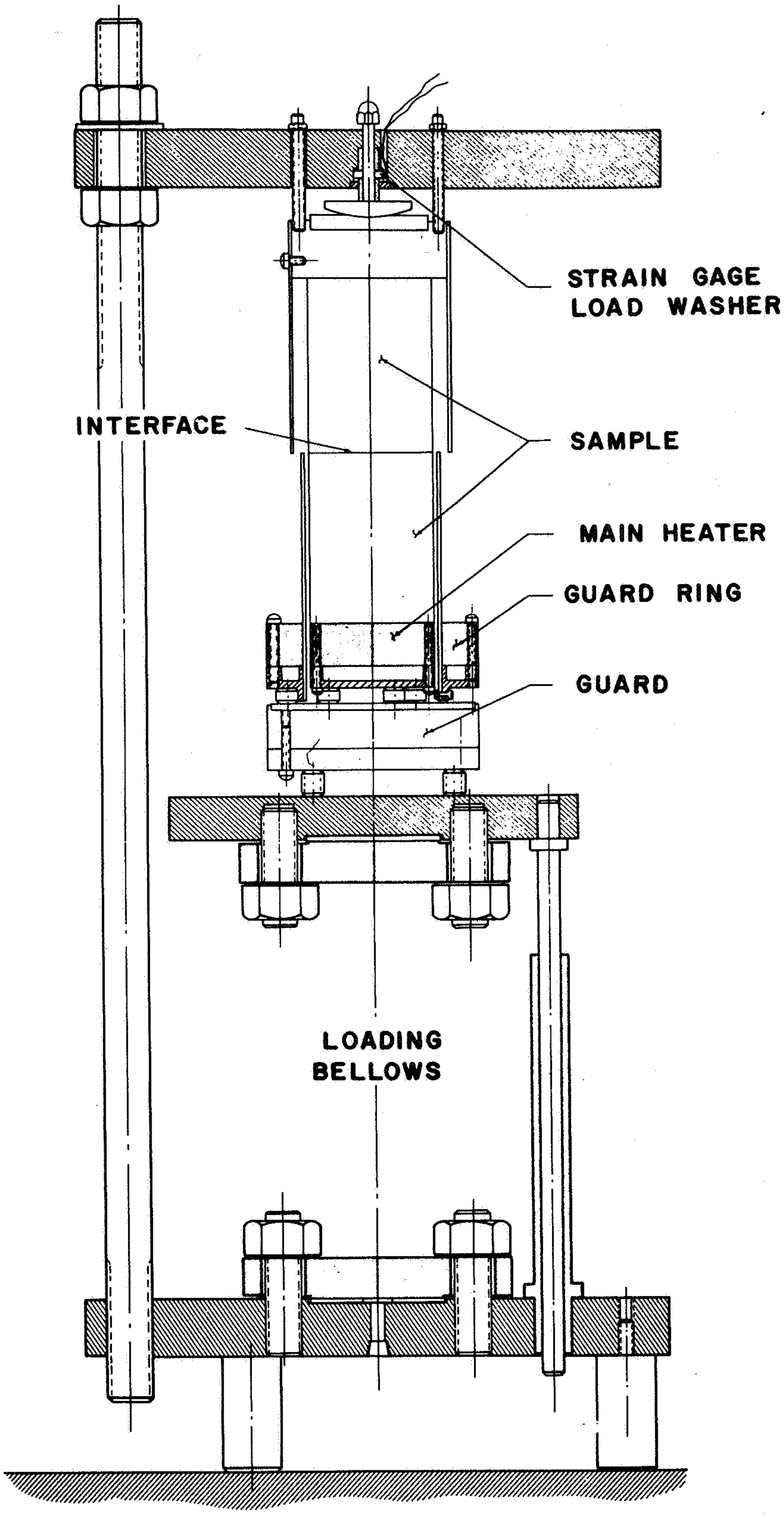

FIGURE 1. VARIABLE PRESSURE-THERMAL INTERFACE CONDUCTANCE APPARATUS

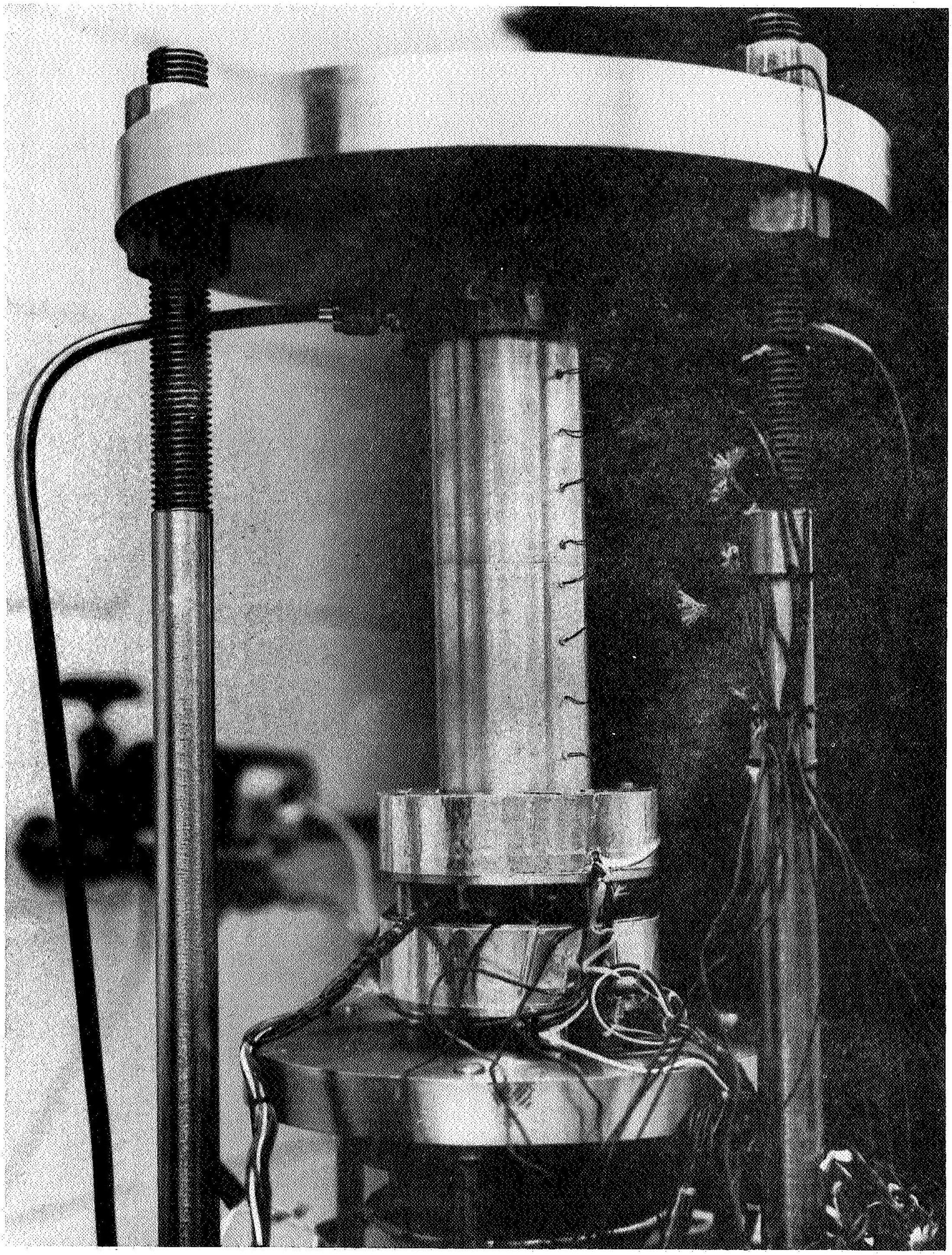

Fig. 2 THERMAL CONDUCTANCE APPARATUS WITH SAMPLE

REPRESENTATIVE TEMPERATURE GRADIENT

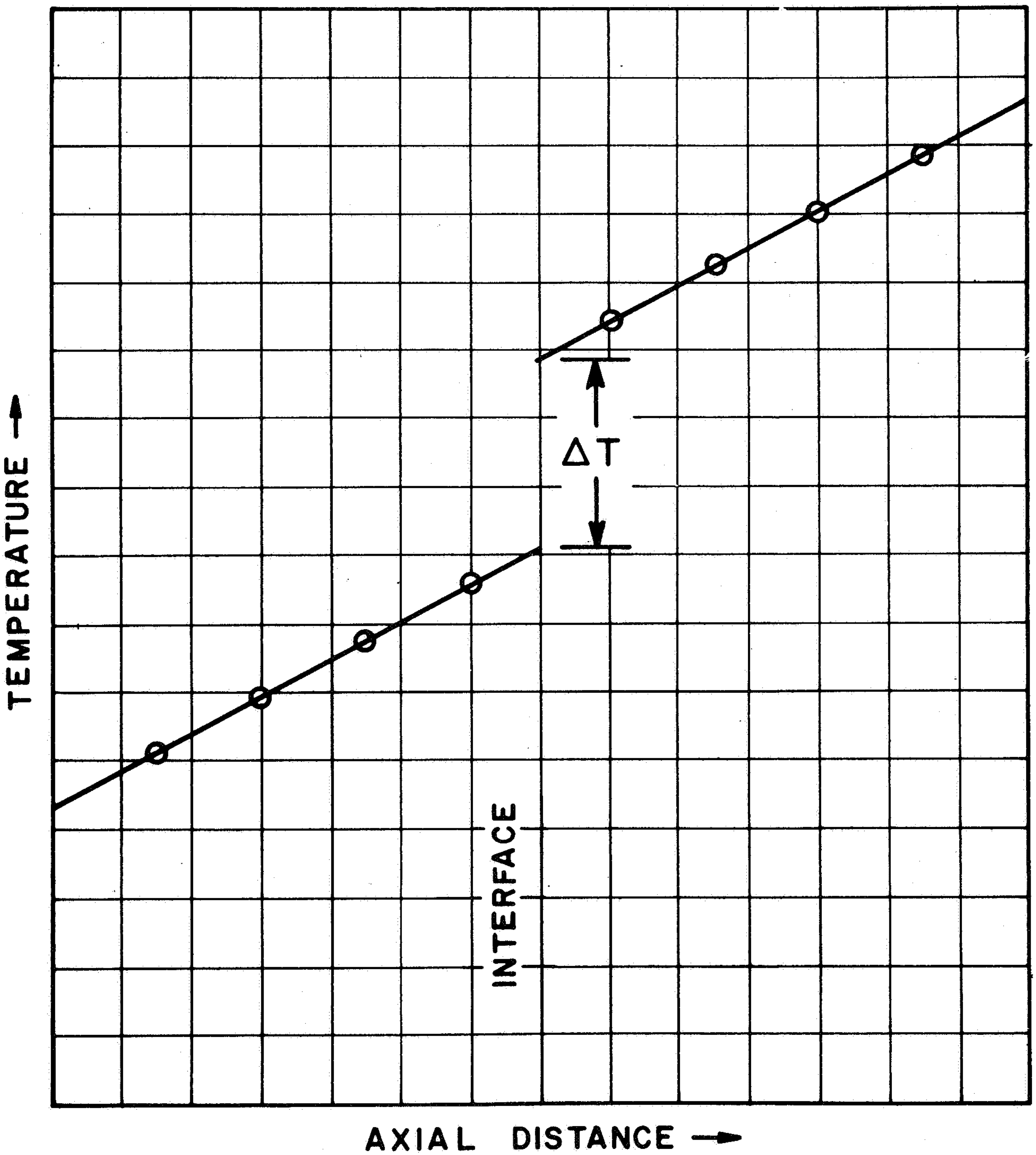

Fig. 3

TEST APPARATUS AND ASSOCIATED EQUIPMENT

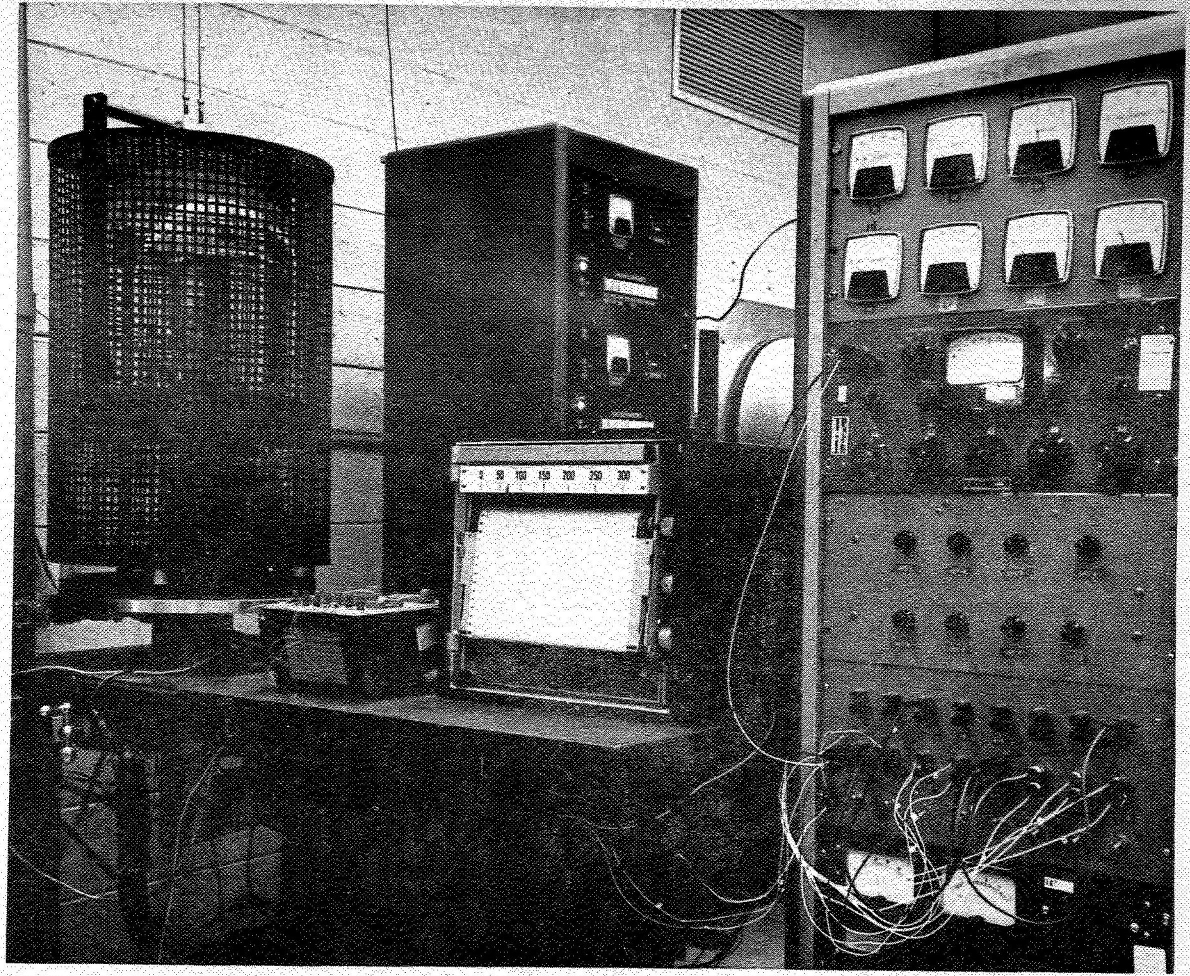

Fig. 4

"TALYSURF" TRACE FOR COPPER SPECIMEN TAKEN THROUGH CENTER

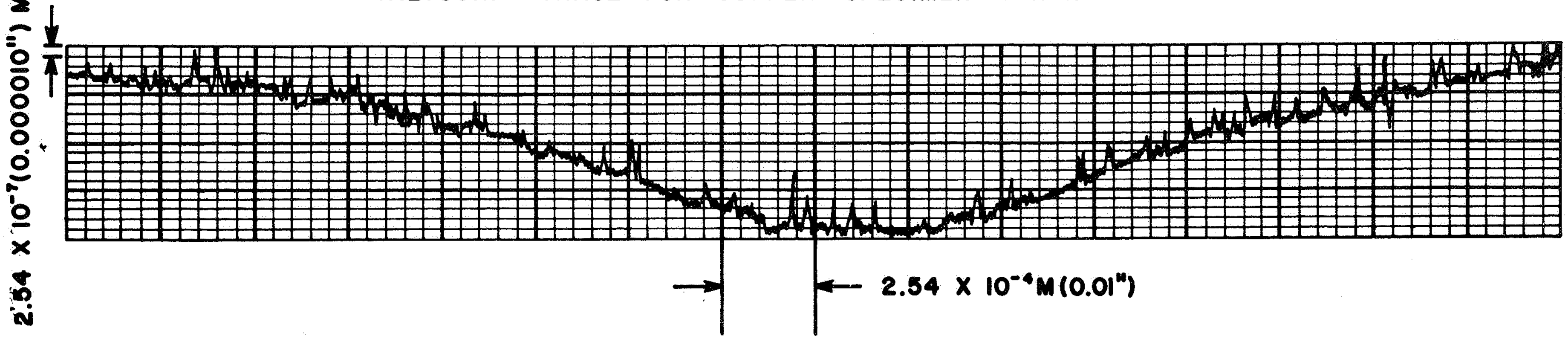

Fig. 5

THERMAL CONTACT CONDUCTANCE VS. APPLIED PRESSURE

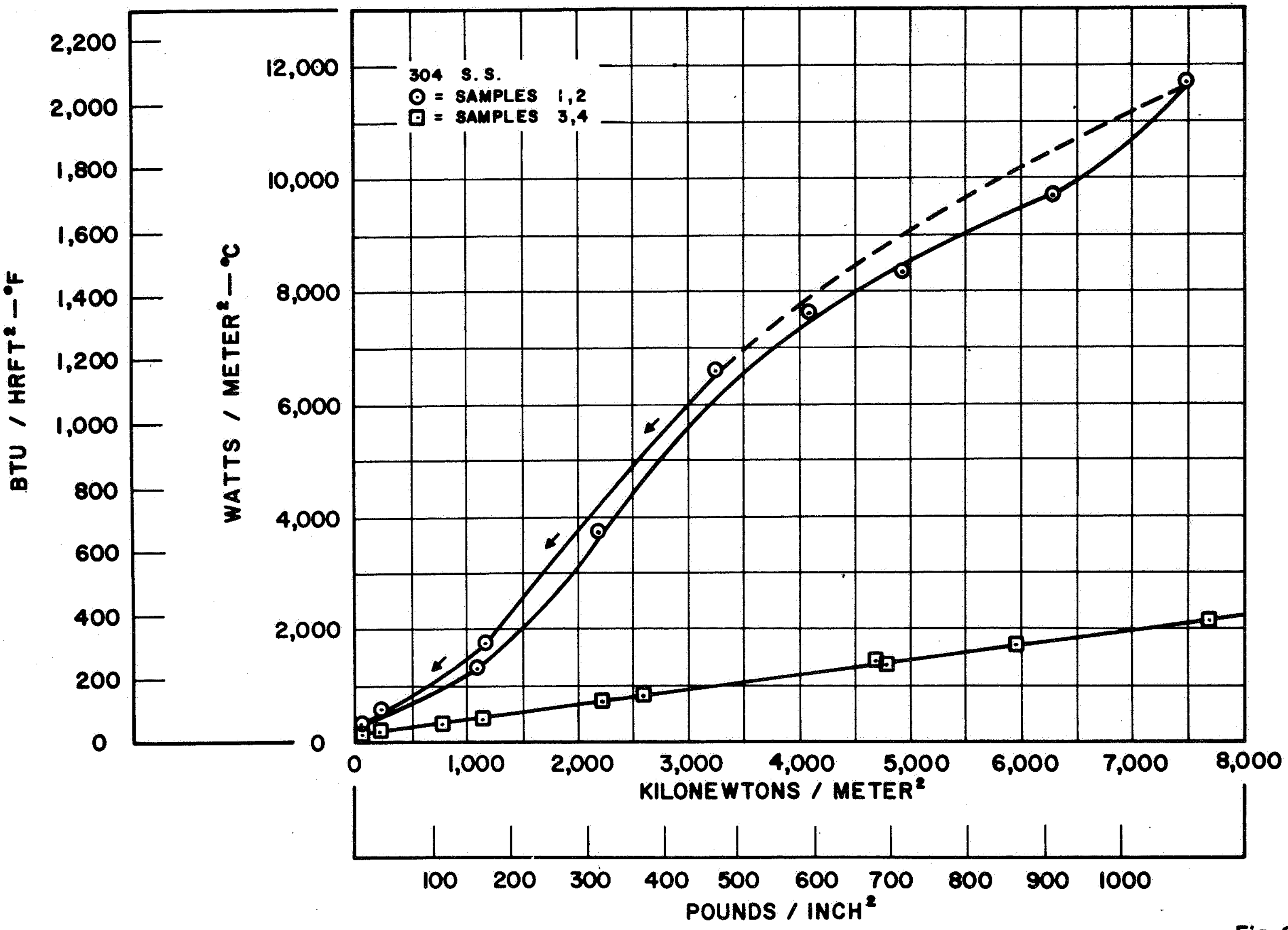

Fig. 6

THERMAL CONTACT CONDUCTANCE VS. APPLIED PRESSURE

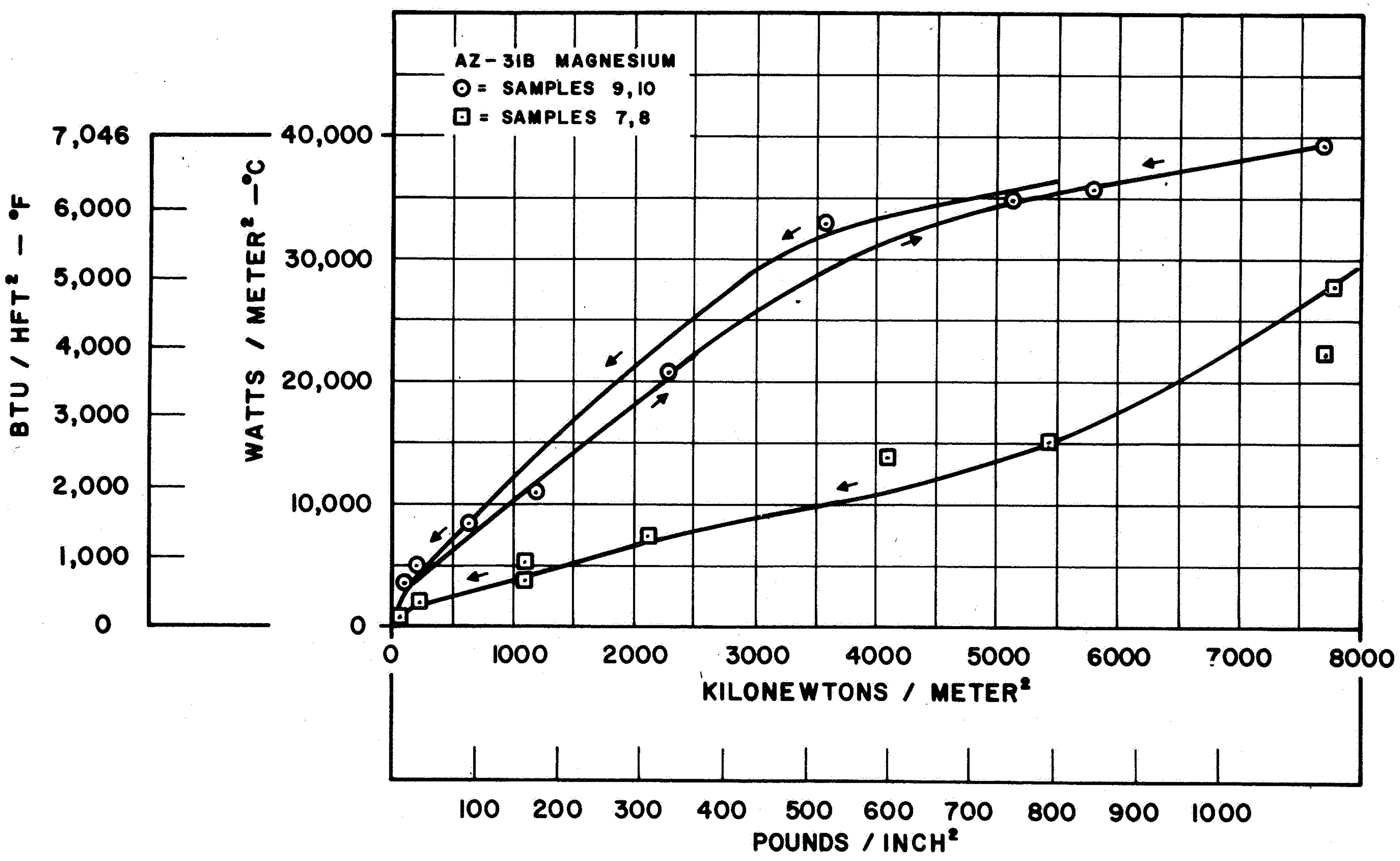

Fig. 7

THERMAL CONTACT CONDUCTANE VS. APPLIED PRESSURE

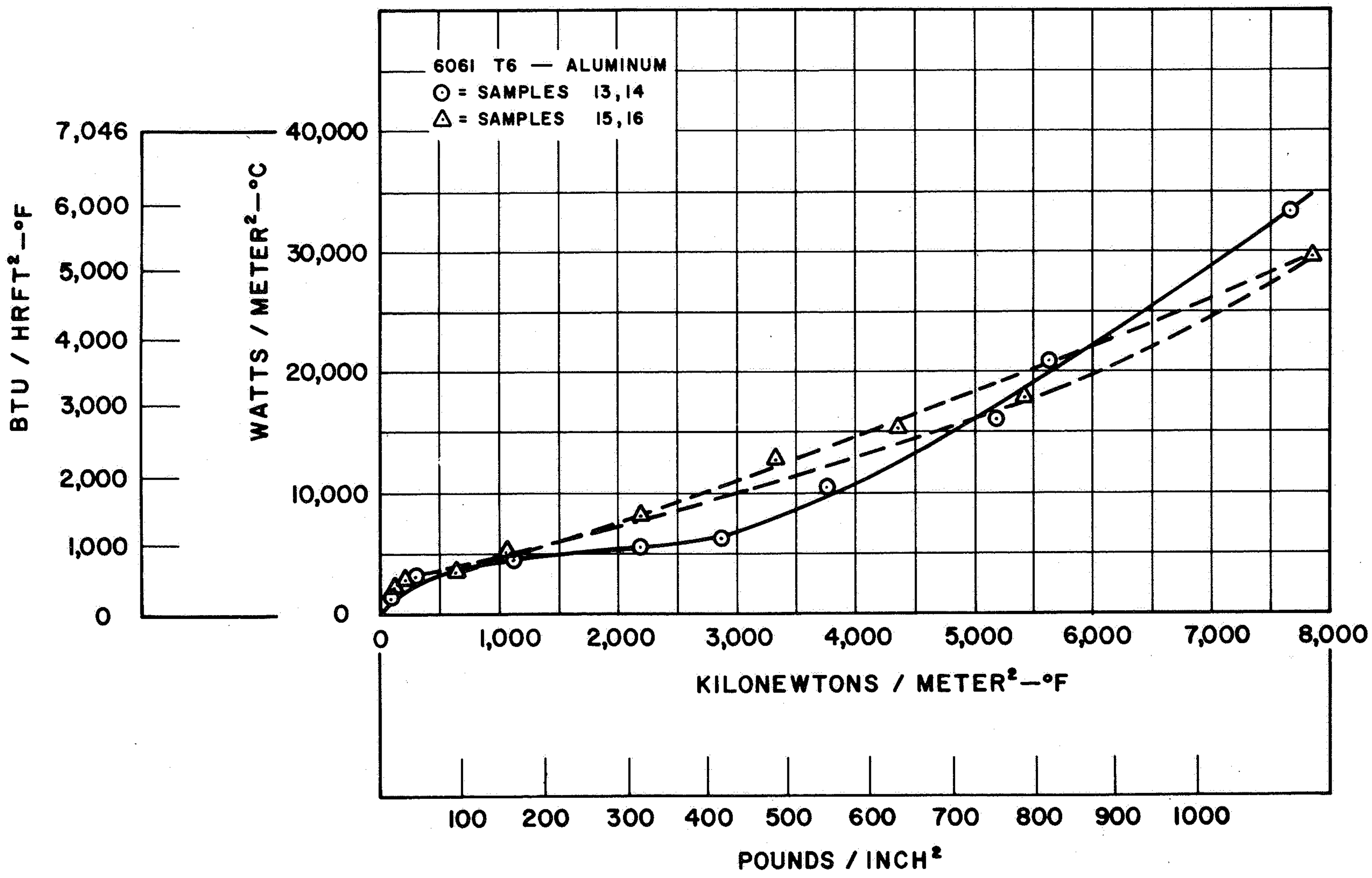

Fig. 8

THERMAL CONTACT CONDUCTANCE VS. APPLIED PRESSURE

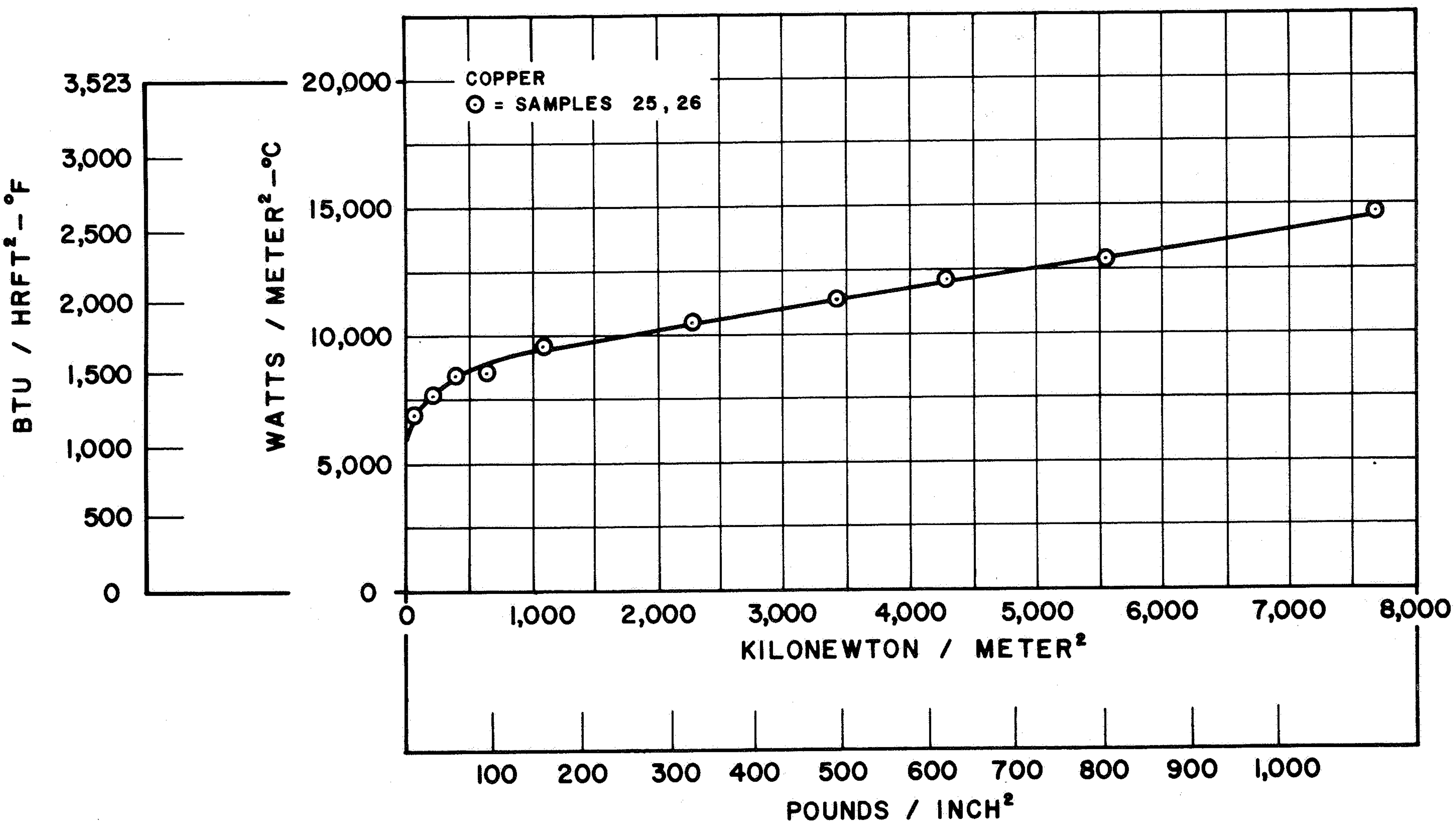

Fig. 9

DEFORMATION MODELS

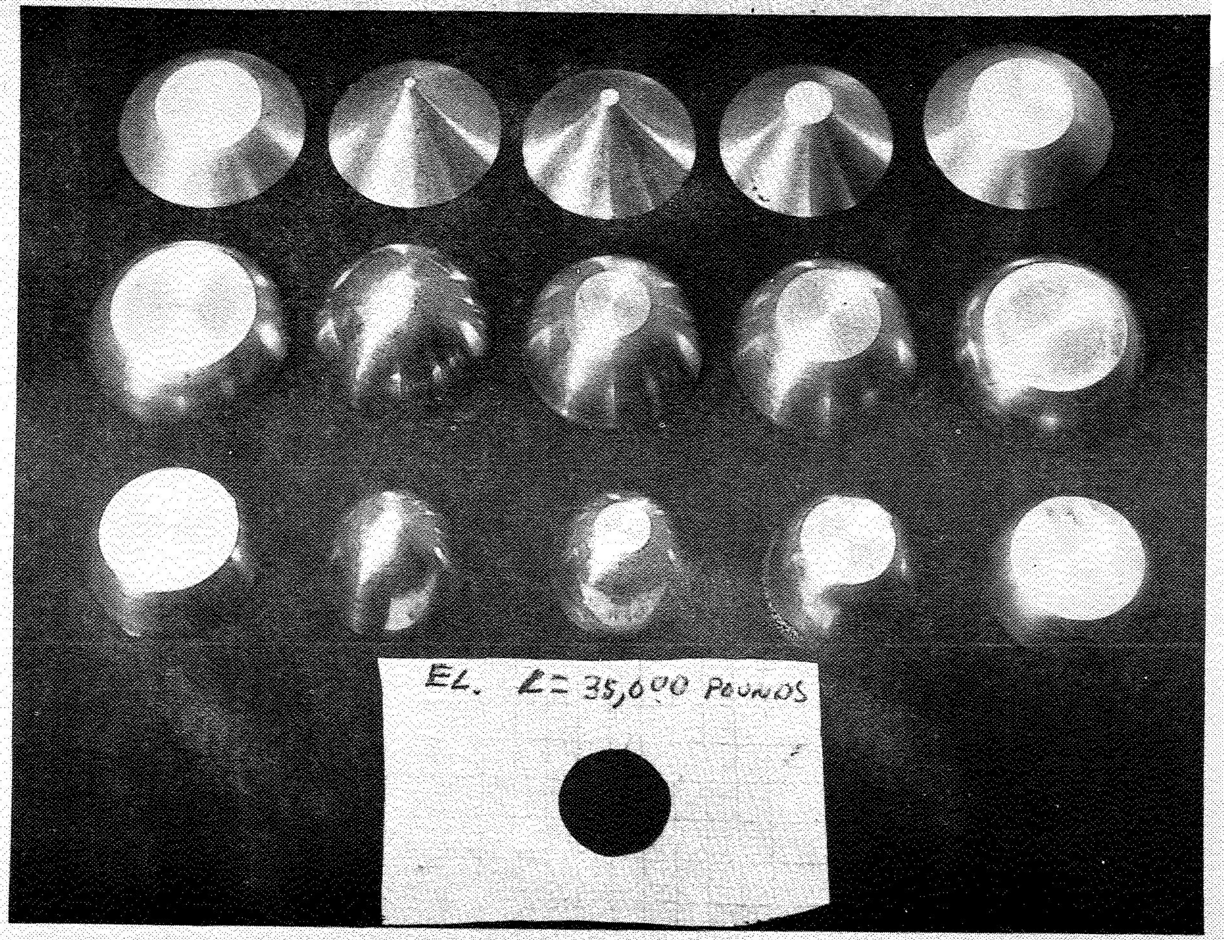

Fig. 10

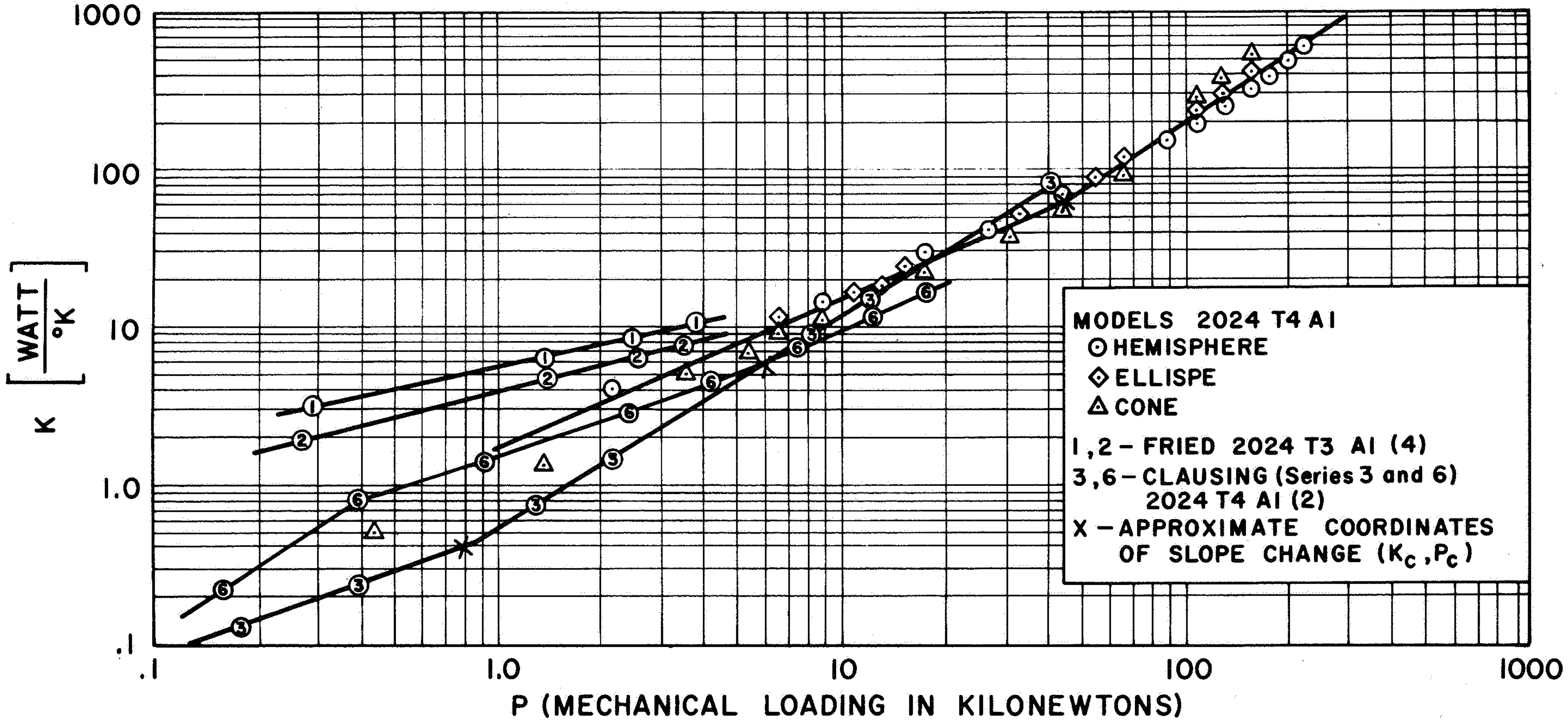

Fig. 11 COMPARSION OF SLOPE CHANGE OF THERMAL INTERFACE CONDUCTANCE DATA AND MODELS

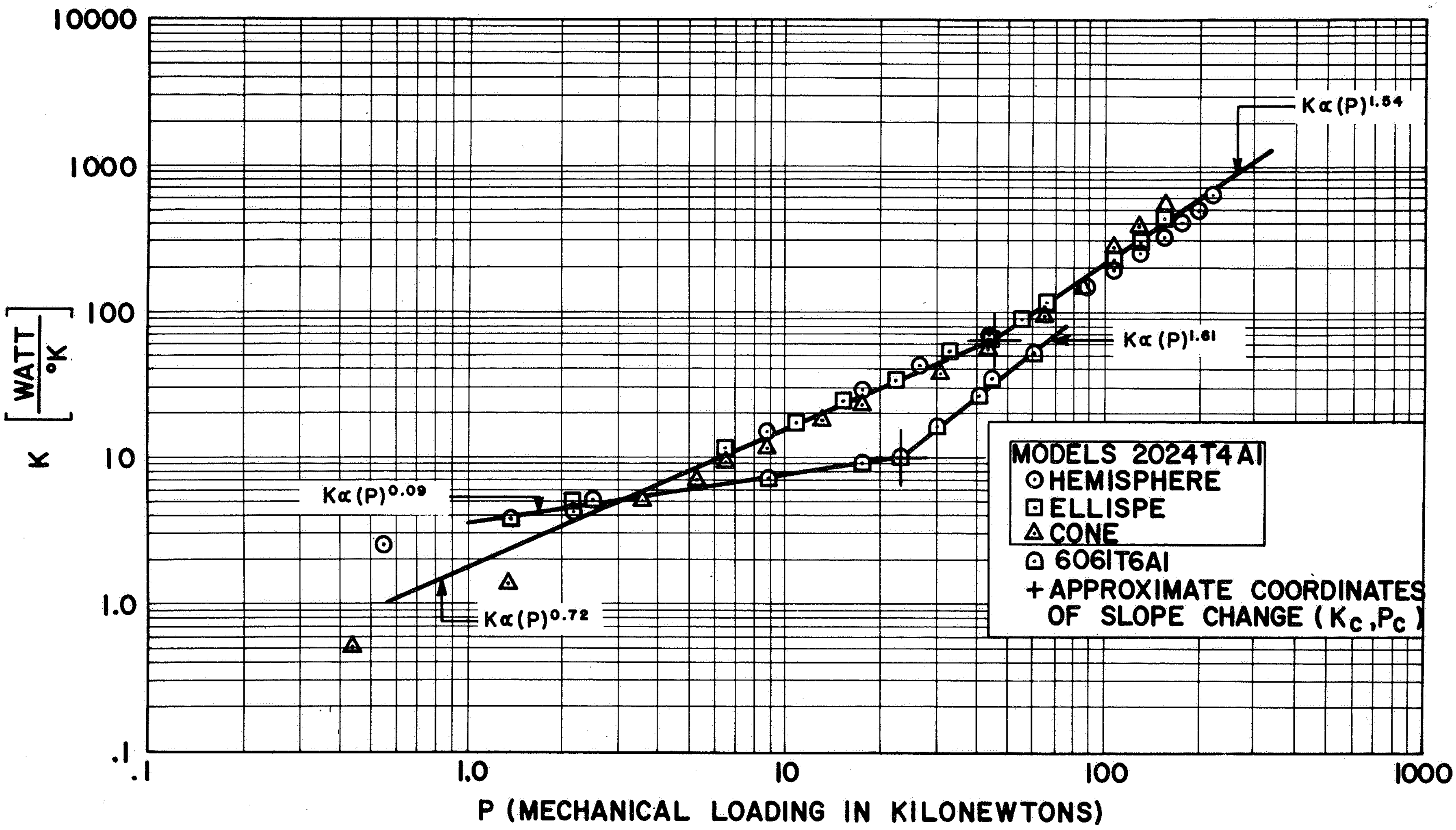

Fig. 12 COMPARSION OF SLOPE CHANGE OF THERMAL INTERFACE CONDUCTANCE DATA AND MODELS

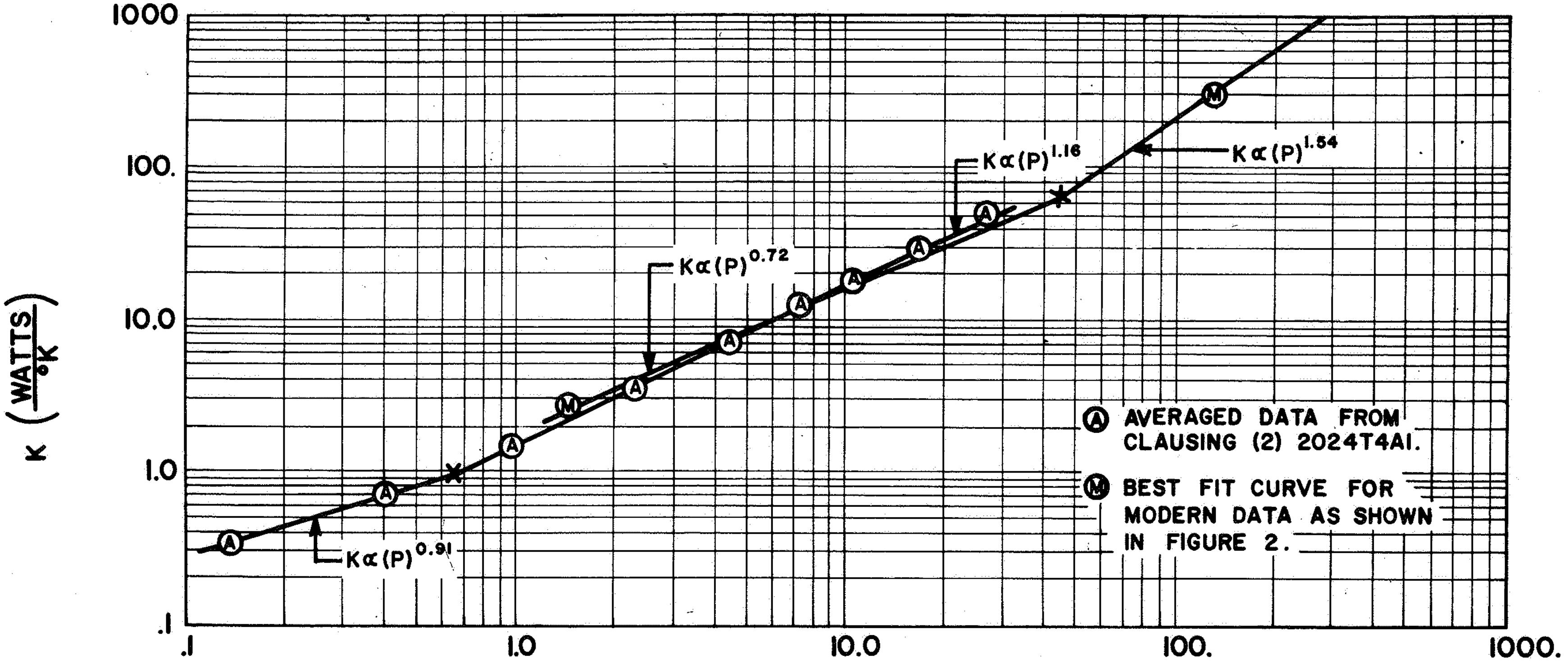

Fig. 13 P (MECHANICAI LOAD IN KILONEWTONS)

COMPARISON OF SLOPE CHANGES OF K_I AVERAGED DATA AND MODELS.